Impact of extremely cold temperatures on the safety of flameproof motors

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Abstract

International requirements for flameproof equipment are contained in International Electrotechnical Commission standard IEC 60079-1. Flameproof equipment is designed so that if an internal explosion of gas or vapour occurs, it will not be transmitted to the surrounding flammable atmosphere. The standard includes two fundamental tests. The first is "Tests of ability of the enclosure to withstand pressure" which includes pressure determination and then overpressure (generally based on the maximum pressure from the previous test with a factor applied). The second is "Test for non-transmission of an internal ignition". However, there is an apparent lack of research data to clearly support some of the testing approaches, in particular where extremely low temperatures are involved. The situation becomes more complex where a phenomenon called pressure piling is involved. This is unpredictable and can lead to significantly higher pressures. Pressure piling is particularly an issue with electric flameproof motors. So the scenarios for such motors at extremely low temperatures become quite hard to predict. This thesis identifies some of the potential issues with the standard relevant to this situation, in particular when supporting data is lacking. It then reports on experiments carried out as part of the PhD project and the analysis of those experiments. The research also investigates ways to assist in predicting explosion pressures in motors based on historical data from type testing of motors, data obtained from tests carried out during this research and the potential for using Computational Fluid Dynamics (CFD). The thesis provides recommendations for changes to the next edition of the standard, information on how to improve testing processes (particularly for motors), and tools to predict likely pressures to be obtained in flameproof motors at normal and extremely low temperatures. It also identifies areas for further research.

Acknowledgements

One might wonder why at the not so young age of 65 I undertook the task of obtaining a PhD. It was really the result of a number of circumstances. First, it was something I had always thought about doing, and so it was "unfinished business". My big brother Bob did a PhD, and I always seemed to be chasing his achievements through my early days until his untimely death to cancer at the age of 27. Next was when I found my two sons engaged in obtaining their PhDs and I realised that I would be the only male in three generations of my family without a doctorate (my father was a Doctor of Science). Competition is strong amongst the males in my family. My son Rob wrote in his dissertation (for Stanford University in the USA) "Paul, it was especially gratifying to be writing my PhD at the same time as you. I promise not to highlight who finished first". My son Paul wrote in his thesis (for the University of Melbourne) "Rob, you may have beaten me in completing a PhD, but at least we have left Dad playing catch-up". So I may be playing catch up, but I have enjoyed every moment of the experience.

Why the University of Sydney? Well, the family history goes back a long way at that institution. My grandmother, Annie Beaumont, became one of the very early female graduates of the university when she graduated in 1898 with a BA. My father was employed there as a radiophysicist with the Radio Research Board for many years. My brother and I did our undergraduate degrees there, and he did his PhD there. My wife did her BSc and DipEd there, and indeed it was where we met and married (in St Pauls Chapel). Our two sons did their undergraduate degrees there. Thus, it was a logical choice.

So I acknowledge the inspiration from many members of my family. But most of all, I must acknowledge and sincerely thank my wife of 45 years, Marilyn Munro, for the support she has provided during this period of my research for my PhD, which often involved me disappearing to various parts of the world, in particular China.

I would also like to acknowledge the support I have had from three supervisors during this research process, namely Associate Professor Dylan Lu, Professor Joe Dong and Associate Professor Weidong Xiao (my final supervisor). I have special thanks for Dr Wang Jun, Director of Nanyang Explosion Protected Electrical Apparatus Research Institute (CNEx), also known as CQST, in China, who has provided significant resources of staff and facilities at CNEx to carry out this research program. Without this support, the research would not have been possible. Three of these staff were particularly active in assisting me with my research; Alice Kou, Ye Jingnan and Hu Yingzhen; all three of whom have been included as joint authors in at least one of my papers. I visited CNEx/CQST about 10 times during this project and met with positive support each time, despite their busy work program. I am currently in discussion with another of the engineers at CQST who has indicated he is keen to carry on my identified future research as part of a master's degree. Assistance received from the staff at PTB in Germany in the provision of published and unpublished information, advice on use of the PTB artefact, the provision of nozzles for hydrogen, and the check testing carried out regarding the pre-pressurisation formula is acknowledged.

I thank the people at the International Electrotechnical Commission (IEC) for permission to reproduce Information from its International Standards. They were also very supportive in providing me with other materials, such as minutes of the early meetings of committee TC 31 and SC 31A which were very helpful. They have requested that I include the following statement in my thesis:

Contents

1 Literature review

1.1 Background

The first international standard related to constructional requirements and testing of flameproof equipment was published in 1957 by the International Electrotechnical Commission (IEC) as Publication 79 [1]. The standard was developed by IEC Technical Committee TC 31 which was first established in 1948. More recently, as the then Chair of TC 31, I provided some background on TC 31 in a number of articles in Hazardous Area International [2-6]. I earlier presented a paper at an IEE conference [7], but that is now a bit dated. Publication 79 was the first TC 31 standard published by IEC. Since then there have been six further editions of the standard (now called IEC standard 60079-1), with Edition 7 being published in 2014 [8]. A list of all editions of the standards and associated documents is shown in 1.11, together with a summary of major testing requirements. A detailed review of the development of the various editions is addressed separately to this chapter, in particular in Chapters 3, 4 and 5. IEC 60079-1 is now adopted by most countries throughout the world, with the most notable exception being the USA. It has adopted the standard for situations where IEC zoning is used, but most US area classification uses divisions. For this, the US uses a technique which it calls explosion-proof. In the USA the requirements for this technique are addressed in local standards, or in legal instruments, such as laws or regulations.

There was much research resulting in the development of individual country standards and regulations well before the international standard was first published. Most of the early research was done in coal mining research institutes with the explosion-protection techniques later being adapted for above-ground industries where explosive atmospheres of gas, vapours or dusts might exist. In some instances research institutes for above ground industries also evolved.

What drove the formation of these research institutes? Coal mining was always recognised as a hazardous industry, but in the early days it was mostly a "pick and shovel" exercise in mining the coal. Hence sources of ignition for methane (fire-damp) or coal dust atmospheres were low. But open flames were a common source of ignition. The advent of the Davy lamp which is a safety lamp for use in flammable atmospheres, consisting of a wick lamp with the flame enclosed inside a mesh screen, provided one way of dealing with this. It was invented in 1815 by Sir Humphry Davy [9] and would have reduced the possibility of an explosion. But it was clearly not universally adopted; for example, see Figure 1 of a child coal miner wearing a cloth cap with an open flame oil cap lamp in the USA, circa 1900 [10]. The Davy lamp may still be found in some coal mines to the present day as means of detecting the presence of methane.

Figure 1 – Child coal miner

The advent of technology and the push for greater production seems to have led to a significant increase in explosions or other events, such as roof falls, which pushed the death rate higher. An increase in the number of people underground at any time may have also meant a corresponding increase in the number deaths when an explosion occurred. It appears two of the major new sources of explosions were the use of explosives and the use of electricity according to Breslin and Dill [10, 11]. There were three research institutes which seem to have played a key role in the early days. In each case, the main impetus for their establishment appears to have been a dramatic increase in the number of deaths. I will briefly address the establishment of each of these.

For Germany, Dill [11] reports that in Germany when "the annual number of fire-damp explosions reached three figures, it became necessary to act quickly". Hence in 1894, The Westphalian Mining Company Fund Mine established an explosion gallery in Gelsenkirchen-

Schalke to investigate the influence of explosives on firedamp and coal dust. This subsequently became the Institute for Explosion Protection and Blasting Technology (BVS). Its first Director was Beyling (more later about him). Figure 2 is a photo that I took in the year 2000 of a demonstration explosion in one their explosion galleries in Dortmund.

Figure 2 – Explosion in explosion gallery at BVS Dortmund.

In the USA, Breslin [10] states that in the single month of December 1907 there were a number of coal mine explosions that killed more than 600 miners. In one explosion alone, 362 miners died, making it the worse mine disaster in US history. This no doubt was a driving factor in the establishment of the Bureau of Mines in 1910, although research had previously commenced within government departments, particularly looking at permissible explosives to be used underground.

In the UK, Luxmore [12] provides a summary of the early days. When electricity was first introduced in coal mines in the 1880s, almost a million people were employed in the industry. In 1880 there were 4,231 collieries. By 1900 safety legislation was in place, but there were still over 1,000 miners killed every year, and legislation put no restrictions on the use of electricity. In 1902 the Secretary of State for the Home Office created a committee to look at the use of electricity in coal mines. Submissions to this committee included proposals for "flame-tight" constructions for electric motors. These were the forerunners of today's flameproof motors which are the subject of this thesis. The history of UK research establishments in the field is covered by Curran [13]. On 3 May 1911 the Secretary of State for the Home Department, Mr Winston Spencer Churchill, advised that "Treasury have sanctioned the considerable expenditure that will be necessary for the purpose" (of continued experiments into coal dusts). This led to the establishment by the Home Office of an

Experimental Station at Eskmeals in Cumberland. In 1920 the Safety in Mines Research Board (SMRB) was created, and in 1927 it moved to a new laboratory near Buxton. Another site was opened in Sheffield in 1928. In 1946, after nationalisation of the coal industries, the two sites came together as the Safety in Mines Research Establishment (SMRE). The site near Buxton now operates as the Health and Safety Laboratory. The first International Conference of Safety in Mines Research Institutes was held at SMRB near Buxton in 1931. [1]

There were various other research institutes which were established in the early days of mining, in addition to the ones mentioned above. These included: France (CERCHAR - Centre d'Etudes et Recherches des Charbonnages de France), Germany (PTB, in addition to BVS) , Canada (CANMET), South Africa (SABS), Russia (Skochinsky Institute of Mining), India (CSIR-Central Institute of Mining & Fuel Research, Dhanbad), China (China Coal Research Institute) and Japan (Research Institute of Industrial Safety (Japan) - RIIS).

Most, if not all, were government owned. Today most of the research institutes have closed or changed their focus to commercial testing and certification. However, some still retain a research capability. Many have now been privatised. Where research is now carried out, it is mainly on the basis of research grants for specifically identified projects. Some research continues to be done by universities and other research institutions. Where relevant, this review has drawn on papers published by those bodies.

Relevant product research is also carried out within companies, but the research may not be published, and the results are often commercial-in-confidence. Some may also lead to patents. Interesting results may also be found as a result of testing of manufacturers' products for the purpose of certification, but again the results are generally commercial-in-confidence.

1.2 The origins of the "flameproof" technique

The "flameproof" type of protection for equipment is the earliest and is probably still the most widely used type of protection to ensure electrical equipment does not cause an explosion in an explosive atmosphere of gas or vapour. It is also sometimes used for non-electrical equipment, such as diesel engines. The basic concept involves not excluding a gas or vapour from an enclosure but ensuring that, if there is an explosion within the enclosure, then the explosion does not spread to the surrounding explosive atmosphere. This means the enclosure needs to be strong enough to withstand the explosion and there must be a means of ensuring the transmission of the explosion via joints of the enclosure does not cause an external ignition. More detail about this approach will be given later in this thesis. This type of protection goes by a few names. In the USA it is mostly called explosion-proof. It is also commonly called Ex d or flameproof enclosure "d" with the "d" coming from the German words "druckfeste kapselung" which translates as "flameproof enclosure". Throughout this document, unless otherwise indicated, the terms flameproof, explosion-proof, Ex d and flameproof enclosure "d" may be considered to be synonymous.

Published literature suggests that this approach was first developed in the late 1800s and early 1900s. In the UK, the first term used was "flame-tight". Luxmore [12] states that this was referenced in the UK by a committee formed in 1902 "to enquire into the use of electricity in coal and metalliferous mines and the dangers attending to it". The committee (amongst other things) recommended that "all terminal (sic) should be enclosed in a flame-tight casing". He also indicated that experiments had begun in Germany by Beyling in 1884. Luxmore further provides evidence that there was work going on in the UK at that time, for example, Henry Davis of Davis Ltd submitted a report to the 1902 committee describing a flame-tight dc motor that he had designed.

The first major publication on this subject was a report by Dr Ing Carl Beyling in 1906 [14] describing the results of extensive research done at BVS. This report provides some key information; much of which remains valid to this day. The report is in German, but Dr Wolf Dill (personal communication 24 February 2015), a former head of that body, has provided me

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[1] This conference continues to this day with SMRE again hosting the conference in 1983. I prepared and presented a paper at that conference, the 20 International Conference of Safety in Mines Research Institutes (Lloyd and Munro 1983) dealing with the another major technique for explosive atmospheres, intrinsic safety.

by email with the following English summary of some of the main outcomes of the research included in the publication, as follows:

- also non-sparking motors were assessed to be an ignition hazard, because damage of insulation and hot spots because of overload (page 10)
- flammable atmosphere was expected to ingress any enclosure with gaps, even very small ones, by thermally induced “breathing” or by diffusion (page 14)
- determination of the methane concentration (7-8 %) for the maximum explosion pressure 6.5 bar (page 27, 29)
- explosion pressure rise as function of methane concentration (page 28)
- influence of the atmospheric pressure (e.g. underground elevated) on the maximum explosion pressure (page 29)
- proposal to include a safety factor for the maximum pressure in the design of the equipment (page 29)
- determination of the influence of internal components in enclosures
- first attempt by installing a sort of hopper in the test chamber (page 30)
- second attempt by installing a wood board separating the volume in the relation 2:3 and with a 30 mm hole
- resulting explosion pressure curve see fig 41 (page 31)
- velocity of explosion pressure front is higher than the velocity of the flame zone (page 31)
- explosion pressure in connected enclosures (page 32, figure 43); explosion pressure 16 bar
- experiments with “labyrinths” to cool down the exploding gas when leaving the enclosure (page 36)
- experiencing that even small holes (which could not have a cooling effect) could prevent ignition transmission (page 36)
- experiments with single or multiple holes and also a slit (page 37)
- finding that the difference between pressure of the exploding mixture and the outside atmosphere is significantly influencing the cooling effect (by expansion) on the escaping hot gas (page 39)
- finding that the place of the ignition source influences the results of the ignition transmission experiments (page 39)
- mentioning that a flat gap of 0.5 mm will be safe concerning ignition transmission, regardless of the place of the ignition source (page 40)

Clearly, the work of Beyling was widely valued in the international community as, according to McMillan [15], Beyling was awarded the medal of the UK Institution of Mining Engineers in 1938 for his work on safety in mines. Of particular interest to the research covered by this thesis is the reference of Beyling to the effect now called "pressure piling". This occurs in a flameproof enclosure when there is a restriction between one side of an enclosure and the other. This effect will be examined more closely in later chapters.

1.3 Explanation of the "flameproof" explosion protection technique

IEC 60079-1 Edition 7 [8] has the following definition for flameproof enclosure “d”:

> enclosure in which the parts which can ignite an explosive gas atmosphere are placed and which can withstand the pressure developed during an internal explosion of an explosive mixture, and which prevents the transmission of the explosion to the explosive gas atmosphere surrounding the enclosure

Munro in the first edition of HB13 *Electrical equipment for hazardous areas* which had its latest edition issued in 2007 [16] and a Training Manual No. 181-1 (Munro, 1998) has explained the important aspects of an earlier version of the definition. The following analysis draws on that, but modifies it to relate it to the latest definition:

Can withstand the pressure developed. Substantial pressures can be generated due to an explosion within a flameproof enclosure. Typical pressures are in the range of 200 to 1,000 kPa, but in some cases can rise even further. It is most important that an enclosure can withstand the particular pressures that it may encounter in service. The pressure created by the explosion within the enclosure is released to the atmosphere so that the enclosure is not permanently deformed in a way that can impair the integrity of the enclosure.

Which prevents the transmission of the explosion. As the explosive pressure within the enclosure forces its way through the gaps in the enclosure, the explosion flame is carried with it. If the energy of the explosion is not reduced as it forces its way through the gaps the explosion pressure front could have sufficient energy to ignite a surrounding explosive atmosphere. The specially designed gaps and joints in the enclosure are referred to as flame paths.

More detail will be provided in later chapters on how IEC 60079-1 applies tests to check the above.

Figure 3 shows examples of Ex d equipment. The first two are of a flameproof junction box with the cover off and then partially fastened.

Figure 3 – Examples of Ex d equipment

1.4 Pressure piling

For normal enclosures, the explosion pressure develops reasonably uniformly through the enclosure. However, when an enclosure incorporates some form of restriction between two parts of the enclosure the situation changes.

When an explosion occurs on one side of the restriction, the gas or vapour in the other side is compressed prior to ignition by the flame front. This leads to a higher pressure than when no restriction is present. As noted earlier, this was recognised early on by Beyling [14]. Later, in 1929, Grice and Wheeler [17] published a Safety in Mines Research Board paper looking closely at this subject.

IEC 60079-1 [8] has the following definition of pressure piling:

> **pressure-piling**
> results of an ignition, in a compartment or subdivision of an enclosure, of a gas mixture precompressed, for example, due to a primary ignition in another compartment or subdivision

NOTE IEC 60079-1 shows the above definition as "pressure-piling", but the standard sometimes uses it in the form with the hyphen and sometimes without, ie "pressure piling". The IEC International Electrotechnical Vocabulary IEV 60050-426 [18] shows the same definition but without the hyphen. So generally within this thesis, it is used without the hyphen unless referencing material where the hyphen is used.

However, there are other factors involved than just the pre-compression. Di Benedetto, Russo and Salzano [19] state that

> the pressure piling phenomenon is the result of the combination of: (1) the precompression effect arising from the jet flow from the ignition vessel); (2) the turbulence induced by the fast flame propagation (jet ignition) in the secondary vessel; and (3) the vent flowing toward the ignition vessel, which mitigates the peak pressure.

Figure 4 below shows the process diagrammatically, with an ignition in the left-hand compartment pressurising the gas/air mixture in the right-hand compartment which once ignited creates a higher pressure.

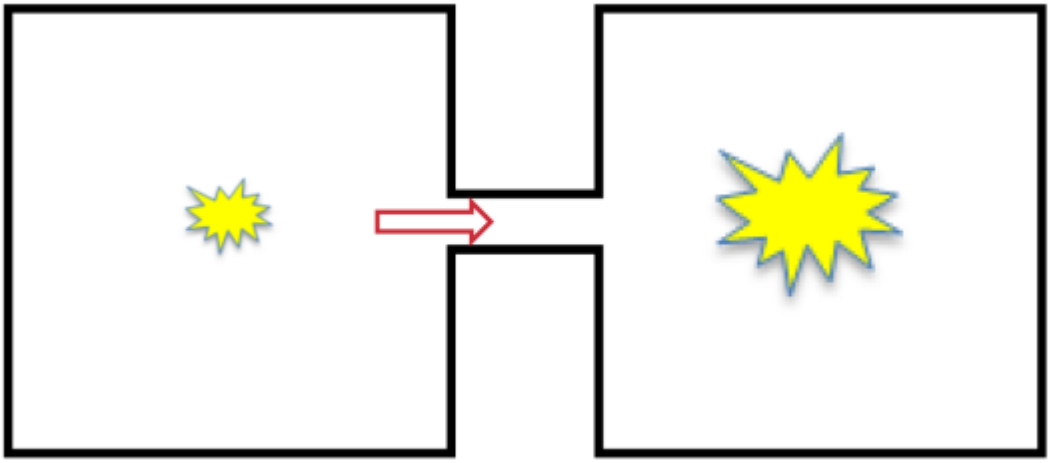


Figure 4 – Pressure piling

Pressure piling is of relevance to flameproof motors incorporating an air gap between the stator and rotor, because this can often provide the conditions necessary for pressure piling to occur. Other communication paths can also occur, such as cooling ducts or open connections to the terminal box. The problem can be significantly exacerbated by low temperatures, as will be explained later, thus establishing one of the most significant issues associated with flameproof motors at extremely low temperatures.

There is limited published research on pressure piling in flameproof motors. There have been some recent publications on work done in Romania [20-23] and not quite so recently in India [24]. But the amount of data provided on maximum explosion pressures obtained is limited or missing entirely.

Over the years since Beyling published his work, there have been a number of studies into pressure piling for other than motors, and this review draws on those studies.

1.5 Studies on explosion pressures at very low temperatures

The studies on explosion pressures at very low temperatures are minimal. I have only been able to locate two relevant investigations, one is 40 years old [25] and the other, (by PTB) about 20 years old. Only the former study addresses pressure piling. It has been published in one report and two papers [25-27]. However, there are some discrepancies between the graphs shown in the report and those in the papers. In this thesis the data from the report has been used. The data from the PTB study was purportedly used to develop requirements in IEC 60079-1 for testing equipment designed for very low temperatures, but a report on the testing was never published. PTB have provided the raw data from that testing to me when I visited them (personal communication, 20 July 2015).

The work of Lobay above looked at the effect of ambient temperature upon maximum explosion pressures in a single chamber apparatus and in a pressure piling test apparatus. The experiment covered hazardous atmospheres in (USA) Groups A, B, C, D and coal mining applications. The results for the tested temperature range of approximately -50 °C to +40 °C indicated a linear increase in explosion pressures as the temperature is reduced. This is not unexpected as the explosion pressure is very closely linked to the gas density (number of moles) which increases as temperature decreases.

However, different gases did exhibit different slopes. This is potentially at variance to IEC 60079-1 which specifies one factor for all test gases.

The following concentrations of gas were used: propane 4.6%, methane 9.8%, ethylene 8.0%, hydrogen 32% and acetylene 14.5%. The series of explosions started at -50 °C and was increased at increments of not more than 3 °C to +40 °C. More detail and analysis on the report by Lobay are provided in 2.3.2.

The concentrations used fall within the tolerance of those in the IEC 60079-1, although the concentrations for hydrogen and acetylene are different to the median figure specified. No tests are reported for the mixture of (24 ± 1) % hydrogen/methane (85/15) which is included in the standard for Group IIB for cases where pressure piling may occur.

The temperature range tested only goes down to -50 °C. IEC 60721-2-1 [28] shows temperatures can be as low as -60 °C in areas designated as "polar". Personal communication has suggested that temperatures can occasionally get down to -70 °C.

The data supplied by PTB show testing in the range of -50 °C to -20 °C with hydrogen and acetylene only. The concentrations shown for hydrogen and acetylene fall within the tolerance of those in IEC 60079-1.

The PTB work has the same temperature restriction as Lobay's work. The range of gases used is more restricted.

1.6 Published data on explosion pressures for flameproof motors

I have only been able to locate limited published data on possible pressure figures for flameproof motors at any temperatures, and even less published data for motors at low temperatures. Hence the likelihood of manufacturers being able to predict the pressure they need to design their motors to withstand is probably based on their own previous experiences when equipment has been tested for certification. Sometimes the lessons are only learned when a motor fails test and has to be redesigned. This can be a costly exercise. Magyari et al [20, 21] have attempted to provide motor manufacturers with guidance, but this seems to focus on eliminating pressure piling. This can be very hard to do with a flameproof motor without compromising other design considerations such as efficiency and ventilation. The only references I can find to possible pressures in motors at low temperatures are included in a paper by Phillips [29] where he quotes some figures provided privately by Schram of UL, and in three very similar papers by Gallant and Jackson [30-32]. I have also been provided with some information from manufacturers about motors they have had tested at extremely low temperatures.

An outcome of my research will provide manufacturers with a better understanding of pressures that can be developed in flameproof motors, particularly at very low temperatures.

1.7 Detonation

Detonation is a type of combustion involving a supersonic exothermic front accelerating through a medium that eventually drives a shock front propagating directly in front of it. It is not referred to in IEC 60079-1. However, it does sometimes occur in flameproof equipment under test. The resultant pressure is much higher than normal pressures, and higher than those as a result of pressure piling. Of further concern when this happens is that the pressure transducers, which are designed for measuring deflagration explosions, may not be capable of accurately measuring pressures of a detonation. So the possible occurrence of detonation needs to be considered when looking at flameproof motors. Phillips has addressed this phenomenon and recognised its significance [29]. The scenario can become complex. He states that "With detonation the maximum pressure is recorded when the detonation is just being formed close to the pressure transducer, and the fuel concentration needs to be adjusted to find this condition". Thus there are critical elements related to time, gas concentration and position of pressure measurement.

1.8 Computational Fluid Dynamics

The use of Computational Fluid Dynamics (CFD) may present a tool for motor designers. There is a body of published literature on the use of this that may be relevant to flameproof enclosures, including when pressure piling may be present, for example, theses/dissertations by Middha [33] and Rogstadkjernet [34]. Both make use of the CFD program FLACS, with the second document looking at combustion of gas in closed, interconnected vessels where pressure piling may occur. 20 years ago, Gallant made some reference the potential of CFD for predicting explosion pressures in flameproof motors and implied he was progressing research in this area [30-32]. However, I can find no indication of any later published work on the use of CFD for motors by him or anyone else.

Skjold el al [35] looked at CFD simulations using FLACS and DESCA, involving dust and gas explosions in a 3.6 m flame acceleration tube. The gas used was propane. They achieved

some good correlations. However, the paper makes the following statement: "The present study was limited to 3.0 cm cubical grid cells throughout the computational domain, since further refinement would be in violation with stated grid guidelines". It will be seen later that this is a critical issue in this exercise of simulation of explosions.

A comparison exercise done by Garcia et al [36] provides some insight into CFD models, but this was only done for large-scale hydrogen deflagration in open atmosphere. So it is not of direct relevance to flameproof enclosures. However, it does provide some information on other CFD programs.

An exercise carried out at the Health & Safety Laboratories in Buxton, UK [37] in the mid-1960s on the prediction of explosion pressures in confined spaces provided an early look at the opportunities to use CFD for enclosures such as flameproof enclosures. This has been cited by numerous later studies. Many of these look at the scenarios involving pressure piling and detonation. The Health & Safety Laboratories later issued a report in 2002 [38] *A Review of the State-of-the-Art in Gas Explosion Modelling*.

However, I was able to locate only minimal work regarding the use of CFD for predicting explosion pressures in motors at ambient temperatures, and I located no evidence of its use for determining explosion pressures in motors or enclosures at very low temperatures. Hence, I decided to investigate the <u>potential</u> of using CFD as a tool to predict explosion pressures in flameproof motors, including at very low temperatures.

The magnitude of this exercise in addition to other proposed research precluded committing to an exhaustive study, but the intention was to at least provide an indication of its potential value. This investigation is reported on in Chapter 10.

1.9 Flame transmission

The mechanism that ensures there is no flame transmission from a flameproof enclosure to a surrounding atmosphere is a complex one and still subject to ongoing research. Phillips [39] in his paper "The Physics of The Maximum Experimental Safe Gap" delivered to the 1987 "International Symposium on the explosion hazard classification of vapors (sic), gases & dusts" in the USA, has provided a summary of the mechanism for the ignition of a flammable atmosphere by the jet of hot gases emerging from a gap. He stated it occurs in stages:

- entrainment of cold unburnt gases into the jet followed by burning of the entrained gases;
- heat transfer from hot gas to cold flange surfaces followed by entrainment and burning; and
- heat transfer, taking into account the internal explosion pressure, followed by entrainment and burning.

Much earlier work led to the above understanding, in particular, work by Phillips [40-45]. Work continues seeking a better understanding, for example, Sadanandan [46] in the paper "Detailed investigation of ignition by hot gas jets". I am also aware that work on this topic is currently being done in PTB in Germany, having attended a demonstration at PTB in Braunschweig, Germany in July 2014. I also met with the AMME Combustion Group at the University of Sydney to get a better understanding of this topic and the research they are currently doing. In addition, I have been able to draw on the extensive CFD experience of Adjunct Professor David Fletcher at the University of Sydney.

An important aspect I wish to draw on here is that in addition to possible structural integrity issue, there is also the effect that internal pressure has on flame transmission. The higher the internal pressure from the explosion, the more likelihood that there will be flame transmission. This has been demonstrated for motors by Magyari et al [20] where they state:

> The researches (sic) conducted in the specialized Laboratory of INSEMEX Petrosani, on a very large number of flameproof motor samples have identified the pressure pilling (sic) phenomenon as the main responsible for the transmission of an internal explosion in the case of self ventilated electrical motors.

For motors at low temperatures, the scenario becomes more complex. At low temperatures, the likelihood of transmission through a flamepath appears to have been assumed to be reduced. Lunn [47] has some information on the effect of temperature on the value of

Maximum Experimental Safe Gap (MESG). See more information on MESG in 1.10 below. But there is limited published information on the effect of temperature on MESG and hence flame transmission. Perhaps due to the lack of information, IEC 60079-1 does not require equipment designed for extremely low temperatures to be tested for non-flame transmission at other than normal ambient temperature. But, the standard does not take account of the higher pressures encountered at very low temperatures, in particular where pressure piling or detonation may be present, and the potential effect on flame transmission.

I have been unable to find published research that looks at the correlation of increased pressures at very low temperatures and the possible consequence of flame transmission. This is particularly relevant where pressure piling may be present. Hence, this was identified as an area of research for this PhD project. This research is reported on in Chapter 3.

1.10 Maximum Experimental Safe Gap (MESG)

The MESG of a gas or vapour is determined in accordance with the procedure shown in IEC 60079-20-1 [48] which defines MESG as:

> maximum gap between the two parts of the interior chamber which, under the test conditions specified below, prevents ignition of the external gas mixture through a 25 mm long flame path when the internal mixture is ignited, for all concentrations of the tested gas or vapour in air

The scope of that standard includes the following explanation:

> [It is] a test method intended for the measurement of the maximum experimental safe gaps (MESG) for gas- or vapour-air mixtures under normal conditions of temperature and pressure so as to permit the selection of an appropriate group of equipment.

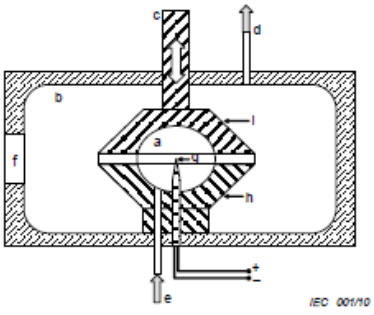
The apparatus used for this testing is shown schematically in Figure 5 below. Both the internal chamber and the external enclosure are filled with a gas or vapour mixed with air at normal conditions of temperature and pressure. The adjustable part, which is often a micrometer arrangement, is used to accurately achieve the desired gap between the gap plates which provides a flamepath of 25 mm in length. The mixture in the internal chamber is ignited and flame propagation, if it occurs, can be seen through the observation window. The MESG will be the maximum value of gap that will prevent ignition of the mixture in the external enclosure.

IEC 60079-20-1 shows the subdivision of Group II equipment based on the MESG limits as:

Group IIA: MESG ≥ 0,9 mm.

Group IIB: 0,5 mm < MESG < 0,9 mm.

Group IIC: MESG ≤ 0,5 mm.



Key

a interior spherical chamber
b exterior cylindrical enclosure
c adjustable part
d outlet of mixture
e inlet of mixture
f observation windows
g spark electrode
h lower gap plate, fixed
i upper gap plate, adjustable

Figure 5 – MESG apparatus

NOTE The number of IEC 60079-20-1, will change for the next edition which is expected to be published sometime in 2018. The new number will become ISO/IEC 80079-20-1. The figure above has been taken from the current standard with the kind permission of IEC.

1.11 Review of published standards for Ex d

The published IEC standards and related documents directly relevant to Ex d are shown in TABLE 1 below. Since 1983 requirements common to more than one explosion-protection technique have appeared in IEC 60079-0 "Explosive atmospheres – Part 0: Equipment – General requirements", with the latest edition published in 2011 [49].

TABLE 1 – IEC STANDARDS PUBLICATION DATES

Type	Number	Date	Edition	Title
Publication - IEC recommendation	79	1957	1	Recommendations for the construction of flameproof apparatus
Publication - IEC recommendation	79-1	1971	2	Electrical apparatus for explosive gas atmospheres Part 1 - Construction and test of flameproof enclosures of electrical apparatus
International standard supplement	79-1A	1975	2 First supplement	First supplement to international standard 79-1 (1971) Electrical apparatus for explosive gas atmospheres Part 1 - Construction and test of flameproof enclosures of electrical apparatus Appendix D: Method of test for ascertainment of maximum experimental safe gap
Amendment	79-1	1979-09	2, Amendment 1	
International standard	79-1	1990-12	3	Electrical apparatus for explosive gas atmospheres Part 1 - Construction and verification test of flameproof enclosures of electrical apparatus
Amendment	79-1	1993-08	3, Amendment 1	
Amendment	79-1	1998-05	3, Amendment 2	
Consolidation	79-1	1998-08	3.2	
International standard	60079-1	2001-02	4	Electrical apparatus for explosive gas atmospheres Part 1 - Flameproof enclosures “d”
Interpretation Sheet	60079-1	2007-02	4th Edition/ I-SH 01	
International standard	60079-1-1	2002-07	1	Electrical apparatus for explosive gas atmospheres – Part 1-1: Flameproof enclosures “d” – Method of test for ascertainment of maximum experimental safe gap
International standard	60079-1	2003-11	5	Electrical apparatus for explosive gas atmospheres Part 1 - Flameproof enclosures “d”
Interpretation Sheet	60079-1	2007-02	5th Edition/ I-SH 01	
International standard	60079-1	2007-04	6	Explosive atmospheres – Part 1: Equipment protection by flameproof enclosures “d”
Corrigendum	60079-1	2008-09	6th Edition/ Corrigendum 1	
International standard	60079-1	2014-06	7	Explosive atmospheres – Part 1: Equipment protection by flameproof enclosures “d”

1.12 Major tests

For the testing the equipment to establish compliance with IEC 60079-1, there are three major types of types of explosion-related tests that are carried out. Generally this testing will be done by a third-party testing laboratory as part of the process of obtaining certification to that standard. Such tests are carried out on equipment, often prototypes or samples, supplied by the manufacturer. These tests are:

- Determination of the explosion pressure (reference pressure)
- Overpressure test

- Test for non-transmission of an internal ignition

1.12.1 Determination of the explosion pressure (reference pressure)

This test is carried out to determine the reference pressure which is the highest value of the maximum smoothed pressure, relative to atmospheric pressure, observed during a number of tests.

The test involves igniting an explosive mixture inside the enclosure and measuring the pressure from the resultant explosion. An ignition source, such as a spark plug, is used to ignite the mixture. A device inside the enclosure which produces sparks may also be used. Dynamic pressure transducers are used to measure the pressure produced by the explosion. A range of gases mixed with air is specified relating to the Equipment Group of the equipment, and these may also take into account the possibility of pressure piling. The following gases may be used: methane, propane, ethylene, hydrogen, acetylene and a hydrogen/methane mix. The precise mixtures to be used are specified. In some cases more than one type of explosive gas is used for an Equipment Group.

The test is carried out a minimum of three times. But for complex equipment, such as motors, many tests may be involved. Any gaskets supplied with the equipment are kept in place for these tests. Rotating electrical machines are tested at rest and running. The maximum pressure obtained becomes the "reference pressure". The "rise time" is also measured and a rise time below 5 ms may lead to additional testing measures.

If equipment is intended for use in ambient temperatures at or above -20 °C, testing is done in normal ambient conditions. This could be anywhere in the range of -20 °C to +40 °C.

If equipment is intended for use in ambient temperatures below -20 °C, three options are presented. This will be dealt with in more detail later, but the following summarises the options:

1) Test at minimum ambient temperature for which the equipment is intended. For example, an item of equipment intended for a minimum temperature of -40 °C would be tested at -40 °C.
2) Test at normal ambient temperature but at increased pressure. The absolute pressure of the test mixture *(P),* in kPa, is calculated by the following formula, using $T_{a,\min}$ in °C:

   $P = 100[293 / (T_{a,\min} + 273)]$ kPa
3) Test at normal ambient temperature and then apply a test factor for reduced ambient conditions to obtain the reference pressure. Depending on the size of the enclosure, there may be conditions regarding the overpressure that must be used and the provision for routine pressure testing. This option is not permitted for rotating electrical machines such as electric motors.

There is no evidence in published literature, or through discussions with people active in the development of the standard, of investigations to correlate all three of the above approaches. In particular, I could find no published literature to demonstrate the use of increased pressure produces a result consistent with tests at low temperatures, especially in the case of pressure piling, which is relevant for motors.

1.12.2 Overpressure test

The pressure applied is based on the reference pressure times a factor. This factor can be 1.5, 3 or 4. If reference pressure determination has been impracticable due to the small size of the equipment, the standard specifies pressure figures to be applied. If the factor applied is 1.5, then every enclosure manufactured must be subject to a routine pressure test.

The overpressure test can be applied statically or dynamically. For the dynamic test, the pressure of the mixture inside the enclosure is increased by a factor of 1.5. The standard is not clear how a dynamic pressure test would be applied for temperatures designed for very low temperatures when tested at ambient temperature.

1.12.3 Test for non-transmission of an internal ignition

For this test, the enclosure under test is placed in a chamber such that both can be filled with an explosive gas. There are a number of options for how a factor of safety can be achieved, including increasing gaps, using test mixtures with a factor of safety and using increased pressures. Equipment for use in very low temperatures, including electric motors, can be tested at normal ambient. The test is carried out at least five times.

A range of gases mixed with air is again specified relating to the Equipment Group of the equipment. The following gases may be used with air: methane-hydrogen, hydrogen and acetylene. Where Group IIA or IIB enclosures may be damaged by test, it is permitted to use propane or ethylene respectively. In addition to mixtures with air, there are also hydrogen-oxygen-nitrogen and acetylene-oxygen-nitrogen mixtures which can be used. The precise mixtures to be used are specified and are different to those for pressure determination, even when the same gas is used. There are various means of achieving the relevant factor of safety depending on the gas used.

The standard takes no account of the possible effect of increased pressures due to lower temperatures that could lead to a transmission. As noted earlier, I could find no published literature to verify this is a viable approach.

For equipment with flamepaths other than threaded joints, and intended for use at an ambient temperature above 60 °C, the non-transmission tests are to be conducted under one of the following conditions:

- at a temperature not less than the specified maximum ambient temperature; or
- at normal ambient temperature using the defined test mixture at increased pressure using defined factors; or
- at normal atmospheric pressure and temperature, but with the test gap i_E increased by specified factors.

1.13 Research proposals arising from the above literature review.

As a result of the above literature review, a project plan incorporating five major elements was developed. These were based on two major aspects; first, in relation to standards, and secondly, in relation to providing better information for manufacturers with respect to motors at normal and extremely low temperatures. The project plan was:

1) Investigate the suitability of the current factors for pressure testing in IEC 60079-1 at "normal" and extremely low temperatures.
2) Carry out tests/experiments to look at the impact of increased pressures at extremely low temperatures that could lead to flame transmission.
3) Carry out investigations and tests/experiments to check the validity of current tests in IEC 60079-1 using increased pressures at "normal" ambient temperature to test equipment, especially motors, intended for extremely low temperatures.
4) Develop information for manufacturers regarding indicative pressures, based on a combination of existing information and tests carried out by this project. This was later extended to look at how the information could be used by certification and testing bodies, and in standards development.
5) Investigate the potential to make use of CFD as a tool to predict pressures in flameproof motors.

Each of the above is addressed in the following chapters of this thesis. In 2016 I presented peer-reviewed papers at international conferences/symposia on the first three topics, and two of those papers have subsequently been published as peer-reviewed papers in journals. More detail on these publications is provided elsewhere in this thesis.

2 Suitability of pressure safety factors

2.1 Introduction

Chapter 1 provided an introduction to the development of international standards in this field with TABLE 1 showing the key standards developed for the flameproof technique. This chapter will go into more detail on the development of those standards, including deliberations at standards meetings. Later chapters will look more closely at the development of the standards requirements for flame transmission and overpressure testing.

Most of the content of this chapter was presented to IEEE PCIC Europe conference in Berlin in June 2016 [50]. A section providing an historical introduction has been dropped here because it is covered in this thesis in 1.1.

2.1.1 First four meetings of IEC TC 31

The first meeting of the newly formed IEC “Advisory Committee TC 31: Flameproof Enclosures” took place in London from 7 to 9 July 1948. With the kind permission of the IEC, some information can be provided from those meetings. Of interest is an opening statement from the Chairman of the British National Committee on Flameproof Enclosures as recorded in the minutes:

> during the war, much electrical equipment imported into the United Kingdom from the U.S.A. had been made to U.S.A. standards, which differed in some respects from British standards. This created problems for technical people and government officials concerned, resulting in suggestions being made to the B.S.I. that, if possible, international agreement should be obtained on the requirements of flameproof enclosures.

TC 31 held three further meetings prior to the publication of the first flameproof standard. These took place in Paris in November 1949, London in April 1953 and Philadelphia, USA in September 1954. During the meetings the decision was also taken to include in the publication the words: "The term ‘flameproof’ is synonymous with the term ‘explosion-proof’." That has been dropped from more recent editions of the flameproof standard. At the third meeting the name of the committee was changed to "Technical Committee No. 31: Flameproof Enclosures". It is clear from the minutes that the question of what pressure an equipment enclosure should withstand occupied a significant part of those meetings. A decision was taken to include a test of one and a half times the "equivalent of the maximum dynamic pressure". But it was further agreed to defer questions for "factor of safety" to the second edition.

2.1.2 Publishing first IEC flameproof "standard"

As noted earlier, in 1957 IEC published Publication 79 "Recommendations for construction of flameproof enclosures of apparatus". According to the TC 31 minutes, this was originally intended to be a specification, but it was changed to a recommendation to resolve a negative vote. The preface of the standard indicates that after the meeting in Paris and "examination by the Editing Committee in Brussels" the document was circulated in September 1953 for approval under the Six Months’ Rule. After the meeting in Philadelphia, the revised draft was circulated under the Two Months’ Procedure in 1955. 16 countries voted in favour of the document and none voted negative.

The requirements in the first edition relevant to the mechanical strength of the apparatus and enclosure, and hence overpressure testing, are quoted below:

> 7. Mechanical strength of apparatus
>
> The mechanical strength of the apparatus as a whole, shall be such as to withstand the normal conditions of use in industry and for the purpose for which it is intended.
>
> 7.1 The flameproof enclosure, in all its parts, shall be capable of withstanding the maximum dynamic pressure resulting from an internal inflammation of the most explosive mixture with air of the gas or vapour for which it is designed, or of a representative gas or vapour for the group for which it is designed, without suffering damage, or such deformation as would weaken any part of the structure, or would enlarge permanently any joints in the structure so as to exceed the permissible

dimension. Normally the maximum pressure will be ascertained with the enclosure having all its mechanical and electrical parts assembled as in use. It is recommended that motors shall be tested while not running and also while running without load. Where necessary, control gear shall be tested under electrical overload conditions.

7.2 In addition to the foregoing requirement, the enclosure shall be capable of withstanding without damage a testing pressure of not less than one and a half times the maximum explosion pressure attained when undergoing the flameproof tests, with a minimum of 3.5 kg/cm^2 (50 lb/in^2).
This overpressure may be applied either statically or dynamically at the discretion of the competent national authority concerned.

This standard included four groups, namely Group I, Group II, Group III and Group IV based on the Maximum Experimental Safe Gap (MESG). These corresponded roughly to the current equipment groups of Group I, Group IIA, Group IIB and Group IIC.

The following is an analysis of the above based on discussions at the meetings:

1) The increase of one and half times is not referred to as a factor of safety in the standard, and that term is still not used. However, that term was sometimes referred to in the minutes. At the first meeting, the British delegation said that the "50% additional pressure was relied on to cover variables between prototypes tested and subsequently produced apparatus of the same type. An obsolescent British Standard issued in the same year BS 229:1957 [51] does refer to it as a factor of safety.
2) This standard recognised the possibility of testing either statically (commonly this is done with water) or dynamically. For this latter approach, the UK delegation indicated they normally used "an explosive, such as gun-cotton, under controlled conditions."
3) There is no indication that routine overpressure testing was expected. However, the standard does indicate that testing would be done at the manufacturers.

2.2 Subsequent editions

TABLE 2 below provides a summary of the various editions that have been published since the first edition, including amendments. The titles can be found in the references for this chapter and in TABLE 1.

TABLE 2 – EDITIONS OF THE IEC FLAMEPROOF STANDARD

Number	Edition	Date
Publication 79	Edition 1	1957
Publication 79-1	Edition 2	1971
International Standard 79-1A	First Supplement to Edition 2	1975
Publication 79-1	Amendment 1 to Edition 2	1979-09
International Standard 79-1	Edition 3	1990-12
IEC 79-1	Amendment 1 to Edition 3	1990-08
IEC 60079-1	Amendment 2 to Edition 3	1998-05
IEC 60079-1	Edition 3.2	1998-05
IEC 60079-1	Edition 4.0	2001-02
IEC 60079-1	Edition 5.0	2003-11
IEC 60079-1	Edition 6.0	2007-04
IEC 60079-1	Corrigendum 1 to Edition 6.0	2008-09
IEC 60079-1	Edition 7.0	2014-06

2.2.1 Second edition 79-1

It took 14 years until the next edition of IEC 79-1 [52] was published (in 1971). The title also changed to "Electrical Apparatus for Explosive Atmospheres Part 1: Construction and test of flameproof enclosures of electrical apparatus". The preface shows that this standard had now become part of a series of standards with other types of protection covered, such as pressurized enclosures, intrinsically safe apparatus, sand-filled apparatus, oil-immersed apparatus and type of protection “e”. 26 countries voted in favour of Section One (General) of the standard. Slightly smaller numbers voted in favour of Section Two (Checks and tests) and

Section Three (Special requirements for Group IIC). This edition was prepared by TC 31 Subcommittee SC 31A *Flameproof enclosures.*

There were some significant changes from the first standard. The standard introduced the, now commonplace, approach to the use of groups. Enclosures were classified into two groups as follows:

- Group I: for application in coal mining
- Group II: for application in other industries

Enclosures in Group II were further sub-divided according to the MESG into the same sub-groups currently in the latest standard, ie Groups IIA, IIB and IIC. But Group IIC only covered hydrogen. The test approach established is still used. Tests are broken down into the following;

1) Determination of explosion pressure;
2) Pressure test;
3) Test to determine whether the enclosure is flameproof (not addressed in this chapter); and
4) Routine checks and tests.

For determination of explosion pressure the following mixtures were now specified ("volumetric ratio with air")

- Group I: 9.8% methane
- Group IIA: either 3.6% butane or 3.1% pentane or 4.6% propane
- Group IIB: either 8% ethylene, or 24% of 85/15 hydrogen-methane or between 3% and 4.2% ethyl ether
- Group IIC - no gas mixture defined

It stated that when doing the test, the mixture should be “suitably agitated” and that the test must be done at least three times. For the pressure test, it still used the factor of 1.5 but applied this to the “highest of the maximum smoothed pressures obtained”. A minimum of 3.5 bars was still applied (with the units changed). For the static test, the factor was increased to three times the reference pressure if the rise time was less than 5 ms. It also provided for a pressure test of four times for enclosures that would not be subject to routine test (specified in 16.2). It required motors to be tested at rest and running. It also required pressures to be measured at the ignition end and opposite end, plus in the terminal box where it is not a separate enclosure.

In the static pressure test, it required the pressure to be maintained for at least one minute. There was now a clear responsibility for the manufacturer to carry out a routine pressure test unless specifically exempted.

2.2.2 Amendment 1 to second edition 79-1

Amendment 1 to the second edition [53], issued in 1979 contained some significant changes. For determination of explosion pressure the following mixtures were now specified (“volumetric ratio with air”):

- Group I: (9.8±0.5)% methane - tolerance added.
- Group IIA: (4.6±0.3)% propane - options of butane and pentane dropped and tolerance added for propane.
- Group IIB: Normally the test mixture is (8±0.5)% ethylene. In cases where pressure piling may occur the test shall be made at least five times with a mixture of (8±0.5)% ethylene and it is repeated afterwards at least five times with a mixture of (24±1)% hydrogen-methane (85/15). Ethylene now was mandated as the only test gas with a tolerance added (ethyl ether dropped completely) and for pressure piling an additional number of tests and the additional use of hydrogen-methane with tolerance was mandated.
- Group IIC: Still no test gas defined.

Missing from the test approach was the need to agitate the test mixture. This appears to have been replaced by a note that stated that “Alternative explosive mixtures to be used when

turbulence is present are under consideration". Turbulence of course occurs with motors. Some changes were made to the details, with the principle of testing at rest and rotating being retained, but only as an option "at the discretion of the testing authority". Perhaps the most significant issue was the dropping of the three times pressure test option for enclosures with pressure piling. The rationale for this was not given and published literature seems to provide no clues. However, Note 1 in Clause 15.2.2.4 of Edition 7.0 states:

> The standard indicates that the need to conduct this repeat testing is based on the principles that (1) when pressure piling is not involved, ethylene will result in worst case representative pressures, and (2) when pressure piling is involved, it will not. Therefore, under this premise, when pressure piling is an issue, the additional testing with the mixture of (24 ± 1) % hydrogen/methane (85/15) is included.

For Group IIB perhaps the hydrogen/methane mixture was expected to provide a higher pressure, comparable to when the factor of three was used (see note below). However, nothing similar occurs for Groups I and IIA. Further, for this testing, the mixture given is the stoichiometric mixture. This can be expected to give the highest pressure for a simple enclosure, but for a complex enclosure this may not be the case. There may be situations where internal flame transmissions in an enclosure only occur at mixtures other than the stoichiometric mix; thus producing pressure piling that would not occur when using the mixture in the standard. It is worth noting that in the USA local standards, for example by UL [54] and FM Approvals [55] require pressure determination testing to be done over a range of mixtures.

NOTE (additional to published paper) More clarity on the background to the inclusion of the hydrogen/methane based on further research is provided at the end of this chapter, including the likelihood that Note 1 of the standard above is misleading. The above paragraph has been retained in the form above because it is included in the published paper.

A reason for the above change can be postulated. Applying a higher factor to an already higher determination of pressure may be seen as a doubling the overall factor of safety. However, pressure piling, and the more significant scenario of detonation, are complex phenomena and it is hard to be confident that the small number of tests and restricted gas mixtures will in fact provide the highest pressure figure. Some clear factual support for this approach seems to be needed. A further significant change for the pressure test, which had its name changed to "overpressure test", was the dropping of the time to apply the pressure from "at least one minute" to "not less than 10 s and not more than 1 min". Some changes occurred to the dynamic pressure test.

2.2.3 Third edition of 79-1

The third edition of 79-1 [56] was published in December 1990. This was the first time a general requirements document had been produced, IEC 79-0 [57]. Thus some of the requirements in IEC 79-1 were presumably transferred to that document. Also for the first time, the standard clarifies the applicable ambient range of temperatures which it repeats from IEC 79-0 as being from "-20 °C to +60 °C for explosive gas atmosphere characteristics" and from "-20 °C to +40 °C for the operation of electrical apparatus". It notes that for "ambient temperatures below -20 °C, stronger enclosures may be required due to the higher pressures generated at low temperatures and the possibility of brittle fracture of the enclosure materials". It also referred to temperatures above 60 °C and the possible need to use smaller gaps.

For the first time reference was made on how to achieve a "smoothed pressure". A note suggested that one way to do this is to use a "5 kHz ± 10% filter in the signal circuit". There were no changes to the mixtures to be used for pressure determination for Groups I, IIA and IIB. The following mixtures were included for Group IIC (which now included acetylene):

- 5 tests at (31±1)% hydrogen (H_2); and
- 5 tests at (14±0.5)% acetylene (C_2H_2)

The static pressure test was still done at 1.5 times the reference pressure with a minimum of 3.5 bar. The period of application of pressure was more precisely defined as 10 +2 -0 s. The provision for a four times test to avoid routine testing was retained. For small enclosures where the reference pressure could not be measured, and the dynamic method was not practicable the following static test pressures were given: 10 bar for Groups I, IIA, IIB and 15 bar for Group IIC.

2.2.4 Amendments 1 and 2 to third edition of 79-1

Amendments 1 [58] and 2 [59] were subsequently made to the standard addressing breathing and draining devices. A version of the standard IEC 60079-1 Edition 3.2 [60] was issued in May 1998 incorporating the two amendments and adopting the new IEC numbering system.

2.2.5 Fourth edition of 60079-1

Edition 4.0 of IEC 60079-1 [61] was issued in February 2001. Based on my memories, as the then relatively new Chair of TC 31, this edition had a short and chequered history. Using an agreement between the European Committee for Electrotechnical Standardization (CENELEC) and IEC, called the Dresden Agreement, the European version of the standard was submitted for vote to the national committee members of Subcommittee SC 31A. Since the number of affirmative votes met the rules for acceptance, this edition of the standard was published in IEC with only editorial changes from the CENELEC version, for example referring to IEC standards. Thus it did not directly evolve from the previous edition of IEC 60079-1, and there was no opportunity to make technical changes. Hence some technical requirements from the previous edition were lost. When the ramifications of this approach were realised, a short revision cycle was instigated to allow incorporation of appropriate technical changes.

A significant omission from this edition was reference to the applicability of this standard for low and high temperatures that was in the previous edition. The speed to be used when doing pressure determination on rotating electrical machines was “between 90 % and 100 % of the rated speed of the machine”. Where reference pressure determination was impracticable a range of pressures to be used between 10 and 20 bar, depending on Group and enclosure size, were specified. The period for pressure testing as “at least 10 s but shall not exceed 60 s”. The use of a frequency limit for smoothing of 5 kHz ± 10% was mandated for the first time.

In the context of pressure determination testing, the standard introduced the following about pressure piling:

> NOTE There is presumption of pressure-piling when
>
> - either the pressure values obtained during a series of tests involving the same configuration, deviate from one to another by a factor of ≥1,5, or
> - the pressure rise time is less than 5 ms

The gas mixtures to be used for pressure determination did not change, but the number of tests for Group IIC dropped from five to three for both acetylene and hydrogen. However, where pressure piling (see above) could occur, tests had to be done “at least five times”. This applied to all Groups.

2.2.6 Fifth edition of 60079-1

Edition 5.0 of 60079-1 [62] was issued in November 2003. The most significant pressure testing requirements introduced into this edition of the standard were those for temperatures below -20 °C. The following requirements were included for pressure determination:

> For electrical apparatus intended for use at an ambient temperature below –20 °C, the reference pressure shall be determined at a temperature not higher than the minimum ambient temperature.
>
> As an alternative, for electrical apparatus
>
> - of Groups I, IIA, or IIB; or
> - of Group IIC with internal free volume < 2 l,
>
> other than rotating electrical machines (such as electric motors, generators and tachometers) that involve simple internal geometry such that pressure piling is not considered likely, the reference pressure may be determined at normal ambient temperature using the defined test mixture(s), but at increased pressure.
>
> The absolute pressure of the test mixture (*P*), in bar, shall be calculated by the following formula, using $T_{a,min}$ in °C:

$$P = [293 / (T_{a,\min} + 273)] \text{ bar}$$

While this is based on a common law of physics, Amontons' Law of Pressure-Temperature, there is a lack of published literature to demonstrate that the use of increased pressure produces a result consistent with tests at very low temperatures, especially in the case of pressure piling, which is particularly relevant for motors. On a more general matter, the approach to smoothing pressure now required the use of a low-pass filter with a 3 dB point of 5 kHz ± 10 %. Presumably this made no real difference to the actual application. The test gases to be used and the number of tests to be done for pressure determination remained the same as the previous edition. This included the need to do five tests for all groups for pressure determination when there was a presumption of pressure piling. The requirements for rotating electrical machines were changed to bring some discretion into whether to test running, with the provision:

> Rotating electrical machines shall be tested at rest and, when the testing station considers it necessary, when running. When they are tested running, they may be driven either by their own source of power or by an auxiliary motor. The speed shall be between 90 % and 100 % of the rated speed of the machine.

2.2.7 Sixth edition of 60079-1

Edition 6.0 of 60079-1 [63] was issued in April 2007. It removed reference to "electrical apparatus" and instead used the term "equipment". That was consistent with changes in terminology across the TC 31 standards at that time. The standard introduced more detailed requirements for extremely low temperatures as shown below.

> For electrical equipment intended for use at an ambient temperature below –20 °C, the reference pressure shall be determined by one of the following methods:
>
> - For all electrical equipment, the reference pressure shall be determined at a temperature not higher than the minimum ambient temperature.
> - For all electrical equipment, the reference pressure shall be determined at normal ambient temperature using the defined test mixture(s), but at increased pressure. The absolute pressure of the test mixture (P), in kPa, shall be calculated by the following formula, using $T_{a,\min}$ in °C:
>
> $$P = 100[293 / (T_{a,\min} + 273)] \text{ kPa}$$ (After correction by corrigendum [64])
>
> - For electrical equipment other than rotating electrical machines (such as electric motors, generators and tachometers) that involve simple internal geometry (see Annex D) with an enclosure volume not exceeding 3 l, when empty, such that pressure-piling is not considered likely, the reference pressure shall be determined at normal ambient temperature using the defined test mixture(s), but is to be assumed to have a reference pressure increased by the factors given in the table below.
> - For electrical equipment other than rotating electrical machines (such as electric motors, generators and tachometers) that involve simple internal geometry (see Annex D) with an enclosure volume not exceeding 10 l, when empty, such that pressure piling is not considered likely, the reference pressure shall be determined at normal ambient temperature using the defined test mixture(s), but is to be assumed to have a reference pressure increased by the factors given in the table below. Under this alternative, the test pressure for the overpressure type test in 15.1.3.1 shall be 4 times the increased reference pressure. The 1,5 times routine test is not permitted.

The reference to Annex D appears puzzling as that Annex only deals with certification of empty component enclosures. However, it is likely the reference is meant to make use of the clarification of "simple internal geometry" shown in D.3.2, as follows:

> Ex component enclosures shall consist of a basically simple geometry of only square, rectangular, or cylindrical cross-section with taper not exceeding 10 %.
>
> NOTE When major dimensions exceed any other dimension by 4:1 for group I, IIA and IIB, or exceed any other dimension by 2:1 for group IIC, additional considerations may be necessary.

The table containing the test factors (the origin of which will be discussed later in this chapter) is as follows below in TABLE 3:

TABLE 3 – TEST FACTORS

Minimum ambient temperature, °C	Test factor
–20 (see Note)	1,0
≥ –30	1,37
≥ –40	1,45
≥ –50	1,53
≥ –60	1,62
NOTE This covers equipment designed for the standard ambient temperature range specified in IEC 60079-0.	

This edition of the standard had the following requirement regarding the overpressure test for low temperatures:

> For electrical equipment intended for use at an ambient temperature below –20 °C, the overpressure test shall be conducted at a temperature not higher than the minimum ambient temperature. Where the tensile and yield strength properties of the material used are shown by material specifications to not decrease significantly at low temperature, the overpressure test may be conducted at normal room ambient.

The test gases to be used and the number of tests to be done for pressure determination remained the same as the previous edition. This included the need to do five tests for all groups when there is a presumption of pressure piling.

The requirements for rotating electrical machines reinstated the mandated requirement to test while running and states the maximum speed shall be “at least 90% of the maximum rated speed “. This last seems only to be a change in wording. The standard also provides more precise requirements on the location of pressure transducers, including the need for three transducers if the termination compartment is interconnected to the motor. This reinstated information that had appeared in earlier editions.

2.2.8 Seventh edition of 60079-1

Edition 7.0 of 60079-1 was issued in June 2014. In this edition requirements for very low temperatures remain the same except that the table with the factors (now called Table 7) includes the following statement under the note “Consideration should be given to applications in which the temperature inside the flameproof enclosure may be substantially lower than the rated ambient temperature”. For testing small enclosures, reference to ambient temperatures below –20 °C has been introduced; see information from Table 8 of the standard which is shown as TABLE 4 of this document.

TABLE 4 - PRESSURES FOR SMALL ENCLOSURES BELOW 20 °C

Volume, cm^3	Group	Pressure [a], kPa
≤10	I, IIA, IB, IIC	1 000
>10	I	1 000
>10	IIA, IIB	1 500
>10	IIC	2 000
[a] For equipment intended for use at an ambient temperature below –20 °C, the above pressures shall be increased by the appropriate test factors noted in Table 7.		

The mixtures for pressure determination remain the same, but five tests for Group IIC for acetylene and hydrogen are again required, even if there is no pressure piling. This is the same as the requirement that was originally in the third edition. For pressure piling, the requirement for testing five times with ethylene and hydrogen/methane remains for Group IIB but is dropped for Groups I and IIA. This does not seem logical and may be an error. There was another change to specifying the filter with the statement: “a low-pass filter with a 3 dB point of 5 kHz ± 0.5 kHz shall be used”. There is a new option for overpressure testing introduced of three times the reference pressure, if the routine overpressure test is replaced by a batch test. Again there is a change in specifying the period of application of the pressure, which is now “at least 10 s”. The issue of turbulence (for other than rotating electric machines) gets a mention as follows:

> The continuous effects of devices inside enclosures, such as rotating devices, which can create significant turbulence that may result in an increase in reference pressure shall be considered.

This is significant, as turbulence can lead to higher pressures. One of the earlier references to turbulence was by Grice and Wheeler in 1929 in a UK Safety in Mines Research Board paper [17]. This was clearly recognised in the second edition with the requirement to agitate the mixture for all testing. However, it seemed to get lost or be more narrowly required in intervening editions for situations where agitation may occur in the equipment in normal use, for example in motors, as shown above. The latest wording represents a reasonable approach to this issue.

2.3 Further analysis of overpressure testing

2.3.1 Static overpressure testing

As noted earlier, the IEC standard permits both a static and a dynamic approach to overpressure testing. The most common approach is to use static testing. Dynamic pressure testing normally involves the use of an autoclave style of chamber. These are not universally available in test laboratories around the world and the use of dynamic pressure to achieve a four times test is likely to be restricted due to pressure considerations for the autoclave. I have inspected the majority of testing bodies around the world in this field in my role as an IECEx lead assessor and I have not seen it done. I have also not seen anyone in recent times using explosives, such as gun-cotton. So the analysis in this thesis is focussed on pressure determination and the static overpressure testing that is applied as a result of the pressures from the pressure determination.

NOTE (additional to published paper) Since this paper was published, Tim Krause from PTB has published information about the work he has been doing on investigations of static and dynamic stress of flameproof equipment [65]. His work indicates that: "The results show that the static and dynamic stress, and thus the two different test methods, cannot be considered equivalent". This provides yet another indication of the complexity of this testing.

2.3.2 Pressure determination

Of significance is that for equipment intended for the standard range of temperatures contained in IEC 60079-0 [49] of - 20 °C to +40 °C, no allowance is made for the variation in pressure that may result from the ambient pressure at the time of testing. It is likely that the impact of temperature on pressure was not appreciated at the time the first standard was developed. There have been very few published papers providing data from experiments looking at the impact of temperature on pressure in flameproof enclosures. But there are two relevant investigations that address the issue. One by George Lobay [25-27] is 40 years old and the other by PTB in Germany is about 20 years old. Only the former study addresses pressure piling. It has been published in one report [25] and two papers [26, 27]. The data from the PTB study was purportedly used to develop factors to be applied in IEC 60079-1 for testing equipment designed for very low temperatures, but a report on the testing was never published (internally or externally). PTB have provided the raw data from that testing to me (personal communication, 20 July 2015). The work of Lobay above looked at the effect of ambient temperature upon maximum explosion pressure in a single chamber test apparatus and in a pressure piling test apparatus. The experiment covered hazardous atmospheres in (USA) Groups A, B, C, D and coal mining applications. These can be correlated with IEC Groups I, IIA, IIB and IIC. The results for the test temperature range of approximately -50 °C to +40 °C indicated a linear increase in explosion pressures as temperature is reduced. This is not unexpected. If there is predictable geometry which provides confidence that pressure piling or detonation cannot occur, then the pressure is very closely linked to the gas density which increases as temperature decreases. The following concentrations of gas were used: propane 4.6%, methane 9.8%, ethylene 8.0%, hydrogen 32% and acetylene 14.5%. The series of explosions started at -50 °C and was increased in increments of not more than 3 °C to +40 °C. The concentrations used fall within the tolerance of those in the IEC 60079-1, although the concentrations for hydrogen and acetylene are different to the median figure specified in the latest edition of the standard. No tests are reported for the mixture of (24 ± 1) % hydrogen/methane (85/15) which is now included in the standard for Group IIB for cases where pressure piling may occur. The results from the Lobay study [26] are shown redrawn in Figure 6 below.

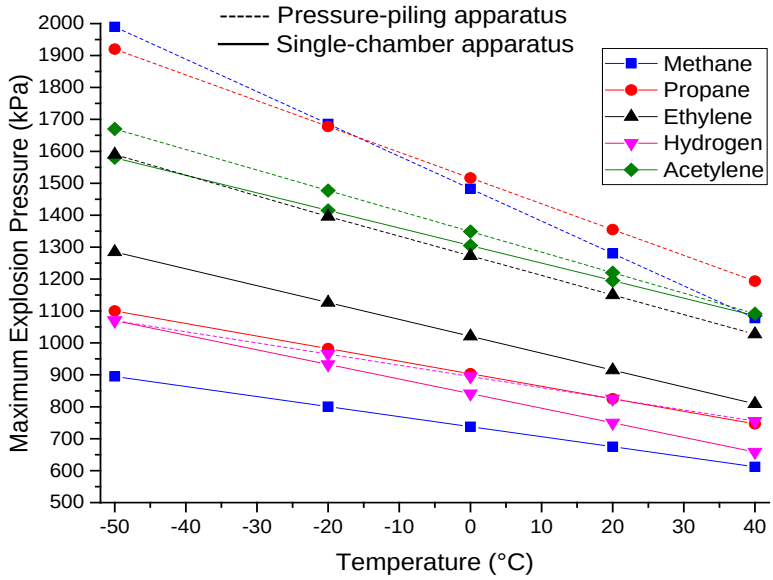


Figure 6 – Lobay, Maximum explosion pressure versus ambient temperature

It can be seen that the temperature range tested only goes down to -50 °C. IEC 60721-2-1 [28] shows temperatures can be as low as -60 °C in areas designated as "polar". Personal communication has suggested that temperatures can occasionally get down to -70 °C. The data supplied by PTB show testing in the range of -50 °C to -20 °C with hydrogen and acetylene only. The concentrations shown for hydrogen and acetylene fall within the tolerance of those in IEC 60079-1. The PTB work has the same temperature restriction as Lobay's work regarding the lowest temperature. The range of gases used is more restricted as only hydrogen and acetylene were used.

No editions of the standard take account of the effect of temperature on pressure in the standard range of -20 °C to +40 °C. Based on the data from Lobay, the potential change in pressure over that range can be as high as 2.75. TABLE 5 below shows an analysis done by me on the Lobay results for three scenarios; (1) no pressure piling (PP), (2) pressure piling based on low pressure piling figure, and (3) pressure piling based on low no pressure piling figure.

The most likely scenario for pressure piling is that shown in the third column. However, the fourth column is included to address situations where the test sequence has not produced pressure piling even though it may in fact be feasible (for example at a slightly different gas mixture). It can be seen that the most dramatic increases for the pressure piling scenario come with methane and propane (Groups I and IIA), with the highest factor approaching three. Hydrogen and acetylene (Group IIC or Group IIB plus H_2) show the least increase. Ethylene (Group IIB) is somewhere between. But since the experiments did not include the hydrogen 85/methane 15 mixture shown in the later editions of the flameproof standard, the factor for that gas combination is not known. The above scenarios indicate that the factor that the pressure varies by could be larger than the factor of 1.5 currently often applied for overpressure testing. Thus it would seem appropriate to address this in the testing specification in the standard.

TABLE 5 – ANALYSIS OF LOBAY'S PRESSURE FIGURES - LOW TEMPERATURE RANGE

Gas	Increased pressure (as a factor) for temperature change from +40 °C down to -20 °C		
	No PP	PP based on low PP figure	PP based on low no PP figure
Methane	1.31	1.56	2.75
Propane	1.32	1.41	2.25
Ethylene	1.39	1.36	1.72
Hydrogen	1.42	1.28	1.47
Acetylene	1.30	1.35	1.36

A similar analysis can be done for the figures in the Lobay tests for very low temperatures. Assuming testing is generally done around +20 °C the analysis is done for that temperature down to -60 °C by extrapolating the Lobay figure from -50 °C. TABLE 6 below shows the results and compares them with the factors in the standard. The approach involving factors for very low temperature testing can only be used where pressure piling is not present.

TABLE 6 – ANALYSIS OF LOBAY'S PRESSURE FIGURES - STANDARD RANGE - NO PRESSURE PILING

Gas	Increased pressure (as a factor) for temperature change from +20 °C down to -50 °C	
	Lobay results	Factor in standard
Methane	1.33	1.53
Propane	1.33	1.53
Ethylene	1.40	1.53
Hydrogen	1.43	1.53
Acetylene	1.32	1.53

The table only shows the analysis for one point (-50 °C), but since results are linear, it is reasonable to postulate from the table that the factors in the standard are appropriate. However, it might be wise to consider making some allowance for experimental error.

There are other factors that can introduce variation into the test results. While not dealt with in detail in this thesis, the following are some factors that are known to affect pressure figures:

1) The temperature of the gas mixture in the enclosure (which may be different to ambient);
2) Ambient pressures (generally due to the height of the test facility above sea level);
3) Position of ignition source;
4) Power of ignition source;
5) Position of pressure sensors;
6) The testing equipment; and
7) The procedures used.

Another factor that could impact on the pressures, particularly when pressure piling is present, is that the mixtures used for pressure testing are at the stoichiometric mix. This does not take account of possible complexities in pressure piling; for example, the scenario when the explosion may only propagate through a restriction between compartments at a mixture other than the stoichiometric mix. In contrast in the US, UL [54] and FM [55] test over a range of mixtures.

The PTB Ex Proficiency Testing Scheme program run in 2013/14 on pressure determination using hydrogen and ethylene showed a significant spread of results. This displays the variation that can occur even when testing identical equipment with many of the test factors above removed. For example, the location of the ignition source and location of pressure transducers were specified.

NOTE (additional to published paper) Some of the spread could have been due to experimental errors, but different testing methods, as allowed by the standard, and the variations in pressure figures that often occur within a series of tests, would have accounted for much of the spread in readings.

2.3.3 Overpressure testing

The use of a factor of 1.5 (often shown as 1,5) as the factor to be used for the overpressure testing has been consistently applied since the first standard, despite uncertainty by the committee during development of the first standard as to whether it was correct. However, other options for certain circumstances have appeared, including factors of 3 and 4. Factors that may be applied to the maximum pressure for very low temperatures also now appear in Table 7 of the standard as shown in TABLE 3 earlier in this chapter. Hence two factors may be multiplied together for the overpressure test.

The factor when pressure piling occurred increased at one stage to three times the reference pressure. As noted earlier, it was introduced in the second edition in 1975 and then dropped in amendment 1 of that edition in 1979. The analysis earlier in this standard suggests that the factor is appropriate and consideration should be given to reintroducing this factor into the standard.

The factors applied in the IEC standard do appear low when compared with UL [54] and FM [55] standards where the factors can range from 2 up to 5. However, the requirements do vary between the two standards. But it should be recognised that these enclosures may be used in the equivalent of a Zone 0 area and so this may lead to a more conservative approach. Nevertheless, based on the variety of reasons articulated in this chapter, there appears to be good cause to critically review some of the factors currently in the IEC flameproof standard. However, it does appear that in any circumstance where the four times overpressure is applied, this can be expected to exceed any pressure that may be developed during an explosion and so may be considered to be appropriate.

2.4 Conclusions and recommendations regarding suitability of pressure safety factors

This study indicated that further research is desirable in a number of areas to provide confidence in the requirements in the existing IEC standard, or to provide recommendations for change if the need is indicated in the outcomes of the research; these include:

1) Investigating the applicability of the formula for applying initial higher pressures when determining explosion pressures for temperatures below -20 °C, particularly for cases involving pressure piling (this was subsequently done as part of this project

   NOTE (additional to published paper) See Chapters 4, 5 6 and 7)

2) Investigating the impact of varying gas concentrations from those specified in the standard when pressure piling is present to see if higher pressures can be obtained in certain circumstances

3) Examining the applicability of the hydrogen 85/methane 15 mixture for pressure determination in the case of pressure piling for Group IIB, including correlation with ethylene

   NOTE (additional to published paper) This was subsequently done as part of the project - see additional remarks in 2.5 below

4) Given the improvement of instrumentation in the past 20 years and more, there may be value in re-validation of experiments done by Lobay and PTB, with hydrogen 85/methane 15 included this time and with testing down to temperatures of -60 °C

   NOTE (additional to published paper) This has been partly done, with all testing being carried out down to -60 °C, plus some investigation and testing with hydrogen 85/methane 15

It is recommended that the specification for testing in the standard ambient range of -20 °C to +40 °C be more closely specified. There are a number of potential options that could be adopted, including restricting the allowable range. However, the best approach might be:

1) To allow testing in the current range;
2) To define a narrower band where no factors apply; and
3) To define factors to be applied for temperatures outside the narrow band but inside the current range.

It is likely the narrow band could embrace most of the ambient temperature conditions present in laboratories around the world.

It is also recommended that the current factors applied for overpressure testing be reviewed, possibly along the following lines:

1) Consider increasing the factor of 1.5 when pressure piling is not present, at least for Group II where ambient temperature ranges are likely to be larger
2) Dependent on how the above is applied, consider increasing factors used for very low temperatures to include provision for experimental error; and

3) Consider restoring the factor of three when pressure piling is present that was in the second edition of the standard prior to the first amendment.

Finally, it is recommended that the requirement from earlier editions, that five tests should be done in the case of pressure piling, should be restored for Groups I and IIA.

TC 31 has not yet achieved the aim that was proposed in its first meeting of TC 31 in 1948 of alignment between US and IEC standards, and it does seem IEC TC 31 may have something to learn from those US standards when it comes to pressure determination and overpressure testing. But the reverse may also be true for other aspects of the standards, also noting that the US standards vary between bodies.

2.5 Additional remarks regarding hydrogen/methane

The earlier part of this chapter is essentially the text of the paper presented to PCIC Europe in June 2016 with editorial changes to integrate it into this thesis. The following remarks are additional to, and in some cases qualify or amend, that information, in particular the information in 2.2.2.

Additional research was subsequently done into the origin of the use of hydrogen/methane for doing pressure determinations for Group IIB as follows:

1) Looking at how the requirements were introduced into the standard;
2) Data from tests using the mixture for motors, as shown in Chapter 8;
3) Results from testing of a 160 frame motor, as shown in Chapter 9; and
4) Simulations with CFD using the mixture, as shown in Chapter 10.

The possibility of its inclusion was discussed in the IEC Sub-Committee SC 31A: "Flameproof Enclosures" meeting in October 1970 (minutes kindly provided by IEC). The initial thrust was to only have one representative gas for each of Groups I, IIA and IIB. But ultimately it was decided to include hydrogen/methane "In special cases where pressure-piling may occur". In support of including the requirement was the statement from the UK that "in the UK an artificial gas mixture was chosen to give a reasonably high peak pressure with a fast rate of rise to enhance pressure piling effects that may be present". Hence the intention was that if pressure piling was expected hydrogen/methane should be used. However, while the requirements in the current standard might be interpreted that way, the notes provide the impression that hydrogen/methane should only be used if pressure piling is already occurring with ethylene. This can be deduced from the first note which is worded as follows:

> NOTE 1 The need to conduct this repeat testing is based on the principles that (1) when pressure piling is not involved, ethylene will result in worst case representative pressures, and (2) when pressure piling is involved, it will not. Therefore, under this premise, when pressure piling is an issue, the additional testing with the mixture of (24 ± 1) % hydrogen/methane (85/15) is included.

The research reported in this thesis shows that statement to be incorrect and misleading.

Further background is provided in an ERA report [66]. This makes it clear that a significant issue at that time was the wide-spread use of town gas which was a hydrogen/methane mix with varying amounts of hydrogen. I have also had personal discussions with Ron Webb, a former researcher from ERA (personal communication, 13 and 14 February 2017). He has suggested that he thinks one of the reasons for using the hydrogen/methane mix was that ethylene has an MESG of 0.65 mm which is higher than the lower limit for Group IIB which is 0.5 mm (see 1.10). The hydrogen/methane mix, which has a lower MESG than ethylene, might produce pressure piling in circumstances where ethylene would not.

However, there is a lack of published evidence on the origin of the 24% mix with air of hydrogen/methane and what the MESG is of that mix. The above ERA report recommends an 18% mix with air and quotes an MESG of 0.017 inches (0.4318 mm) for a 20% mix with air from an earlier ERA report. There are some papers that address how to derive the MESG with mixtures. One useful paper published by Brandes and Redeker [67] provides an approach. I contacted Mrs Brandes by email (personal communication, 10 August 2017), and she indicated that when interpolating the data she ended up with an MESG of 0.43 mm. This makes it less than the Group IIB limit of 0.5 mm. She also indicated that the 24% mix is not the stoichiometric concentration but is close to it.

There is some logic in the selection of the alternative mix, for example in a motor an ethylene explosion might be quenched by an air gap that would not quench a hydrogen/methane explosion. However, in the testing of the 160 frame motor, see 9.3, this was not well supported. In fact, for temperatures of -20 °C and lower, ethylene continued to achieve flame transmission, and hence pressure piling through the air gap. But the hydrogen/methane mixture did not. As shown in Chapter 3, hydrogen is less likely to transmit at lower temperatures and hydrogen is the major component of the mixture. So the principle of using hydrogen/methane would only apply for testing at ambient temperatures. However, at ambient temperatures, the MESG is lower than that required for Group IIB, and so the application of this mixture could lead to pressure piling situations which are not relevant for Group IIB.

Further, it can be seen in later data in this thesis that in most cases the hydrogen/air mixture gives lower pressures than ethylene when both exhibit pressure piling. It is likely that in the situation where both have pressure piling, the slower flame speed of ethylene will lead to higher pre-pressurisation of the second compartment and hence higher explosion pressures in that compartment. The need to retain the hydrogen/methane mixture will require careful consideration by MT60079-1 for the next edition, also noting that with the effective removal of town gas from daily life, the need to retain it for hazards arising from that source seems unnecessary. Most, perhaps all, countries have replaced town gas with other gases such as natural gas, although gasification continues for other applications, as indicated by Stiegel and Maxwell [68].

3 Extremely low temperature flame transmission

3.1 Introduction

The international standard for flameproof equipment is IEC 60079-1, currently at Edition 7.0 [8]. This includes requirements for non-transmission testing for flameproof enclosures. However, as shown in 3.2, the standard is silent on the requirements for non-transmission testing at temperatures below -20 °C. This could involve extremely low temperatures down to -60 °C that occur in some parts of the world. 3.2 examines the development of the relevant requirements in IEC 60079-1. 3.3 looks at the validity of the current requirements based on published literature, in particular where pressure piling (see 1.4) is present. 3.4 then looks at the test program that was developed to better consider the various scenarios, and in 3.5 the results that have been obtained from that test program are presented. 3.6 provides an analysis of the test results and an indication of further testing that is proposed. 3.7 provides the conclusions from the research and analysis presented in this chapter.

3.2 Requirements in IEC 60079-1

Earlier chapters in this thesis have looked at the definition and approach used on IEC 60079-1 for flameproof, also called Ex d, enclosures. Also as noted earlier, in the USA the same approach is called explosion-proof or explosionproof, and is covered in more than one standard. For example, there are ANSI/UL 1203 [54] and FM 3615 [55]. Both the international and USA requirements rely on the same approach of ensuring the enclosure is strong enough to withstand an explosion and to avoid transmission of an internal explosion to a surrounding explosive atmosphere. The following is the definition of flameproof enclosure “d” in IEC 60079-1 Edition 7.0 [8]:

> enclosure in which the parts which can ignite an explosive gas atmosphere are placed and which can withstand the pressure developed during an internal explosion of an explosive mixture, and which prevents the transmission of the explosion to the explosive gas atmosphere surrounding the enclosure

For the purpose of this thesis, the critical part of the above definition is preventing the transmission of the explosion to the explosive gas atmosphere surrounding the enclosure. This approach to flameproof protection has been used for over 100 years in various countries and with the first edition of IEC 60079-1 being issued by IEC in 1957 as Publication 79 "Recommendations for construction of flameproof enclosures of apparatus" [1]. The definition in the first edition is slightly different but essentially has the same meaning:

> ...an enclosure for electrical apparatus that will withstand an internal explosion of the inflammable gas or vapour which may enter or which may originate inside the enclosure, without suffering damage and without communicating the internal inflammation to the external inflammable gas or vapour, for which it is designed, through any joints or structural openings in the enclosure.
>
> Note. - The term “flameproof as used in this specification is synonymous with the term “explosion-proof” as used in America for the class of apparatus covered by these Recommendations.

The first edition breaks equipment down into four “Groups”, from I to IV based on the “Experimental Maximum Safe Gap”. It specifies maximum dimensions for Groups I to III. But it does not specify tests for flame transmission. The only tests are for mechanical strength of the enclosure. There is no mention of the ambient temperatures for which the gaps would be considered acceptable.

The second edition of IEC 79-1 [52] published in 1971 first introduces a "Test to determine whether an enclosure is flameproof". It specifies the approach of filling the enclosure to be tested and a surrounding volume in a test chamber with a test mixture, and for the test to be done five times. For the first method of testing involving increasing gaps, the following mixtures are specified:

1) For Group I enclosures: between 7.5% and 9% methane
2) For Group IIA enclosures: either between 3.1% and 3.7% butane or between 4.1% and 4.3% pentane or between 4.1% and 4.3% propane
3) For Group IIB enclosures: either 6.5% ethylene, or between 18% and 20% of 85/15 hydrogen-methane or between 3% and 4.2% ethyl ether

For the second method, involving no artificial gaps, it specifies that a mixture must be selected to achieve a specified experimental safe gap. Neither method includes tests for Group IIC, and there is no reference to the ambient temperature either for testing or for applicability of the equipment for use.

Amendment 1 to IEC 79-1 Edition 2 [53] issued in September 1975 changes the gases to be used for the non-transmission testing to:

1) Electrical apparatus for Group I: 12.5%±0.5% (methane-hydrogen (58%±1% methane and 42%±1% hydrogen) (equivalent to a MESG of approximately 0.8 mm)
2) Electrical apparatus of Group IIA: 55%±0.5% hydrogen (equivalent to a MESG of approximately 0.65 mm)
3) Electrical apparatus of Group IIB: 37%±0.5% hydrogen (equivalent to a MESG of approximately 0.35 mm)

(An explanation on MESG is provided earlier in 1.10).

The above mixtures are not necessarily the most explosive mixtures, but those determined to be most likely to provide flame transmission. The use of these mixtures has continued to the latest edition. But more details were included in later editions on how to prepare samples. Also introduced in this edition was the option to pre-pressurise gases prior to carrying out the test for non-transmission. This research only addresses tests at atmospheric pressure, not with pre-pressurisation. Tests for Group IIC were still not included at this stage. The standard retained the option of using propane and ethylene in the following circumstances, and this was continued in subsequent editions, with the following stated:

> If enclosures of Groups IIA and IIB could be destroyed or damaged by the [overpressure] test ..., it is permitted that the test be made by increasing the gaps above the maximum values specified by the manufacturer. The enlargement factor of the gap is 1,42 for Group IIA electrical equipment and 1,85 for Group IIB electrical equipment. The explosive mixtures to be used in the enclosure and in the test chamber, in volumetric ratio with air and at atmospheric pressure, are as follows:
>
> 1) electrical equipment of Group IIA: (4,2 ± 0,1) % propane; or
> 2) electrical equipment of Group IIB: (6,5 ± 0,5) % ethylene.

Edition 3 of 60079-1 [56] was issued in December 1990 and first introduced tests for Group IIC. Five tests with each of the following mixtures were specified where appropriate gaps are created in flamepaths:

1) (27,5 ± 1,5) % hydrogen (H_2), and
2) (7,5 ± 1) % acetylene (C_2H_2).

These have remained unchanged to the current edition.

This was the first time the standard clarified the applicable ambient range of temperatures which it repeats from the general requirements standard IEC 79-0 as being from "-20 °C to +60 °C for explosive gas atmosphere characteristics" and from "-20 °C to +40 °C for the operation of electrical apparatus". It notes that for "ambient temperatures below -20 °C, stronger enclosures may be required due to the higher pressures generated at low temperatures and the possibility of brittle fracture of the enclosure materials". It also referred to temperatures above 60 °C and the possible need to use smaller gaps. No mention is made of the effect on transmission at lower temperatures.

Edition 4.0 of IEC 60079- 1 [61] was issued in February 2001 but omitted the reference to low and high temperatures that was in the previous edition. This was corrected in the next and subsequent editions. Edition 5.0 [62], issued in November 2003, introduced requirements for testing for temperatures over 60 °C, including testing at actual temperatures or applying factors to increase pressure or test gaps. More detail, but with the same approach for higher temperature flame non-transmission testing, was introduced into Edition 6.0 [63], issued in April 2007. No other changes were made to the requirements for flame transmission. Edition 7.0 [8] introduced a number of changes related to flame transmission as follows:

1) Test for non-transmission of an internal ignition - Clarification regarding grease

2) Reduction in length of a threaded joint for non-transmission test - ISO 965-1 and 965-3 standards in respect of thread form and quality of fit
3) Test factors to increase pressure or test gap - Group IIC adjustments for elevated ambient temperature
4) Test for non-transmission of an internal ignition, Groups I, IIA and IIB - Number of tests to be made
5) Test for non-transmission of an internal ignition, Group IIC testing by increased gap - Number of tests to be made
6) Test for non-transmission of an internal ignition, Group IIC - Oxygen enrichment of test gases

So all editions of the flameproof standard are silent on the issue of flame transmission at temperatures below -20 °C. There are, however, requirements specified for compounds to be used in flameproof joints to be suitable for the minimum service temperature. It can be inferred that there is a presumption that the likelihood of transmission will be the same or less likely as temperature decreases.

3.3 Analysis of previous research

3.3.1 Existing published information

1.9 looked at some existing published information relevant to flame transmission. As noted there, the mechanism that ensures there is no flame transmission from the inside of a flameproof enclosure to a surrounding atmosphere is a complex one and still subject to ongoing research.

1.10 addresses the concept of MESG. But there is limited published information on the effect of temperature on MESG and hence on flame transmission. There is some information that implies the likelihood of transmission through a flamepath is reduced. Lunn [47] in 1982 provided some information on the effect of temperature on the value of MESG. But the most relevant published information on the effect of temperature on MESG is contained in a comprehensive report by Redeker in 1981 [69]. However, although his work covers a range of temperatures, it does not go below +20 °C, and so the effect at low temperatures can only be inferred through extrapolation, assuming the effect is linear at low temperatures. The findings for Redeker are shown in Figure 7 below for gases hydrogen, carbon disulfide, ethylene, n-hexane and methane. To provide better quality, this figure and the next one have been recreated from original data used in the production of the report. This data was provided to me by PTB (personal communication, 19 December 2015).

Redeker also looked at the effect of higher initial pressure and deduced that a higher initial pressure of the gas mixtures will result in reduction of the MESG. He postulated the following approximation based on Figure 8 below:

$$s_{min} - s_{(\frac{1}{p}=0)} = \frac{a}{p}$$

where

s_{min} safe gap in mm of the most incendive mixture;

$s_{(\frac{1}{p}=0)}$ substance-specific safe gap at infinitely high pressure of the mixture;

p initial pressure of the mixture in mbar;

$a = \frac{s_{(\frac{1}{p}=0)}}{0.15.10^{-3}}$ substance-specific constant in mm•mbar.

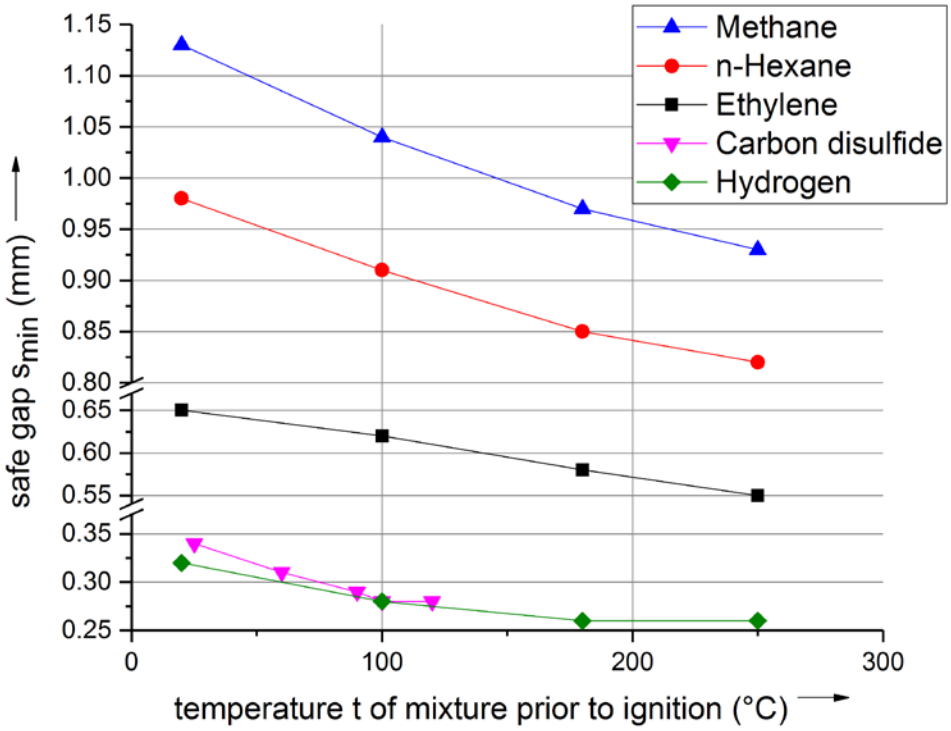


Figure 7 – Redeker, Effect of initial temperature on MESG

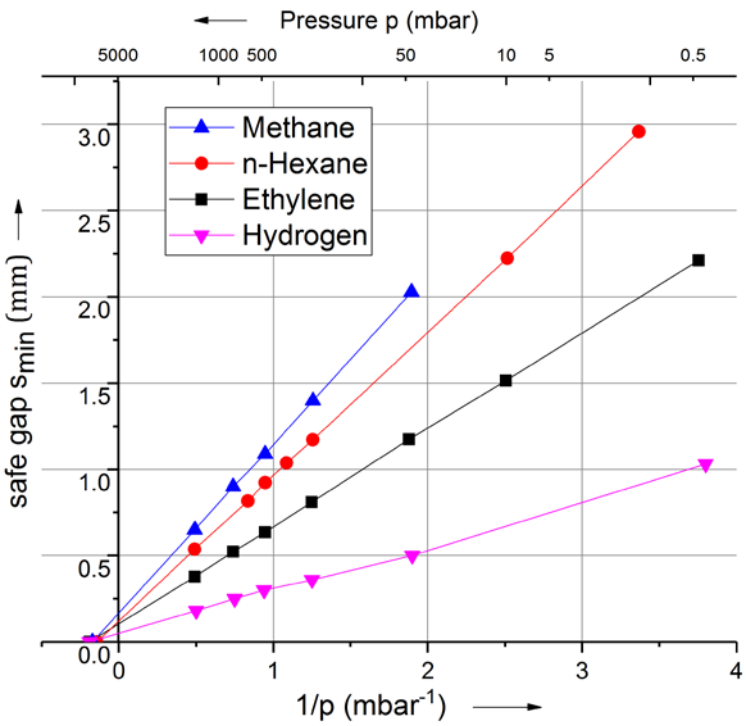


Figure 8 – Redeker, Effect of initial pressure on MESG

In 2.3.2 the two separate studies by Lobay and PTB looking at the effect of extremely low temperatures on explosion pressures were discussed. The results of the study by Lobay are shown in Figure 6.

However, there appears to be a lack of published research that looks at the correlation of increased pressures at low temperatures and the possible consequence of flame transmission. This scenario may be particularly relevant where pressure piling may be present.

3.3.2 Analysis of existing test results

The following is an analysis based on the published data of Lobay. TABLE 7 shows the analysis of Lobay's results looking at the factors associated with increase in pressure based on three scenarios for the range of +20 °C down to -60 °C. The figure for -60 °C is based on linear extrapolation of the Lobay curves from -50 to -60 °C. The first scenario is the increase in pressure for each gas mixture when pressure piling is not present at all. The second is the increase that occurs when pressure piling occurs at normal and low temperatures. The third (less likely but feasible) scenario is for pressure piling only occurring at the low temperature. This last also becomes relevant because the MESG figures on which the flamepath dimensions are based are derived without a pressure piling situation.

TABLE 7 – ANALYSIS OF LOBAY'S PRESSURE FIGURES

Gas	Increased pressure (as a factor) for temperature change from +20 °C down to -60 °C		
	Based on no PP	Based on low figure with PP	Based on low figure with no PP
Methane	1.37	1.63	3.10
Propane	1.38	1.48	2.43
Ethylene	1.46	1.43	1.79
Hydrogen	1.49	1.34	1.47
Acetylene	1.37	1.42	1.45

Looking at the figures from the work of Redeker and assuming a linear extrapolation to -60 °C as shown below, the following graph in Figure 9 can be derived for the commonly used gases of hydrogen, ethylene and methane.

NOTE 1 (additional to published paper) I had the opportunity to meet with Redeker (personal communication, 13 June 2017) and asked if he was aware of, or been involved in, any testing done on MESG at very low temperatures. He said he was not aware of or been involved in such testing.

NOTE 2 (additional to published paper) I am aware of some work that was done about five years ago on MESG of hydrogen at extremely low temperatures, but the work was commercial-in-confidence, and I do not have access to the results.

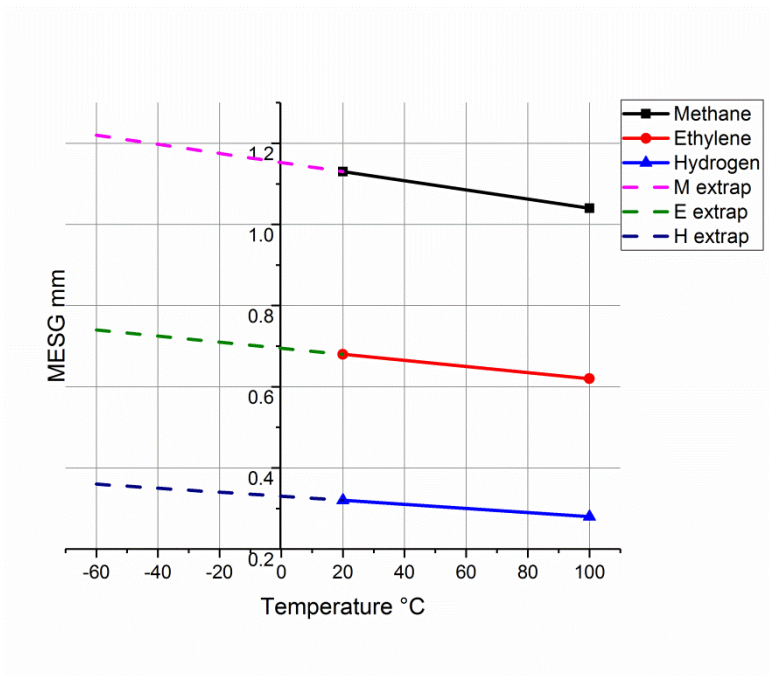


Figure 9 – Redeker, Chart showing effect of initial temperature on MESG

An analysis of Redeker's information is shown in tabular form in TABLE 8 below.

TABLE 8 – ANALYSIS OF REDEKER'S MESG FIGURES

Gas	Calculated MESG	MESG from paper		Increased MESG from +20 °C to -60 °C	
	-60 °C	20 °C	100 °C	%	Factor
Methane	1.22	1.13	1.04	8.0	1.08
Ethylene	0.74	0.68	0.62	8.8	1.09
Hydrogen	0.36	0.32	0.28	12.5	1.13

It can be seen that hydrogen has the most significant potential increase in the factor for MESG with methane the least, and with ethylene in between.

3.3.3 Comparison of the effects of pressure and temperature

The actual change in MESG due to change in pressure is not readily derived. Indeed there is an obvious common factor of temperature that may to some extent be taken account of in the MESG figure. But the method of deriving the MESG does not take account of pressure piling. Notwithstanding this, the factors derived in comparison with the MESG change due to temperature allow some theories that can be postulated and then examined through experiment. It is also necessary to recognise that the pressure figures derived by Lobay occurred at or near the stoichiometric mixture of the gases which is expected to give the highest pressure. Gas mixtures most likely to provide flame transmission, and hence specified in the standard for non-transmission testing of equipment, are different from the stoichiometric mix.

The effects of pressure and temperature are not uniform for different types of gases. It can be seen that, according to Lobay's figures, the pressure factor occurring for hydrogen does not appear to be significant at very low temperatures, even when pressure piling is present. Conversely, the effects for methane and propane are quite significant with the potential for methane to have figures as high as three times those obtained at +20 °C. Ethylene falls somewhere in the middle.

When the direct effect of low temperatures on MESG is looked at, the reverse is true. The most dramatic effect is likely to be on hydrogen. So the data suggests there is a likelihood that at very low temperatures for hydrogen the net effect on MESG will be an increase and hence the possibility of transmission can be expected to decrease as temperature falls. However, the increase in MESG for ethylene and methane is much less. A similar situation may occur for propane, but there is no data from the Redeker study to check. There is also no data from Redeker on the impact of temperature on MESG for acetylene, and the impact of pressure piling on acetylene is less. Thus it is hard to make a prediction for acetylene.

So in summary, gases like ethylene, propane and methane exhibit high increases in pressure and hence are likely to have a lower MESG due to pressure at low temperatures, especially when pressure piling is present. In contrast, ethylene and methane appear to exhibit low increases in MESG due to low temperature. Thus it is reasonable to postulate that the likelihood of transmission of explosions using these gases may increase, rather than decrease at low temperatures, especially at extremely low temperatures. This is most likely to occur when pressure piling is present and is hence the theme of this chapter. It was decided that the best way to test the above premise was through carrying out a comprehensive range of tests to establish the actual scenarios.

The situation is complicated by the current gases used for flame non-transmission tests. It can be seen in the preceding section, that hydrogen is predominately used in IEC 60079-1 for the flame non-transmission tests for all Groups. So testing the likely impact of very low temperatures for other gases requires the use of the representative gases used in pressure determination but with adjusted percentages relevant to flame transmission. IEC 60079-1 Edition 2 and some special provisions in the latest edition provide the most useful indicator of what percentages of gases to use when using gases other than hydrogen. There are also potential issues with water being a by-product of a hydrogen explosion. This will be discussed in more detail later in this chapter.

3.4 Experimental set up to establish relevant data

In an endeavour to come up with relevant data and results to provide clearer evidence on the effectiveness of flamepaths at extremely low temperatures, in particular when pressure piling

is present, a test artefact was developed to allow analysis of a range of explosive gases. This artefact was developed based on a combination of artefacts used in the PTB Ex Proficiency Testing Scheme associated with the IECEx Equipment Certification Scheme. The proficiency scheme involves the comparison of test results from participating laboratories, using identical artefacts for the testing, to evaluate the accuracy of tests by each laboratory through statistical analysis of the results. The first artefact was used for pressure testing, and had two chambers bolted together and separated by an orifice to allow pressure piling to occur. The outside ends of each chamber had bolted covers with various holes for attaching instrumentation and gas supplies. The second artefact was a similar arrangement with the orifice replaced by a nozzle to allow flame transmission to potentially occur (depending on the diameter and length of the hole in the nozzle). A composite artefact was developed having a large chamber (B) separated from a small chamber (A1) by the pressure piling orifice, which in turn was separated from a second small chamber (A2) by a flame transmission nozzle. By igniting the gas-air mixture in Chamber B, pressure piling occurs in Chamber A1 with the potential for flame transmission through to Chamber A2. The arrangement is shown in Figure 10. The complete artefact could then be inserted into an environmental chamber capable of providing temperatures down to -60 °C.

Once in the chamber, the artefact was connected to gas supplies and instrumentation as shown in Figure 10. The instrumentation other connections included:

1) Gas into B and out from A2.
2) Gas out from A1 and back into A2 to assist mixing. Two shut off valves included in the connection (outside of the environmental chamber) to ensure no risk of transmission through the valves.
3) Ignition at the end of B.
4) Pressure transducers at the end of B and A2 and in line out from A1 using an adaptor.
5) Temperature measurement with a PT100 in Chamber A2 and Type K thermocouple near join of B and A1 for indication of the artefact temperature near the nozzle.

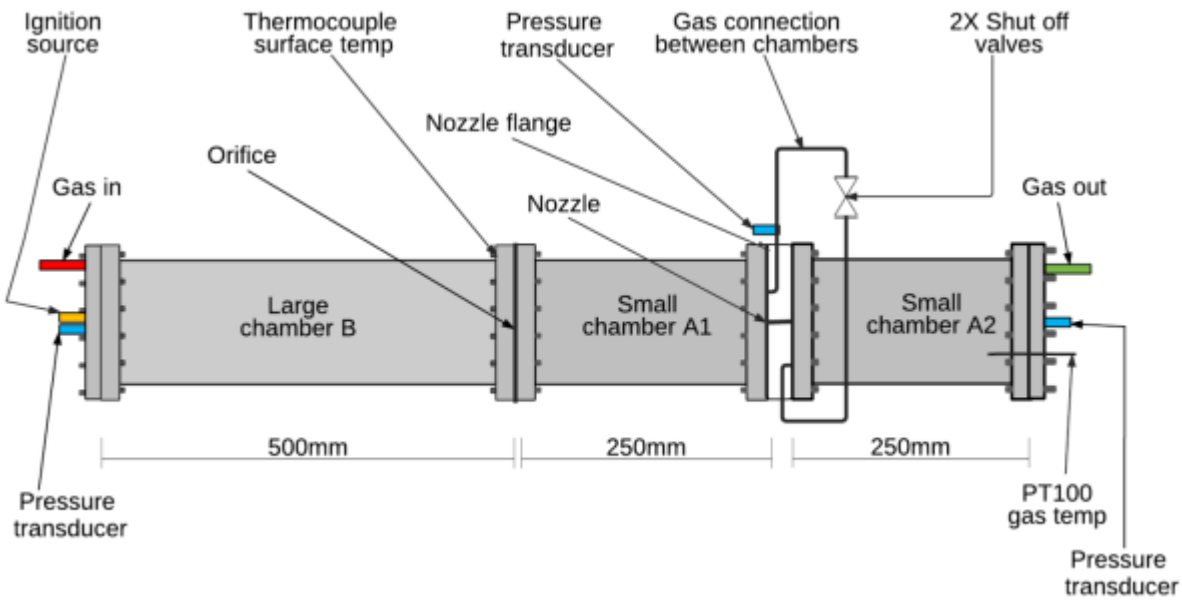
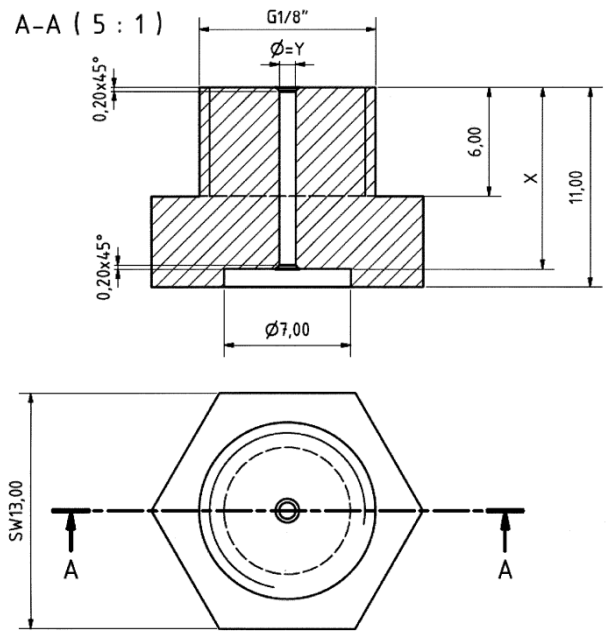


Figure 10 – Test arrangement for pressure piling and flame transmission

The photo in Figure 11 shows the artefact in the environmental chamber when subject to very low temperatures with evident frosting. Depending on the amount of moisture present, it can be assumed similar frosting occurs on the inside.

Figure 11 – Artefact in chamber at very low temperature

The nozzles used for the first round of tests were those used in one of the PTB Ex Proficiency Testing Scheme programs, with a new set being used. The nozzles came with three hole diameters of 0.7, 0.8 and 0.9 mm, with details as shown in Figure 12. All were designed for use with the hydrogen mixture for Group IIC flame non-transmission testing. These were designed so that, without pressure piling, the 0.7/6 mm nozzle should prevent transmission, the 0.8/6 mm nozzle should allow some transmissions and the 0.9/10 mm nozzle should allow transmissions in every case.



Nozzle			
Dimension	Y = 0,7 mm	Y = 0,8 mm	Y = 0,9 mm
X	6 mm		
X		6 mm	
X			10 mm

Figure 12 – Nozzle dimensions for hydrogen

While the earlier analysis in this thesis suggests hydrogen would be likely to have less chance of transmission at low temperatures, knowing the characteristics of these nozzles provided a good opportunity to test out the artefact arrangement and to confirm the analysis was correct.

The research test program provided for doing five tests at each of the following temperatures: +20, -20, -30, -40, -50 and -60 °C for each nozzle to be used and with each test gas used. The number of tests selected was based on the practicalities of the testing and the number of tests used in IEC 60079-1 for flame non-transmission testing. If found necessary, additional numbers of tests at some temperatures may be done at a later date to improve the statistical probability associated with this research.

It was advised that for the PTB Ex Proficiency Testing Scheme program above, nozzle sizes were developed by "trial and error" plus experience with using similar nozzles for flame transmission experiments. So no precise calculation was associated with their design. Hence it was decided to use the above nozzles as a reference base for developing nozzles for other gases, using the MESG of the gases to predict the likely diameters of the holes. TABLE 9 shows the results.

TABLE 9 – NOZZLE DIAMETER CALCULATIONS

Gas	Formula	MESG	Base-line nozzle diameter, mm	Nozzle diameter based on MESG, mm
Hydrogen	H_2	0.29	0.7	
			0.8	
			0.9	
Acetylene	C_2H_2	0.37		0.9
				1.0
				1.1
Ethylene	C_2H_4	0.65		1.6
				1.8
				2.0
Propane	C_3H_8	0.92		2.2
				2.5
				2.9
Methane	CH_4	1.12		2.7
				3.1
				3.5

The "X" dimensions used in the proficiency testing program were 6 mm and 10 mm. Hence to provide a wider range of nozzles, the new nozzles were specified with "X" dimensions of 6, 8 and 10 mm for each diameter nozzle. TABLE 10 shows the nozzles for ethylene.

TABLE 10 – NOZZLES FOR ETHYLENE

Diameter of hole, mm	1.6	1.8	2.0
Length of hole (X), mm	6	6	6
	8	8	8
	10	10	10

Tests were then carried out to determine which nozzles would provide a similar scenario to those used for hydrogen. Once the nozzles had been selected, a range of testing similar to the testing done for hydrogen was carried out using the same temperatures.

3.5 Test results

3.5.1 Test results for hydrogen

The hydrogen/air mixture shown in IEC 60079-1 Edition 7.0 for non-transmission testing was used for this test. This is a mixture of (27.5 ± 1.5) % hydrogen in air. However, to make allowance for experimental error and other factors such as the paramagnetic effect, the

tolerance was halved so that the target percentage was hydrogen and air (27.5± 0.75) %. It would also be possible to choose the stoichiometric mixtures of gases which should give higher pressures. This may be considered for later research.

TABLE 11 below shows the results for hydrogen using the 0.8 mm diameter, 6 mm long nozzle.

TABLE 11 – RESULTS FOR 0.8/6 NOZZLE - HYDROGEN

Nominal temperature, °C	+20	-20	-30	-40	-50	-60
Number of tests	5	5	5	5	5	3
No of ignitions	5	5	2	0	0	0

Testing with hydrogen proved to be difficult at very low temperatures. A by-product of a hydrogen explosion is water. At very low temperatures this turns to ice or forms a frost. This can inhibit the explosion and in particular block the nozzle. The effect can be exacerbated when the artefact full of humid ambient air is cooled for testing. A number of measures were put in place to address or monitor this issue once it became apparent. When first cooling the artefact from ambient to a low temperature, it was first filled with a dry gas mixture to minimise the amount of water vapour. In addition, the flow of the mixture through the nozzles could be checked. This was done by closing the external valves connecting Chambers A1 and A2. This only permitted flow through the nozzle. It was possible to detect this flow at the end of the output gas line. Hence during the above tests when no flow was detected when filling for the third test at -60 °C, it was known the nozzle was blocked. An attempt at backflushing by reversing the gas flow was attempted, but it failed to clear the nozzle. So testing was discontinued after that test.

Since the above tests indicated a lesser chance of ignition at lower temperatures, the testing was continued with the larger (0.9 mm diameter 10 mm long) nozzle only, not the small nozzle. TABLE 12 below shows the results for the 0.9/10mm nozzle.

TABLE 12 – RESULTS FOR 0.9/10 NOZZLE - HYDROGEN

Nominal temperature, °C	+20	-20	-30	-40	-50	-60
Number of tests	5	5	5	7	5	3
No of ignitions	5	5	2	2	0	0

3.5.2 Test results for ethylene

The tests with ethylene to determine appropriate nozzles to use were carried out. IEC 60079-1 Edition 7.0 makes provision to use ethylene for non-transmission testing for Group IIB enclosures in circumstances where an enclosure may be destroyed using the more usual hydrogen mix. This is also the mixture that was specified in IEC 60079-1 Edition 2. Hence this mixture was used for this testing. The mixture is (6.5 ± 0.5) % ethylene. Again to make allowance for experimental error and other factors, the tolerance was halved so that the target percentage was ethylene and air (6.5 ± 0.25) %.

Tests with three nozzles at +20 °C were able to indicate the likely scenarios of just preventing flame transmission, just allowing flame transmission and marginal for flame transmission. This was consistent with the three nozzles used in the proficiency testing program for hydrogen. TABLE 13 below shows the results for the actual nozzles at +20 °C with five tests done for each nozzle:

TABLE 13 – SELECTION OF NOZZLES FOR ETHYLENE

Nozzle size		No of ignitions (out of 5)
Diameter, mm	Length, mm	
1.8	6	4
1.8	8	0
2.0	8	0

It could reasonably be inferred from the above that a nozzle of 2.0 mm diameter and 6 mm length would provide consistent flame transmission, but it was not deemed necessary to check this. Based on the above results, it was decided to carry out tests on the 1.8/6 mm

nozzle and then the 2.0/8 mm nozzle. The results are shown in TABLE 14 and TABLE 15 below. For easy comparison, the results at +20 °C are repeated in the tables.

TABLE 14 – RESULTS FOR 1.8/6 NOZZLE - ETHYLENE

Nominal temperature, °C	+20	-20	-30	-40	-50	-60
Number of tests	5	6	5	5	5	5
No of ignitions	4	6	5	5	4	4

It can be seen that down to -40 °C more ignitions occurred. Below that temperature the same number of ignitions occurred. However, the pressure figures at those temperatures were lower than expected. The reason for this is being investigated and the tests at those temperatures may be repeated.

NOTE (additional to published paper) The above is worded as shown in the published paper. There was not an opportunity to repeat these tests as part of this project, but it is included in Chapter 12 for possible future work.

TABLE 15 – RESULTS FOR 2.0/8 NOZZLE - ETHYLENE

Nominal temperature °C	+20	-20	-30	-40	-50	-60
Number of tests	5	7	5	5	5	5
No of ignitions	0	0	0	0	0	0

The results in TABLE 15 showed no evidence of increased likelihood of transmission at lower temperatures. However, a similar problem to that with the other ethylene nozzle occurred at temperatures of -50 and -60 °C of having lower pressures than would be expected for those temperatures based on the linear increase in pressure as shown in Figure 6.

3.6 Analysis of test results

The results with hydrogen show a decrease in the likelihood of flame transmission using hydrogen. This is consistent with the earlier analysis that the change in MESG due to drop in temperature is likely to be more significant than the impact of pressure due to drop in temperature for hydrogen. There is a possibility that the presence of water, and the resultant ice/frost as a byproduct of testing, has made the effect look more significant. This may be more an issue for testing than in the real environment where multiple explosions are unlikely. However, in each case above, tests were done at low temperatures when the artefact had been dried and then cooled with a gas inside. Testing was then done at potentially marginal conditions with no flame transmission occurring. Thus it should be possible to have reasonable confidence that the results provide an indication that there is a lower likelihood of flame transmission at low temperatures with hydrogen compared to testing at normal ambient.

For the testing with ethylene, the test results with one nozzle indicated that flame transmission with ethylene slightly more likely at lower temperatures down to -40 °C. The tests with the second nozzle were inconclusive, with no evidence of a greater likelihood of ignition with ethylene. However, based on the results for the 0.8/6 mm and 0.9/10 mm nozzles for hydrogen, and 1.8/6 mm nozzle for ethylene, there is a clear trend from less likelihood of transmission at low temperatures with hydrogen to similar or slightly more likelihood of transmission with ethylene. This is consistent with the analysis shown earlier in this thesis and the trend towards more likelihood of transmission can be predicted to continue for some gases that exhibit significantly increased explosive pressures at low temperatures, such as methane. Hence further testing was planned with other gases to provide a complete picture of the scenarios for representative gases covering the full range of Equipment Groups of I, IIA, IIB and IIC. A significant complication expected, as indicated earlier, is likely to be the fact that all flame non-transmission testing is currently done with hydrogen or a hydrogen/methane mix. The above results indicate that if flame transmission can occur more readily with some gases at lower temperatures, using the current flame transmission gases at low temperatures will not be appropriate. Hence the acceptable testing scenarios for testing at temperatures below -20 °C would need to be carefully defined in terms of the gases to be used, their concentrations and the methods of achieving a factor of safety. This is addressed further in 4.8.

3.7 Conclusions regarding flame transmission at low temperatures - hydrogen and ethylene

There is a lack of published information that addresses how flame transmission might occur at low and extremely low temperatures, in particular where pressure piling may occur. Published information on MESG does not address low temperatures. There is limited information on the likely pressures that might be obtained at extremely low temperatures and no published information on the pressures that might be obtained when testing at gas percentages different to the stoichiometric mix.

Based on existing data for MESG and pressures obtained at extremely low temperatures down to -60 °C, the likely outcomes for testing with hydrogen and ethylene were examined. The scenarios were then tested, using a testing artefact that could simulate flame transmissions under pressure piling conditions at a range of temperatures down to -60 °C. The results for hydrogen indicate that there is a decreased probability of transmission at temperatures of -20 °C and lower temperatures, but that the presence of water resulting in ice and frost can be a factor in preventing transmission. The results for ethylene indicate a similar or slightly increased chance of flame transmission at lower temperatures which is different to hydrogen. This confirms the trend from the analysis that could see some gases have increased possibility of flame transmission at low temperatures. Additional research is expected to clarify the situation for other gases, such as acetylene, propane and methane. Based on the results to date, it appears that one or more of these gases is likely to provide an increased chance of flame transmission.

It is anticipated that the results of this research will be considered by IEC maintenance team TC 31 MT60079-1 when the next edition of IEC 60079-1 is prepared. I am a member of that maintenance team.

The above content of this chapter was presented as a paper at the IEEE IAS 2016 Petroleum and Chemical Industry Committee (PCIC) conference in Philadelphia, PA, USA in September 2016 [70] and subsequently published in the IEEE Transactions on Industry Applications [71].

3.8 Additional research - use of methane and propane

3.8.1 Introduction

The following examines the additional testing that was attempted using methane and propane. This information was not included in the above papers.

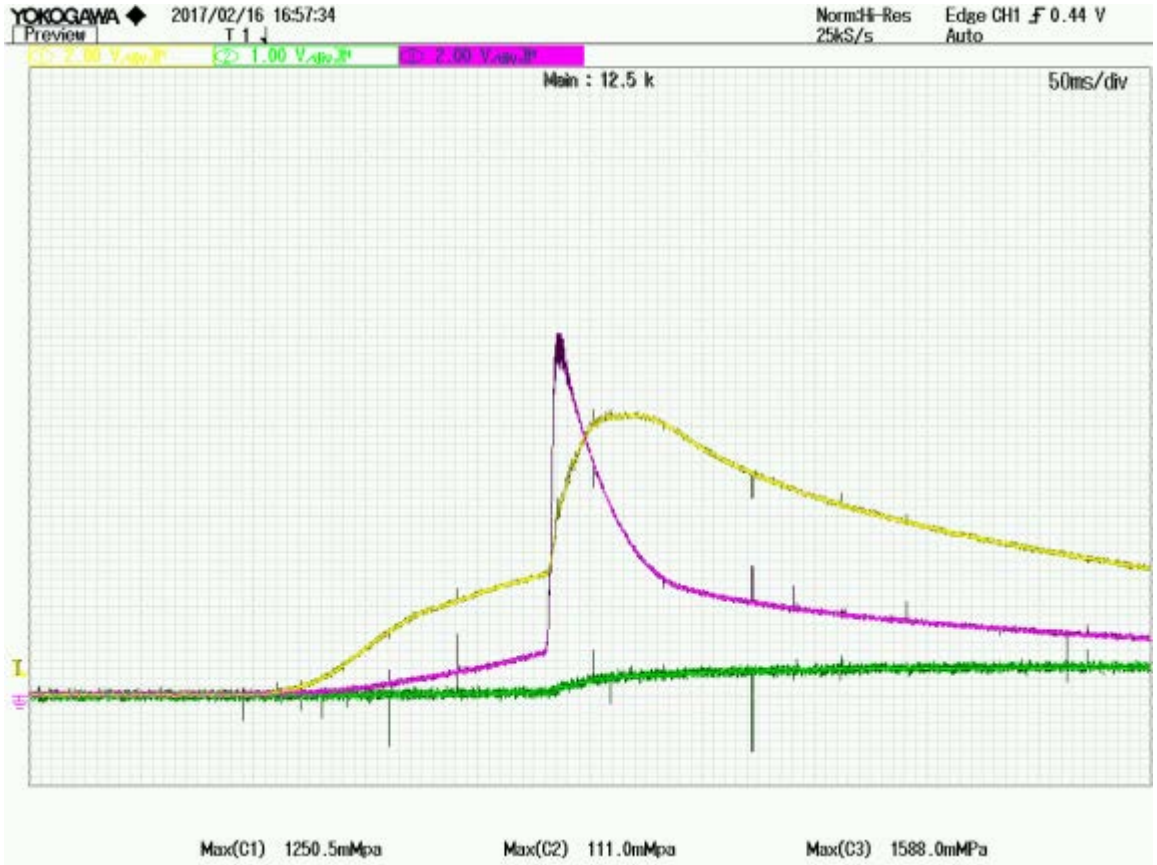
3.8.2 Testing with methane

As noted above, nozzles for testing with methane were initially obtained based on the relative ratio of MESG for hydrogen and methane. TABLE 16 shows the initial set of nozzles.

TABLE 16 – NOZZLES FOR METHANE

Diameter of hole, mm	2.7	3.1	3.5
Length of hole (X), mm	6	**6**	**6**
	8	**8**	**8**
	10	10	**10**

Five nozzles from this batch were tested, being those shown in bold and underlined above. During this testing, there was some uncertainty at times whether transmission had occurred or not. Quite high pressures were obtained in Chamber A1, mostly over 1,000 kPa and with the highest being 1,722 kPa. Due to those high pressures and the large size of the hole through the nozzle, the pressure transducer in Chamber A2 at times was showing a trace that looked like an explosion may have occurred. However, the pressure figures were lower than would have been expected and the PT100 did not indicate a significant increase in temperature. It was therefore concluded that no transmission had occurred into Chamber A2. This conclusion was later further justified by including an ignition source in Chamber A2 and proving that the gas in Chamber A2 could be ignited after the ignition had occurred in Chambers B and A1. Figure 13 shows an example of the pressure waveforms that were obtained when testing with methane. The yellow waveform is in Chamber B, the purple waveform in Chamber A1 and the green waveform in Chamber A2.



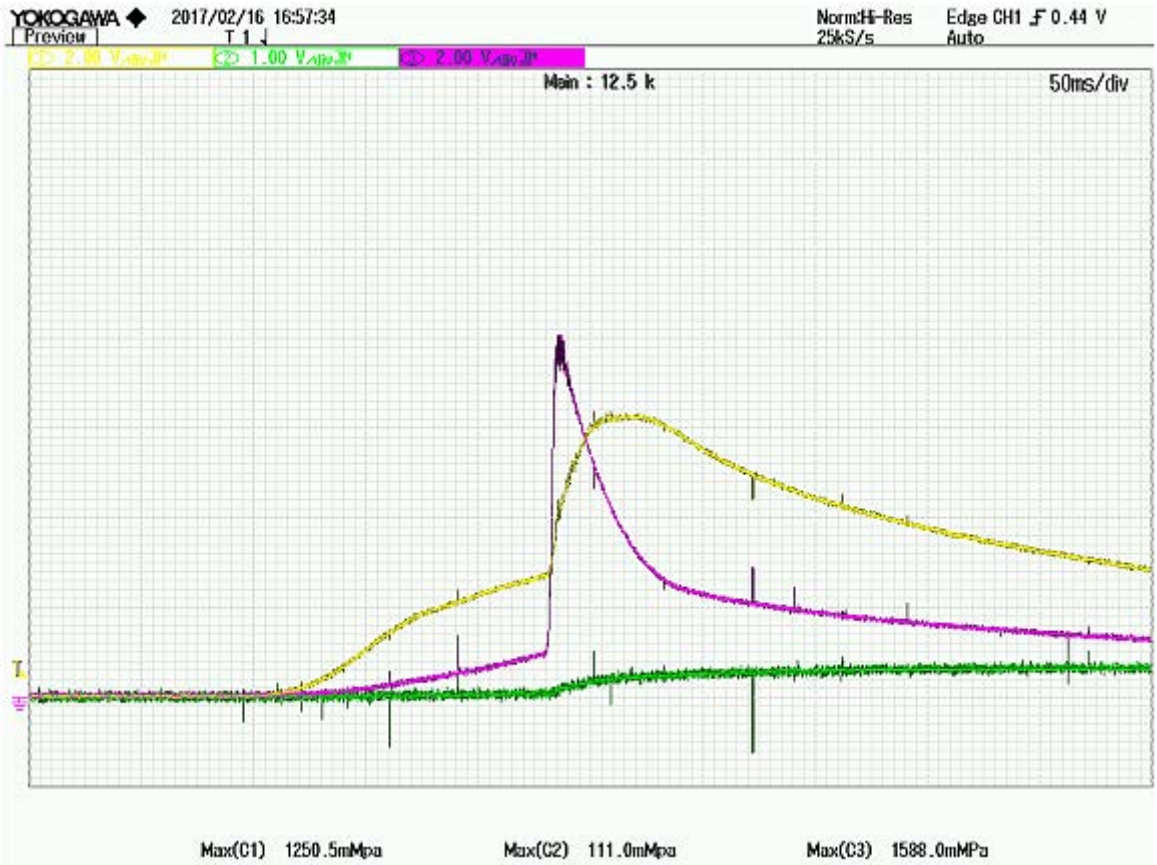


Figure 13 – Example of pressure trace with methane nozzles

A program was then put in place to try to establish the larger nozzle sizes that would permit flame transmission. Two larger sets of nozzle were purchased and at one stage nozzles that were thought to have rough bores and poor chamfers were replaced. TABLE 17 shows the

full range of nozzles which were purchased, with those which were tested shown in bold and underlined.

TABLE 17 – LARGER NOZZLES FOR METHANE

Diameter of hole, mm	3.9	4.3	4.7	5.1	5.5	5.9
Length of hole (X), mm	6	6	**6**	**6**	6	**6**
	8	8	8	8	8	8
	10	10	10	10	10	10

However, even the larger sizes failed to produce transmission. Some variations in the testing approach were tried to investigate the situation. Test mixtures were tried at both stoichiometric and at percentages that early editions of IEC 60079-1 had included for flame transmission for Group I. The nozzle was also tried on either side of the plate. The gas mixture was introduced in the opposite direction. Testing without a nozzle was tried, and transmission did appear to occur, although the mixture in the Chamber A2 was not tested afterwards. A couple of the nozzles were also tested at low temperatures, but there was no evidence of transmission. However, the pressure curve for Chamber A2 did again look like an explosion pressure curve but with the pressure figures quite low.

During this selection process for methane nozzles, considerable attention was paid to the possible scenarios, including discussing the situation with combustion experts. Figure 14 shows a photograph of the largest diameter methane nozzles on the left and a hydrogen nozzle on the right. Figure 15 shows a diagram of the largest nozzle diameter and shortest hole for the methane nozzles, and it is relevant to some of the discussion below. Also shown for comparison is the original diagram for the hydrogen nozzle in the same scale. The parts shown in green are the holes through the nozzles and associated geometry. The large difference in nozzle hole size is evident in both the photograph and the diagram.

Figure 14 – Methane and hydrogen nozzles

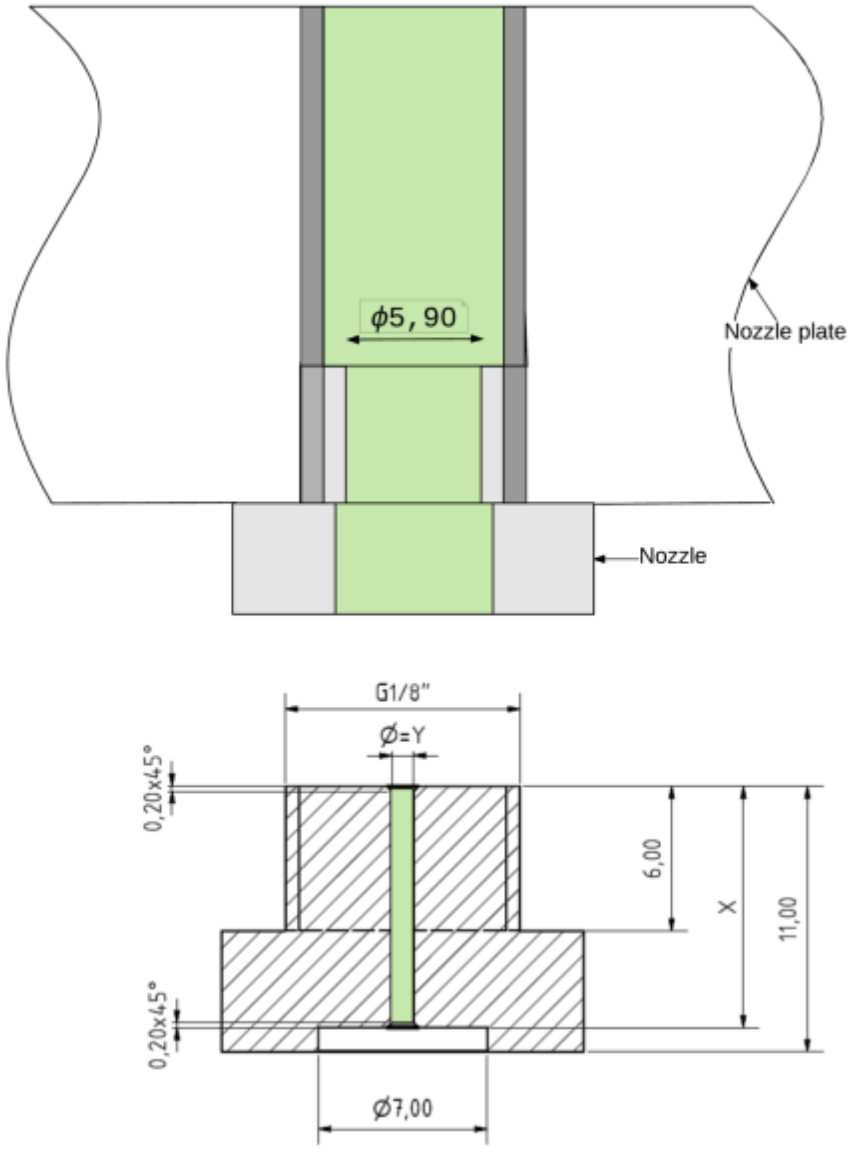


Figure 15 – Methane nozzle with the largest hole and the hydrogen nozzle

There are a number of possibilities that might be the cause of the non-transmission, either singly or in combination:

1) The hole size is still too small, with the dynamics of the explosion changing with regard to hydrogen and ethylene, so that the direct correlation using MESG no longer applies. Work by Rogstadkjernet [34] on a similar pressure piling setup indicated that quenching always occurred for 4 mm holes for methane. So that would be consistent with the smaller nozzles above not transmitting an explosion. His reported experiments show nozzles of around 6 mm were providing transmission.
2) The hole in which the nozzles are screwed is 22 mm long, and the nozzle has a thread 6 mm long. Hence there is a significant length of hole that may affect the transmission. The hole is a G1/8" thread. This has a tap hole of 8.0 mm and a maximum diameter of 9.73 mm to the depth of the thread. So it is starting to become in the order of the magnitude of the large nozzle holes. This can clearly be seen in the above figure.
3) The diameter of the machined indented portion at the outside of the nozzle also starts to become not much larger than the diameter of the large nozzle holes. This can also be seen in the above figure.
4) As indicated earlier, the much larger size of the methane nozzle resulted in noticeable pressures occurring in Chamber A2. The presence of the pressure in A2 may have an

impact on flame transmission for methane. It is unlikely to have been an issue for testing with hydrogen and ethylene as the pressures in A2 were much smaller for those gases.

Producing nozzles with even larger diameter holes was no longer a possible simple solution because of the above issues in 2) and 3) regarding possible interfering geometry would become even more significant. The other issue is that the material left in the nozzles might become too small to produce nozzles with the required diameter hole.

Some possible solutions to consider, that might work singly or in combination, include:

1) Using the largest hole feasible with existing geometries, but there is not much material for a larger hole
2) Using a thinner plate for the nozzles, but then there would only be passage of gas through the nozzle and not externally, and measurement of explosion pressure in A1 would become a challenge
3) Machining a section of the existing plate around the nozzle hole to reduce the thickness to 6 mm
4) Machining a larger diameter indent in the outside of the nozzle, but there is also not much material for this if a 6 mm long hole is needed
5) Using nozzles of larger outside size than current ones that would permit larger sizes in nozzle hole, mounting hole and indent diameter
6) Reducing the likelihood of pressure occurring in Chamber A2 prior to ignition, for example by some means of pressure relief

However, there were some issues with proceeding with the above. Due to the number of potential problems, there was no confidence that just increasing the nozzle hole by the small amount possible to the maximum would solve the problem. There was also a reluctance to modify the mounting plate because it is used in proficiency testing programs.

3.8.3 Testing with propane

It was decided to investigate if the propane nozzles would follow the pattern based on MESG that worked for ethylene (but not for methane). So the propane nozzle that met that criteria that were most likely to give transmission was tested. This was the nozzle with 2.9 mm diameter and 6 mm long hole. No transmission occurred. Testing was also done at -40 °C with the same nozzle with no transmission occurring.

According to IEC 60079-20-1, propane has a boiling point of -42 °C. Thus experiments with it at very low temperatures down to -60 °C, below the temperature used above may become problematical.

3.8.4 Conclusion and discussion

In view of the difficulties arising, the fact the two artefacts were about to be needed for a new proficiency testing program by the two testing bodies that provided them, and other very interesting elements which were evolving as part the overall PhD project, it was decided that future work on this element of the project would best be deferred until after completion of the PhD research. So it has been highlighted, along with other items, for possible future research as shown in Chapter 12. Clarity is needed on the issue regarding whether it will be necessary to change the next edition of IEC 60079-1 and so this research remains an important priority.

3.9 Additional test data

To provide some additional supporting information regarding the test results, an extract of testing data has been provided below in TABLE 18. This shows the maximum pressures obtained for each of the four gases used at 20 °C and -40 °C in Chamber A1 (pressure piling) with the corresponding pressure for that test in Chamber B (no pressure piling). These were the only two temperatures at which testing was carried out for all four gases.

TABLE 18 – ADDITIONAL PRESSURE TEST DATA

	Temperature = 20 °C		Temperature = -40 °C	
	Max pressure Chamber A1. kPa	**Corresponding max pressure Chamber B. kPa**	**Max pressure Chamber A1. kPa**	**Corresponding max pressure Chamber B, kPa**
Hydrogen	1,040	650	1,698	918
Ethylene	1,601	581	2,890	664
Propane	1,680	412	2,096	524
Methane	1,709	347	2,011	561

It is interesting to note that, unlike Lobay's results, ethylene produced higher pressures with pressure piling when testing at -40 °C than methane and propane. Some of this may have been due to pressure relief through the nozzle, but the results in Chapter 5 indicate that this would not have been significant.

4 Validity of using increased pressures at ambient temperatures for pressure determination for low temperatures - hydrogen

4.1 Introduction

4.1.1 Overpressure testing of flameproof equipment

As noted in earlier chapters, flameproof enclosures are subject to pressure whenever an explosion occurs inside them. To ensure the enclosures are strong enough to withstand these explosions, they are subjected to an overpressure test during testing and certification. This can be done statically or dynamically. When determining the reference pressure, the enclosure is filled with a representative gas/air mixture at atmospheric pressure, and the mixture ignited. The resulting pressure is measured using pressure transducers. The test is repeated a number of times as defined by the relevant standard. The value of the maximum pressure, as a reference pressure, is then multiplied by a factor and the resultant figure is used to apply a static or dynamic pressure test to the enclosure. The most widely used standard for this testing is the international standard IEC 60079-1 which is currently at Edition 7.0 [8]. Most commonly, the factors applied by this standard are 1.5 and 4. The factor of 4 can only be applied for enclosures that do not incorporate welded constructions, and the test with this factor exempts the enclosures from routine pressure testing by the manufacturer.

4.1.2 Pressure piling

The effect of pressure piling is addressed in 1.4. As noted there, the situation occurs when there is a restriction between compartments in a flameproof enclosure. The explosion in the first compartment precompresses the gas in the second compartment before the flame from the explosion reaches the second compartment. Thus the pressure of the gas in the second compartment is at a pressure higher than ambient pressure when it is ignited. This leads to higher pressures and faster rise times. A flameproof motor provides a typical example of where this occurs. For a motor, the explosion ignited at one end has to pass through the air gap or other connecting paths before reaching the compartment at the other end. Pressure piling can also occur between the motor body and the terminal box if there is a connecting path for the explosive gas. Thus where pressure piling occurs, enclosures need to be stronger to be able to withstand the increased pressure from internal explosions.

4.1.3 Background on relevant IEC standards

The development of the international standard IEC 60079-1 has been addressed earlier in this thesis. An overview was done in 1.11. The development in relation to pressure determination was covered in Chapter 2. But some of the information is repeated below as it is directly relevant to the topic of this chapter.

Edition 5.0 of IEC 60079-1 IEC [62] introduced significant pressure testing requirements for temperatures below -20 °C. The following requirements were included for pressure determination:

> For electrical apparatus intended for use at an ambient temperature below –20 °C, the reference pressure shall be determined at a temperature not higher than the minimum ambient temperature.
>
> As an alternative, for electrical apparatus
>
> - of Groups I, IIA, or IIB; or
> - of Group IIC with internal free volume < 2 l,
>
> other than rotating electrical machines (such as electric motors, generators and tachometers) that involve simple internal geometry such that pressure piling is not considered likely, the reference pressure may be determined at normal ambient temperature using the defined test mixture(s), but at increased pressure.
>
> The absolute pressure of the test mixture (*P*), in bar, shall be calculated by the following formula, using $T_{a,\min}$ in °C:
>
> $$P = [293 / (T_{a,\min} + 273)] \text{ bar}$$

It did limit the use of the approach to situations where pressure piling does not occur and for small IIC enclosures. However, things changed with Edition 6.0 of IEC 60079-1 IEC [63]. This edition of the standard introduced more detailed requirements for extremely low temperatures. In addition, it changed the applicability of the above formula by allowing it to be used for all equipment. Hence it permitted the use of the approach for equipment where pressure piling might occur. The restriction on only using the approach for Group IIC enclosures with internal free volume < 2 l was also removed. It also changed the formula from bars to kPa as follows:

$$P = 100[293 / (T_{a,\min} + 273)] \text{ kPa}$$ (After correction by corrigendum IEC [64])

The current edition, Edition 7.0 of IEC 60079-1, has the same approach as the previous edition in accepting this method of testing for very low and extremely low temperatures.

It is not clear from published literature what the justification was to initially permit the use of the formula in the standard, even if restricted to equipment with “simple internal geometry”, and only for Group IIC enclosures with internal free volume < 2 L. Similarly there is also a lack of published literature to support the subsequent broader approach of allowing pressure determination of any equipment to be done using this formula.

4.1.4 The effect of low temperatures on explosion pressures

In 2.3.2 the two separate studies by Lobay and PTB looking at the effect the effect of extremely low temperatures on pressures were discussed. The results of the study by Lobay are shown in Figure 6.

As noted earlier, there is a lack of published literature to demonstrate that the use of increased pressure produces a result consistent with tests at very low temperatures in the dynamic situation occurring in an explosion, particularly when pressure piling is present. Further, the number of moles of the gas increase at low temperatures and the formula does not take this into account.

NOTE (additional to published papers) The last statement above which was included in the published papers, but subsequent tests and analysis have suggested that this may not be correct. This is discussed further in the later chapters in this thesis.

Hence I devised experiments that would test the validity of the formula under practical situations, including the presence of pressure piling. Experiments were then carried out at CNEx in China using the resources of that organisation. This chapter reports on the outcomes of the initial round of this testing using a hydrogen/air mixture.

4.2 Experiments - hydrogen

4.2.1 Experimental setup

It was necessary to devise an experimental setup that could check the correlation for pressure determination testing between the actual scenario of decreased temperature and the approach permitted by the standard of increasing the initial pressure. For this, it was decided to make use of an artefact that had been used in the PTB Ex Proficiency Testing Scheme associated with the IECEx Certified Equipment Scheme. In the first round of the proficiency testing scheme an artefact was used to assess test laboratories’ ability to measure explosion pressures in accordance with IEC 60079-1. The artefact could be used as a single chamber or with two chambers separated by an orifice sized to induce pressure piling to occur.

Figure 16 is an extract from a report of the above testing showing an exploded view of the design of the artefact with both chambers and the orifice.

Figure 16 – Exploded view of the artefact

The following is a list of the components:

- Chamber A: 1 x pipe section including 2 x connecting flanges with a total length of 250 mm
- Chamber B: 1 x pipe section including 2 x connecting flanges with a total length of 500 mm
- 2 x blind flanges with test holes
- 1 x orifice: diameter of the orifice hole (15 ± 0.3) mm
- 4 x flange gaskets
- 24 x connecting screws + 24 x nuts
- 8 x locking screws + 8 x sealing rings

Figure 17 shows the test configuration.

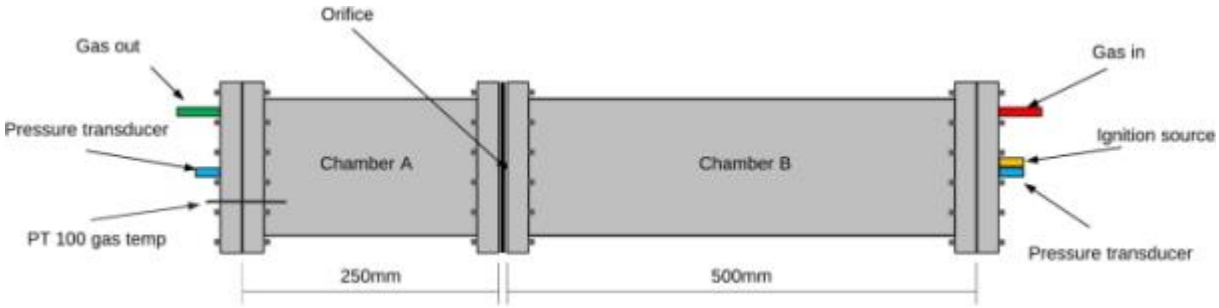


Figure 17 – Test configuration

For the testing reported here, the two chambers were used with the ignition source on Chamber B. This was the configuration that could be expected to produce the largest pressure from pressure piling, with the pressure piling occurring in Chamber A. In addition to the above, a PT100 temperature sensor was inserted partway into Chamber A to enable the temperature of the gas inside the chamber to be measured. This was done to account for the potential temperature differential between the environmental chamber temperature and the temperature inside the artefact. The PT100 sensor was chosen in preference to the other option considered of a K-Type thermocouple because of the adverse effects that hydrogen can have on K-Type thermocouples.

The explosion measurements were made using two Kistler charge amplifiers Type 5018 and associated pressure transducers. The pressure results were displayed on a Yokogawa DLM2024 mixed signal oscillator, Model 710110. The gas concentrations were made with the aid of mass flow controllers and a Servomex Servoflex Micro I.S. 5100is oxygen analyser which provided measurement to two decimal places. Ignition was by means of an electrical spark. For tests involving changing temperature, an environmental chamber Vőtsch C7-1500 Pro was used. For tests involving increased pressure, an autoclave set up for flameproof testing was used. This included a calibrated gauge for measuring pressure inside the autoclave.

4.2.2 Test series

Two series of tests were carried out, one involved varying the temperature and the second series involved varying the initial pressure. A mixture of hydrogen and air (31 ± 1) % as specified by IEC 60079-1 Edition 7.0 for pressure determination was used for all testing. To make allowance for experimental error and other factors such as the paramagnetic effect of the oxygen analyser, the tolerance was halved so that the target percentage was hydrogen and air (31 ± 0.5) %.

4.2.3 Tests with varying temperature

For tests with varying temperature, five explosion tests were carried out at each of the target temperatures of -20, -30, -40, -50 and -60 °C. The explosion pressures in each chamber were recorded.

Figure 18 shows the artefact in the environmental chamber at very low temperatures with frosting on the artefact clearly evident.

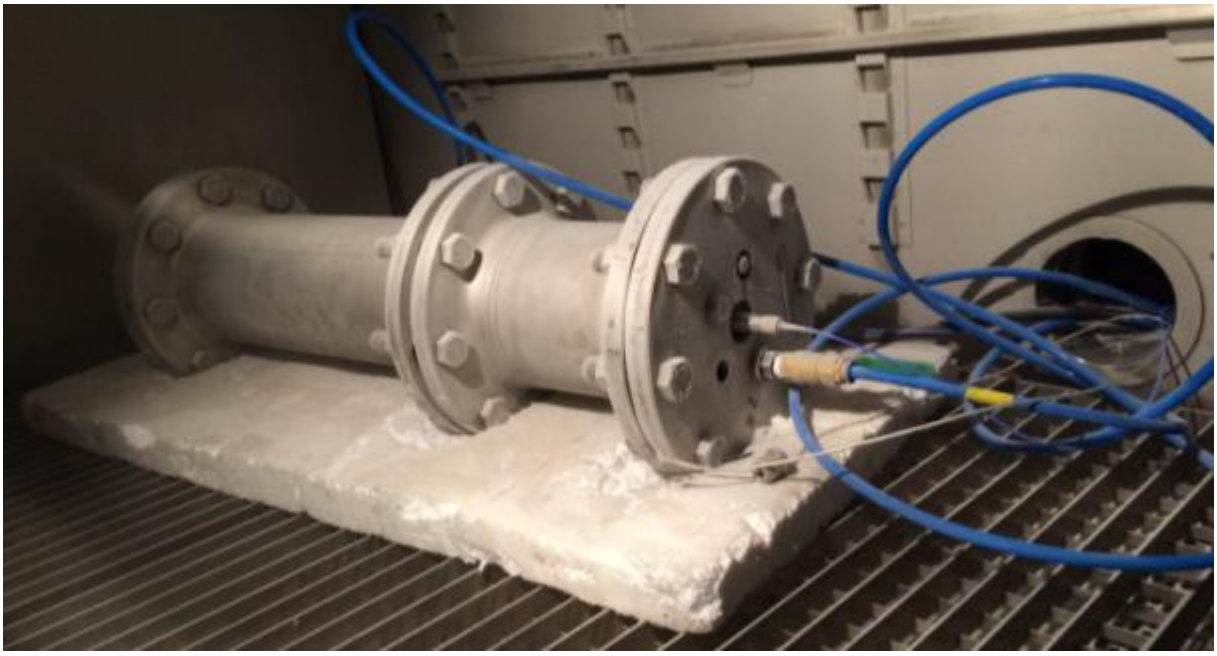


Figure 18 – Artefact in environmental chamber - Tests with varying temperature

4.2.4 Tests with varying pressure

For tests with varying pressure, five explosion tests were carried out at each of the initial pressures, as derived from the above-referenced formula

$$P = 100[293 / (T_{a,\min} + 273)] \text{ kPa}$$

Figure 19 shows the artefact about to be placed in the autoclave for the tests with pressure.

Figure 19 – Artefact about to be placed in autoclave

The initial pressures are shown in TABLE 19 below.

TABLE 19 – INITIAL PRESSURE TO BE APPLIED FOR APPLICABLE TEMPERATURES

Applicable temperature, °C	Initial pressure to be applied, kPa
-20.0	115.81
-30.0	120.58
-40.0	125.75
-50.0	131.39
-60.0	137.56

As it was not possible to control the ambient temperature during the above testing, the ambient temperature was monitored. The formula indicates the calculation is based on an ambient temperature of +20 °C, but testing is permitted by the standard anywhere in the range of -20 to +40 °C. The actual ambient during this testing varied between 13.2 °C and 15.2 °C which is lower than the temperature on which the formula is based.

4.3 Results and discussion - hydrogen

4.3.1 Results

The following results were obtained from the testing, with pressure piling abbreviated to "pp" in the graphs.

4.3.1.1 Comparison of maximum pressures

As noted earlier, five tests were done at each temperature using the environmental chamber. The maximum pressure at each of those temperatures was recorded for both Chamber B, where no pressure-piling occurred, and Chamber A where pressure piling occurred due to the presence of the orifice between the two chambers. Similarly, five tests were done with pre-pressurisation using the autoclave for the corresponding temperatures using the formula. Again the maximum pressures were recorded for both chambers for each set of tests at the corresponding temperature. TABLE 20 shows those maximum pressures side-by-side so a comparison can be made of the two methods of testing. "Temperature" in the first column of the table is the "target temperature" when the temperature was varied and the "Applicable temperature" as shown in TABLE 19 when varying pressure was used.

It can be seen that the testing in the environmental chamber with the actual temperature provided higher pressure figures at each temperature than the pressures produced with pre-pressurisation using the formula for the relevant temperature. This occurred both when pressure piling was present and when pressure piling was not present.

TABLE 20 – COMPARISON OF MAXIMUM PRESSURES - HYDROGEN

Temperature, °C	Chamber A - pressure piling Maximum pressures, kPa		Chamber B - no pressure piling Maximum pressures, kPa	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,830	1,550	940	770
-30	1,836	1,660	940	810
-40	2,090	1,640	1,172	890
-50	2,058	1,850	1,272	900
-60	2,112	1,900	1,422	950

The comparison of the results can be seen more clearly when the results are plotted as shown in Figure 20. The "Temperature" on the x-axis is the "Applicable temperature" as shown in TABLE 19 and the corresponding actual temperature when the temperature was varied in the chamber.

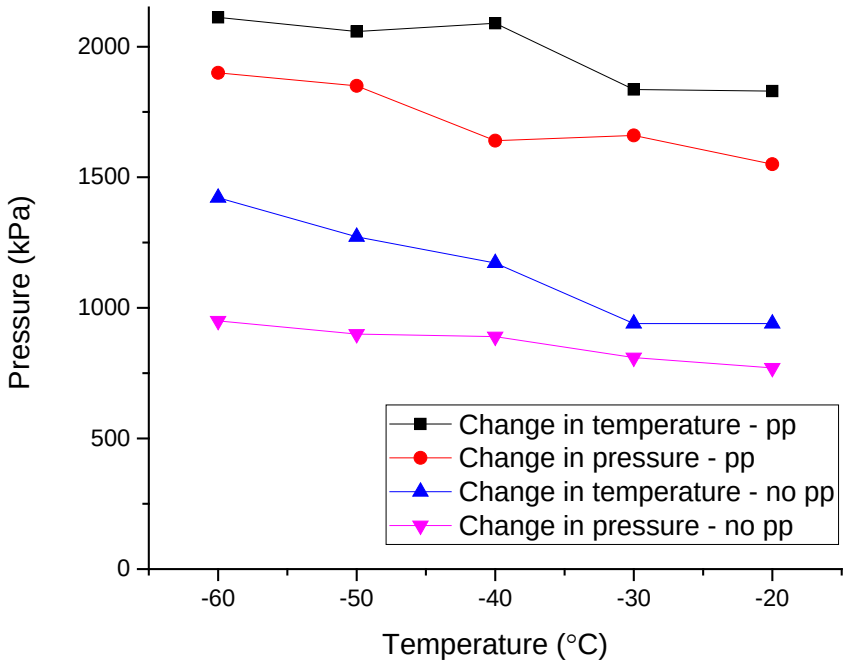


Figure 20 – Graphs of maximum pressure - Hydrogen

A further analysis can be done by looking at the percentage differences as shown in TABLE 21. These show percentage differences ranging from a low of 9.6 % to a high of 33.2 %.

TABLE 21 – PERCENTAGE DIFFERENCES FOR MAXIMUM PRESSURES - HYDROGEN

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	15.3	18.1
-30	9.6	13.8
-40	21.5	24.1
-50	10.1	29.2
-60	10.0	33.2

4.3.1.2 Comparison of average pressures

When doing pressure determination testing to IEC 60079-1, the maximum pressure obtained from all tests done is the pressure figure that is used for the overpressure test with the factor applied. Hence the reason for using the maximum pressure above. However, from a statistical point of view, it was also decided to do an analysis based on the average pressures for each set of five pressure figures. The results are shown in TABLE 22.

TABLE 22 – COMPARISON OF AVERAGE PRESSURES - HYDROGEN

Temperature, °C	Chamber A - pressure piling Average pressures, kPa		Chamber B - no pressure piling Average pressures, kPa	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,623	1,502	869	762
-30	1,741	1,588	906	794
-40	1,921	1,598	1,071	856
-50	2,026	1,728	1,216	882
-60	2,004	1,816	1,257	928

NOTE (additional to published papers) The above table has been changed from that presented at the symposium and published in the Journal of Loss Prevention in the Process Industries, to correct errors in the average pressure figure for no pressure piling for tests with changing temperature at -50 and -60 °C. These corrections have not affected the findings from this testing as expressed in original papers.

Again in each case it can be seen that the testing using actual temperatures provided higher pressure figures at each temperature than the pressures produced with pre-pressurisation using the formula for the relevant temperature. This again was when pressure piling was present and not present. The above results are again plotted as shown in Figure 21 which makes the differences clearer.

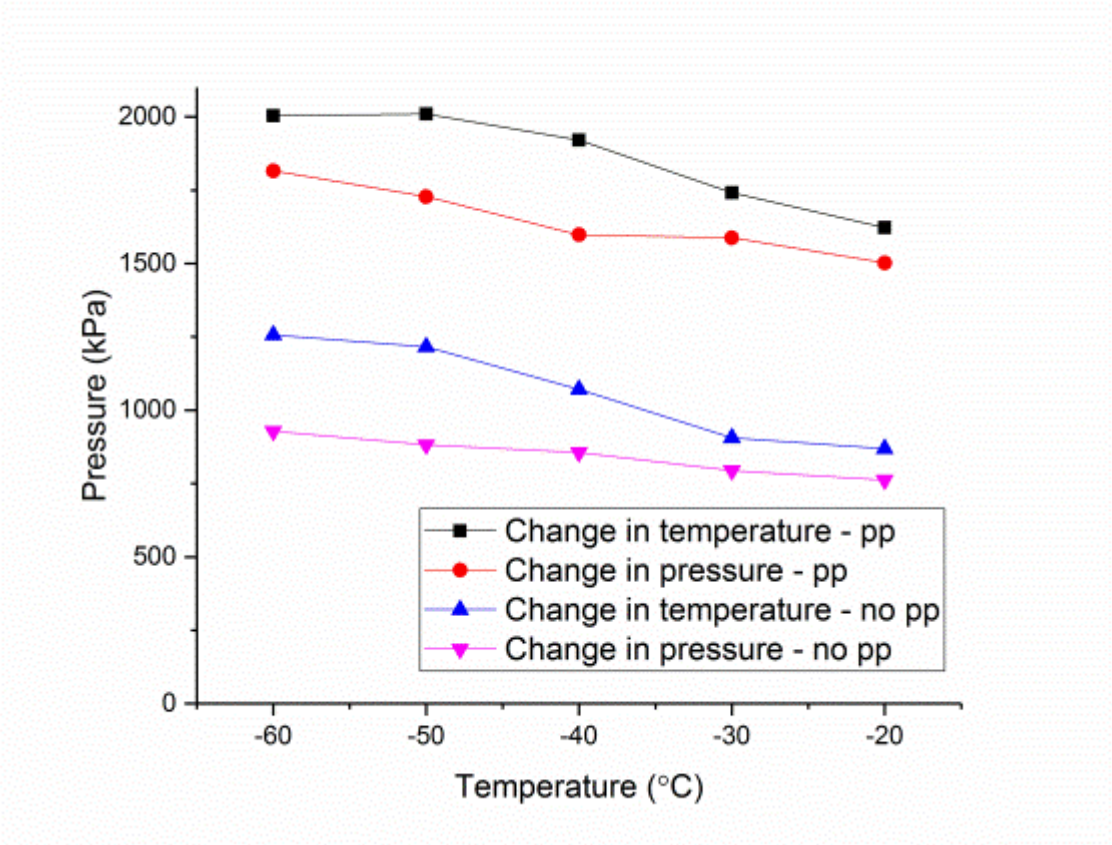


Figure 21 – Graphs of average pressure - Hydrogen

NOTE (additional to published papers) The above graph includes the changes made to TABLE 21.

Again a further analysis can be done by looking at the percentage differences as shown in TABLE 23. These show percentage differences ranging from a low of 7.4 % to a high of 27.4 %.

TABLE 23 – PERCENTAGE DIFFERENCES FOR AVERAGE PRESSURES - HYDROGEN

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	7.4	12.3
-30	8.8	12.3
-40	16.8	20.1
-50	14.7	27.4
-60	9.4	26.2

NOTE (additional to published paper) The above table has been changed to reflect the changes made to TABLE 21as addressed in the note under that table.

4.3.2 Discussion of results

The results from the experiments show a clear difference in results between the two different methods of testing. The pressures obtained using the increased initial pressure were always lower, and in some cases significantly lower, than the pressures obtained when testing at

actual temperatures, with the highest difference being over 32 %. The differences occurred for both chambers, that is with or without pressure piling. The tests using actual temperatures provide the pressures that can be expected to occur in practice and so, based on the results obtained in this testing, it appears doing the testing with pre-pressurisation using the formula can lead to significantly lower pressures.

The testing with increased initial pressures was carried out at ambient temperatures below the +20 °C assumed by the formula. Testing at an ambient temperature of +20 °C would have given lower pressures and hence a greater difference.

It is likely the reason for the differences is that the formula is only valid for steady-state pressure situations with consistent pressure throughout each enclosure. This is not the situation when an explosion occurs in an enclosure. Further, even if the formula where applicable for one gas, it would not be applicable for other gases where the gradients of the curves are different as shown in Figure 6. In addition, as explained in 4.1.4, perhaps just as significant is the fact that the number of moles of the gas increase at low temperatures and the formula does not take this into account.

NOTE (additional to published papers) The statement above which was included in the published papers, but subsequent tests and analysis have suggested that this may not be correct. This is discussed further in the later chapters in this thesis.

An unexpected result from this testing was that in most cases there was less of a difference in the chamber where pressure piling was present compared to the chamber where there was no pressure piling. However, this testing was done with hydrogen which, as can be seen from Figure 6, does not exhibit a steep increase in pressure as temperatures fall and does not show a significant increase in pressure when pressure piling is present. Other gases, in particular methane, exhibit steeper curves and a greater increase due to pressure piling. Hence it may well be expected to provide a greater difference in pressures. Further testing is planned to investigate the impact of testing with one or more of the other gases that are specified in IEC 60079-1 for pressure determination testing.

NOTE (additional to published papers) Some additional testing was carried out and is addressed later in this thesis.

This test arrangement was primarily set up to test for the scenario with pressure piling present. It should be noted that the chamber in which no pressure piling took place (Chamber B) did have the orifice into the Chamber A. It is likely this orifice would have affected the actual pressures because of the pressure relief it provided, but it is difficult to estimate the relative effect on the results of the two different methods of test. It is recommended that consideration be given to repeating this testing using only Chamber B with flanges on both ends (see Chapter 12).

4.4 Conclusions - Pressure formula - Hydrogen

The results from this experiment using hydrogen/air for pressure determination testing indicate that the use of the formula as currently shown in IEC 60079-1 for pre-pressurisation for pressure determination for equipment intended for use in extremely low temperatures provides consistently, and at times significantly, lower pressure figures in comparison to testing with the actual temperatures. This means the application of this test method would lead to lower pressures being used for overpressure testing than desirable and hence there is a possibility that enclosures being used in low and extremely low temperatures may not be capable of withstanding the pressures from explosions that they may experience.

The analysis suggested that further testing with other gases may provide even larger differences between the pressures obtained. As a consequence of this, it was anticipated that it is likely that the formula will need to be modified or the option of its use removed from IEC 60079-1 standard. It is anticipated these options will be considered when the next edition of IEC 60079-1 is developed.

The content of this Chapter was presented to the 11th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions (ISHPMIE) which was hosted in Dalian, China 24-29 in July 2016 [72] and published in the Journal of Loss Prevention in the Process Industries [73].

4.5 Further consideration - Pressure formula - Hydrogen

The discussion in 4.3.2 and conclusions in 4.4 above have been retained to show the actual information presented in the papers and do not represent the final discussions and conclusions that occurred on the basis of the information from additional testing. These revised discussions and conclusions are presented in later chapters of this thesis, including in 5.4, 6.5, 7.4 and 11.3. In addition, some notes have been added to the text of this chapter to clarify where information from later testing has impacted on the discussions and conclusions.

5 Validity of using increased pressures at ambient temperatures for pressure determination for low temperatures - additional testing

5.1 Introduction

Chapter 4 looked at applying the formula below which is in IEC 60079-1[8] to pressurise a gas prior to creating an explosion in an enclosure for the purposes of simulating an explosion at low temperatures with a view to determining the maximum explosion pressure.

$$P = 100[293 / (T_{a,\min} + 273)] \text{ kPa}$$

It compared the use of the formula with tests done at actual low temperatures down to -60 °C. It found that the tests using the formula gave consistently lower pressures than those done at actual ambient temperatures.

However, different gases have different explosion pressures at ambient temperature, and the rate of increase of explosion pressures for those gases at lower temperatures can be different, as examined in 2.3.2 and 4.1.4. This chapter looks at results for testing with methane using the same experimental setup as used for hydrogen. It then analyses the results for methane and compares them with the results for hydrogen.

5.2 Experiments - methane

5.2.1 Experimental setup

The experimental setup again utilised the artefact that had been used in the PTB Ex Proficiency Testing Scheme associated with the IECEx Certified Equipment Scheme. Chapter 4 Figure 16 shows an exploded view of the design of the artefact with both chambers and the orifice. It also includes a list of components.

Chapter 4 Figure 17 shows the test configuration. This again used the two chambers with the ignition source on Chamber B as the configuration that could be expected to produce the largest pressure from pressure piling, with the pressure piling occurring in Chamber A. A PT100 temperature sensor was again inserted partway into Chamber A to enable the temperature of the gas inside the chamber to be measured.

The explosion measurements were made using the same instrumentation as shown in Chapter 4. The operating temperature range of the transducers was checked, and it was found that they can operate in the range of -196 °C to 200 °C. For tests involving changing temperature, the same environmental chamber was used. For tests involving increased pressure, the same autoclave set up for flameproof testing was used.

5.2.2 Test series

Two series of tests were carried out, one involved varying the temperature and the second series involved varying the initial pressure. A mixture of methane and air (9.8 ± 0.5) % as specified by IEC 60079-1 Edition 7.0 for pressure determination was used for all testing. To make allowance for experimental error and other factors such as the paramagnetic effect of the oxygen analyser, the tolerance was halved so that the target percentage was methane and air (9.8 ± 0.25) %.

5.2.3 Tests with varying temperature

For tests with varying temperature, five explosion tests were carried out at each of the target temperatures of -20, -30, -40, -50 and -60 °C. The explosion pressures in each chamber were recorded.

It should be noted that for equipment intended for no less than -20 °C, the standard only requires testing at ambient temperature and pressure. However, the experiments were done to show the whole band from just lower than -20 °C to -60 °C. Starting at -20 °C was a convenient way to do this.

The actual temperatures obtained varied slightly from the target temperature, but this variation was considered not significant enough to impact on the ability to make comparisons between the two approaches. Chapter 4 Figure 18 shows the artefact in the environmental chamber for the original tests with hydrogen. As noted above, the same chamber was used for methane.

5.2.4 Tests with varying pressure

For tests with varying pressure, five explosion tests were carried out at each of the initial pressures, as derived from the above-referenced formula. Similarly to the earlier testing, the actual pressures obtained varied slightly from the target but again were not considered significant enough to affect the comparisons.

Chapter 4 Figure 19 shows the autoclave which was used for the tests with pressure for hydrogen. This autoclave was again used for methane testing.

The initial pressures were the same as for hydrogen testing as shown earlier in TABLE 19. As it was not possible to control the ambient temperature during the above testing, the ambient temperature was again monitored. The formula indicates the calculation is based on an ambient temperature of +20 °C, but testing is permitted by the standard anywhere in the range of -20 to +40 °C. The actual ambient during this testing varied between 14.0 °C and 15.0 °C which is lower than the temperature on which the formula is based. This was similar ambient temperature conditions to the testing with hydrogen.

5.3 Results and discussion- methane

5.3.1 Results

The following results were obtained from the testing, with pressure piling abbreviated to "pp" in the graphs.

5.3.1.1 Comparison of maximum pressures

As noted earlier, five tests were done at each temperature using the environmental chamber. The maximum pressure at each of those temperatures was recorded for both Chamber B, where no pressure-piling occurred, and Chamber A where pressure piling occurred due to the presence of the orifice between the two chambers. Similarly, five tests were done with pre-pressurisation using the autoclave for the corresponding temperatures using the formula. Again the maximum pressures were recorded for both chambers for each set of tests at the corresponding temperature. TABLE 24 shows those maximum pressures side-by-side so a comparison can be made of the two methods of testing. "Temperature" in the first column of the table is the "target temperature" when the temperature was varied and the "Applicable temperature" as shown in TABLE 19 when varying pressure was used.

It can be seen that the testing in the environmental chamber with the actual temperature provided higher pressures figures at each temperature than the pressures produced with pre-pressurisation using the formula for the relevant temperature when pressure piling was present. When pressure piling was not present, however, most results using initial pressure were slightly higher. But it appears the two approaches produced very similar results.

The comparison of the results can be seen more clearly when the results are plotted as shown in Figure 22. The "Temperature" on the x-axis is the "Applicable temperature" as shown in TABLE 19 and the corresponding actual temperature when the temperature was varied in the environmental chamber.

TABLE 24 – COMPARISON OF MAXIMUM PRESSURES - METHANE

Temperature, °C	Chamber A - pressure piling Maximum pressures, kPa		Chamber B - no pressure piling Maximum pressures, kPa	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,806	1,604	518	506
-30	1,900	1,712	504	522
-40	2,004	1,757	559	580
-50	2,059	1,799	592	600
-60	2,171	1,967	609	632

The comparison of the results can be seen more clearly when the results are plotted as shown in Figure 22. The "Temperature" on the x-axis is the "Applicable temperature" as

shown in TABLE 19 and the corresponding actual temperature when the temperature was varied in the environmental chamber.

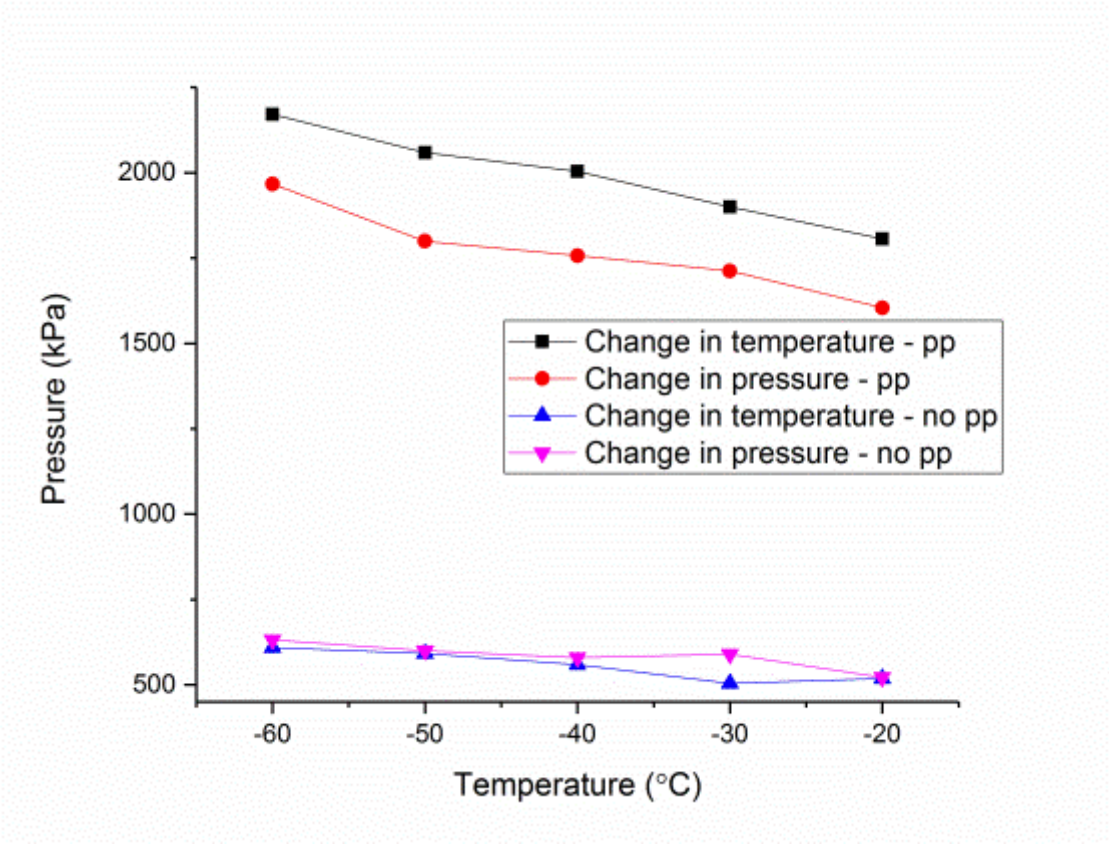


Figure 22 – Graphs of maximum pressure - Methane

As was done for hydrogen, further analysis can be done by looking at the percentage differences as shown in TABLE 25. These show percentage differences ranging from a low of 9.4 % to a high of 12.6 % for the pressure piling situation. Thus it did not meet the expectation of a bigger difference than for hydrogen, but explosion pressures for methane were lower than expected and so this may have been the reason. For the situation with no pressure piling the range is from -1.4 to 14.3 %, and for the majority of temperature points shows better correlation between the two methods than for the hydrogen testing.

TABLE 25 – PERCENTAGE DIFFERENCES FOR MAXIMUM PRESSURES - METHANE

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	11.2	2.3
-30	9.9	14.3
-40	12.3	-3.8
-50	12.6	-1.4
-60	9.4	-3.8

5.3.1.2 Comparison of average pressures

As noted in Chapter 4, when doing pressure determination testing to IEC 60079-1, the maximum pressure obtained from all tests done is the pressure figure that is used for the overpressure test with the factor applied. However, again from a statistical point of view, it was again decided to do an analysis based on the average pressures for each set of five pressure figures. The results are shown in TABLE 26.

TABLE 26 – COMPARISON OF AVERAGE PRESSURES - METHANE

Temperature, °C	Chamber A - pressure piling Average pressures, kPa		Chamber B - no pressure piling Average pressures, kPa	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,769	1,500	510	505
-30	1,811	1,667	493	556
-40	1,913	1,663	527	559
-50	2,030	1,765	566	591
-60	2,024	1,874	568	618

The above results are reasonably comparable to those for maximum pressure and can again be plotted as shown in Figure 23 to make the differences clearer.

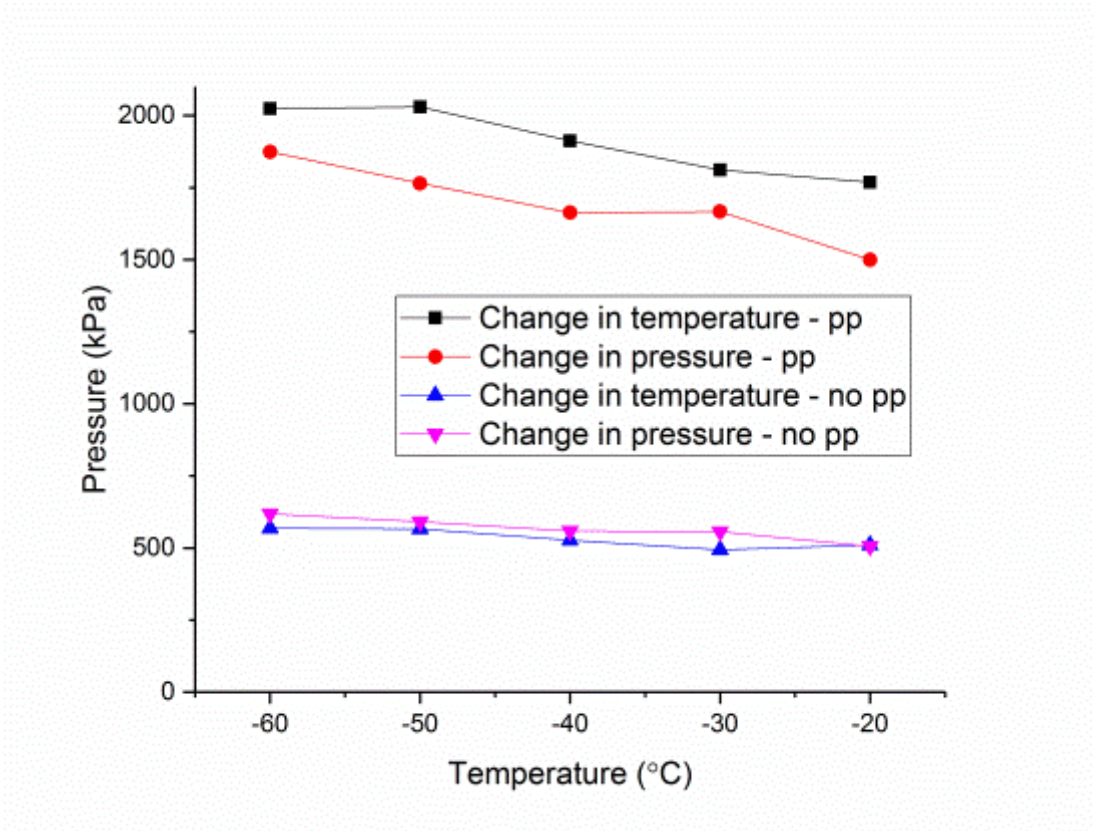


Figure 23 – Graphs of average pressure - Methane

Again a further analysis can be done by looking at the percentage differences as shown in TABLE 27. These show percentage differences ranging from a low of 0.9 % to a high of 15.2 %.

TABLE 27 – PERCENTAGE DIFFERENCES FOR AVERAGE PRESSURES - METHANE

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	15.2	0.9
-30	7.9	-12.9
-40	13.1	-6.1
-50	13.0	-4.3
-60	7.4	-8.9

5.3.2 Discussion of results - including comparison of hydrogen and methane

The results from testing with methane did not follow the pattern that was expected or predicted, based on the results for hydrogen. Hence, some reevaluation of the scenario is appropriate.

The two graphs for maximum pressure are shown side-by-side in Figure 24 for comparison.

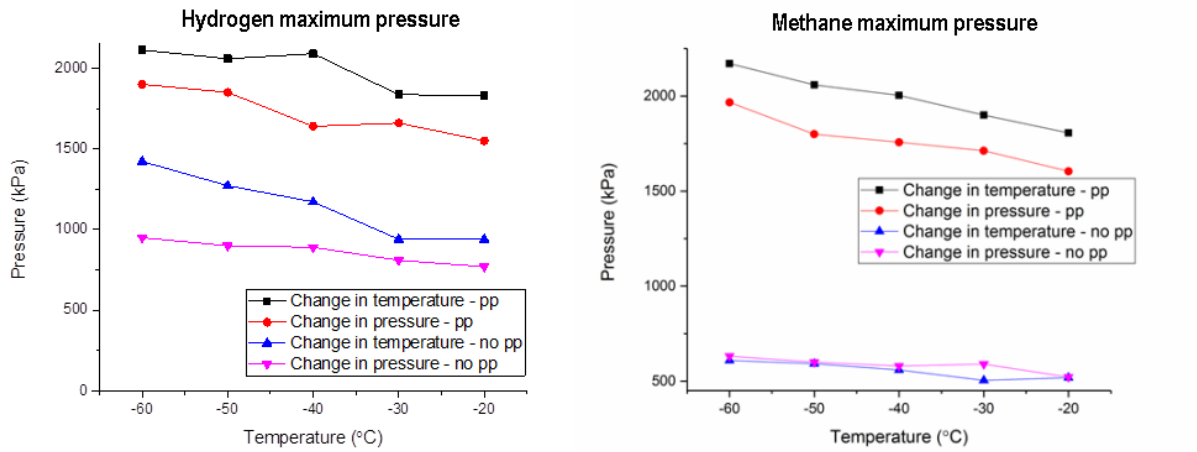


Figure 24 – Graphs of maximum pressure - Hydrogen and methane

There is still a clear difference between the results where pressure piling is present, with tests at actual temperature when using hydrogen and when using methane. However, the differences did not increase as predicted at the conclusion of the hydrogen testing. Time did not permit testing with other gases, but this has been identified as an area for possible additional testing - see Chapter12.

As noted in Chapter 4, the testing for the situation with no pressure piling could have been affected by the fact that the measure was made in a chamber that was linked to another chamber for pressure piling scenarios. It would be informative to carry out additional testing with a single chamber. This has also been identified as an area for possible additional testing in Chapter 12.

The reasons for the difference in results between hydrogen and methane when pressure piling was not present are not immediately clear. It is possible that there was some difference in the dynamics due to the orifice hole. However, of more significance are the results from PTB as shown in Chapter 7. They achieved quite good correlation for hydrogen for the situation with no pressure piling. This is addressed in that chapter. So it is possible that the project pressure figures obtained for hydrogen were abnormally high for some reason, or that the PTB figures were low. Testing with a single chamber, as identified for possible additional testing above, would be a good way to resolve this.

Additional tests with other gases, such as propane, ethylene and acetylene, might provide interesting data in this regard, and again this has been identified for possible additional testing in Chapter12.

Similarly, as for hydrogen, testing with increased initial pressures was carried out at ambient temperatures below the +20 °C assumed by the formula. Testing at an ambient temperature of +20 °C would have given lower explosion pressures and had some effect on the results. The potential for the ambient temperature to be an issue has been addressed when looking at possible revision to the formula in Chapter 6.

5.4 Conclusions - pressure formula

The results from this experiment using methane/air for pressure determination testing have, to some extent, collaborated the results using hydrogen/air when examining the validity of the formula as currently shown in IEC 60079-1 for pre-pressurisation for pressure determination for equipment intended for use in extremely low temperatures.

However, this collaboration only occurred for the pressure piling situation. The results for the no pressure piling situation were inconclusive with methane/air as the formula appeared to return appropriate results for methane.

The results did support the premise that the formula, if retained, may need to:

- be modified;
- restricted to non-pressure piling situations; or
- a combination of the above.

Chapter 6 explores a possible revision of the formula and the testing done to check the revised formula using hydrogen.

6 Validity of using increased pressures at ambient temperatures for pressure determination for low temperatures - revised formula

6.1 Introduction

Previous results in Chapter 4 and in papers presented on the material in that chapter [72, 73], and also in Chapter 5 have shown that the formula for pre-pressurising equipment before doing the pressure determination test in IEC 60079-1 can provide results that are significantly lower than when testing is done at the actual temperatures. The formula currently shown in the standards is:

$$P = 100[293 / (T_{a,min} + 273)] \text{ kPa}$$

Where $T_{a,min}$ is the lowest intended ambient temperature in which the equipment is intended to operate.

Two issues were identified that may impact on the validity of the formula as follows:

1) The formula may not fully take into account the increase in the number of moles in the gas as the temperature decreases.
2) The formula assumes an ambient of +20 °C, whereas IEC 60079-1 assumes normal ambient temperatures can vary anywhere between -20 °C and +40 °C.

6.2 Discussion on the issues affecting the existing formula

The following is a discussion of the two issues listed above:

1) Number of moles - The number of moles impacts on the explosion pressure as discussed in 4.1.3 and 4.3.2. As the number of moles increases with lower temperature, the explosion pressure increases. The pressure results in previous testing and testing for this project have demonstrated that this is a linear increase in pressure. So it is reasonable to assume the contribution of the increase in moles to pressure is linear and inversely proportional to the temperature. It is postulated that if an enclosure were filled with gas at ambient temperature, sealed and then cooled to low temperature, then an explosion is more likely to provide a pressure similar to that produced by the pre-pressurisation method. However, that does not simulate a real-life situation nor the situation that is used when testing enclosures at low temperatures. The gas is passed through the enclosure at the low temperature, and it is only when the enclosure and the gas are at the low temperature that the gas inlet and outlet valves are closed. This means that the number of moles of gas in the enclosure might be higher than if the first approach were used.
2) Ambient temperature - The ambient temperature could have a significant impact on the initial pressure used if the actual ambient is significantly different to +20 °C. Testing for these experiments has indicated a significant range of ambient temperatures with testing being done in areas without any form of cooling or heating and a wide range of ambient temperatures. Other testing facilities may experience similar scenarios. Chapter 2 highlighted the potential change in pressure that might occur over the whole range of permissible ambient temperatures.

6.3 Revised formula

To take account of the above two issues the formula can be modified to make provision for the ambient temperature of the test and the increase in moles at lower temperatures. The following is the proposed formula:

$$P = 100[293 / (T_{a,min} + 273)^2] \text{ kPa}$$

This formula now includes the ambient temperature as part of the formula (rather than assuming +20 °C and introduces an additional factor to attempt to better cater for the number of moles by squaring the denominator.

6.4 Testing with the revised formula

6.4.1 Results

Testing in the autoclave was carried out with hydrogen and again compared with testing at actual temperatures. Five tests were performed for each of the applicable temperatures from -20 to -60 °C. TABLE 28 shows the initial pressures that were applied using the revised formula, which included the need to take account of the ambient temperature for the testing. The calculation was done at the beginning of each series of the five tests representing an applicable temperature, using the ambient temperature as shown in the table.

TABLE 28 – INITIAL PRESSURES APPLIED FOR APPLICABLE TEMPERATURES WITH REVISED FORMULA

Applicable temperature, °C	Ambient temperature, °C	Initial pressure to be applied, kPa
-20.0	10	125.12
-30.0	8	133.72
-40.0	8	145.45
-50.0	9	159.91
-60.0	9	175.28

6.4.1.1 Comparison of maximum pressures

TABLE 29 shows the maximum pressures obtained using the revised formula side-by-side with the original results using changing temperature.

TABLE 29 – COMPARISON OF MAXIMUM PRESSURES - HYDROGEN - REVISED FORMULA

Temperature, °C	Chamber A - pressure piling Maximum pressures, kPa		Chamber B - no pressure piling Maximum pressures, kPa	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,830	1,493	940	847
-30	1,836	1,660	940	903
-40	2,090	1,753	1,172	996
-50	2,058	2,009	1,272	1,116
-60	2,112	2,100	1,422	1,232

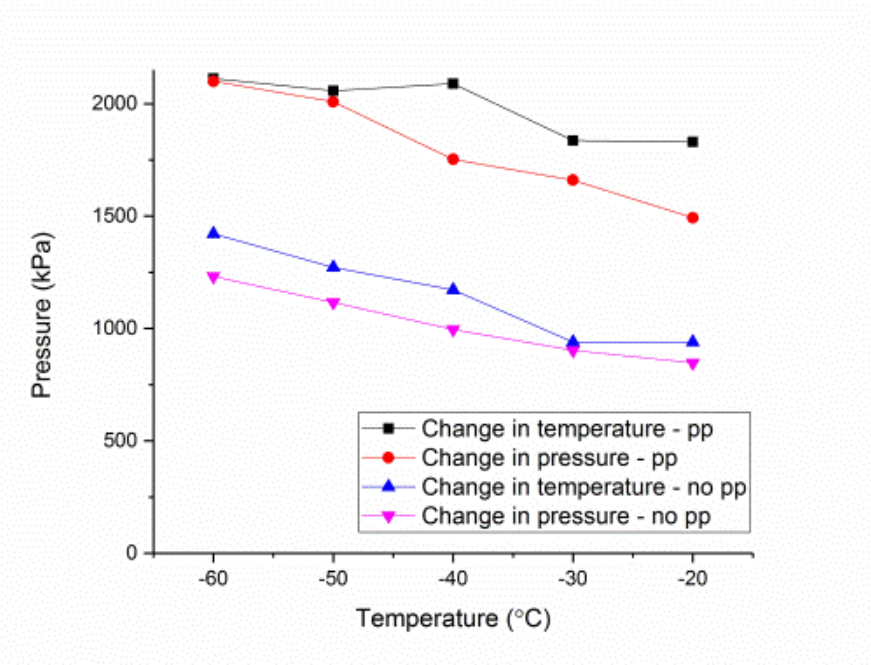


Figure 25 – Graphs of maximum pressure - Hydrogen - Revised formula

The plot showing the results with the revised formula is shown above in Figure 25. The percentage differences are shown in TABLE 30. These show percentage differences ranging from a low of 0.0 % to a high of 18.4 %.

TABLE 30 – PERCENTAGE DIFFERENCES FOR MAXIMUM PRESSURES - HYDROGEN - REVISED FORMULA

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	18.4	0.0
-30	9.6	3.9
-40	16.1	15.0
-50	2.4	12.3
-60	0.6	13.4

6.4.1.2 Comparison of average pressures

The results when looking at average pressures are shown in TABLE 31.

TABLE 31 – COMPARISON OF AVERAGE PRESSURES - HYDROGEN REVISED FORMULA

Temperature, °C	Chamber A - pressure piling		Chamber B - no pressure piling	
	Tests with changing temperature	Tests with changing pressure	Tests with changing temperature	Tests with changing pressure
-20	1,623	1,462	869	829
-30	1,741	1,568	906	902
-40	1,921	1,670	1,071	976
-50	2,010	1,921	1,216	1,101
-60	2,004	2,048	1,157	1,177

The above results are plotted in Figure 26.

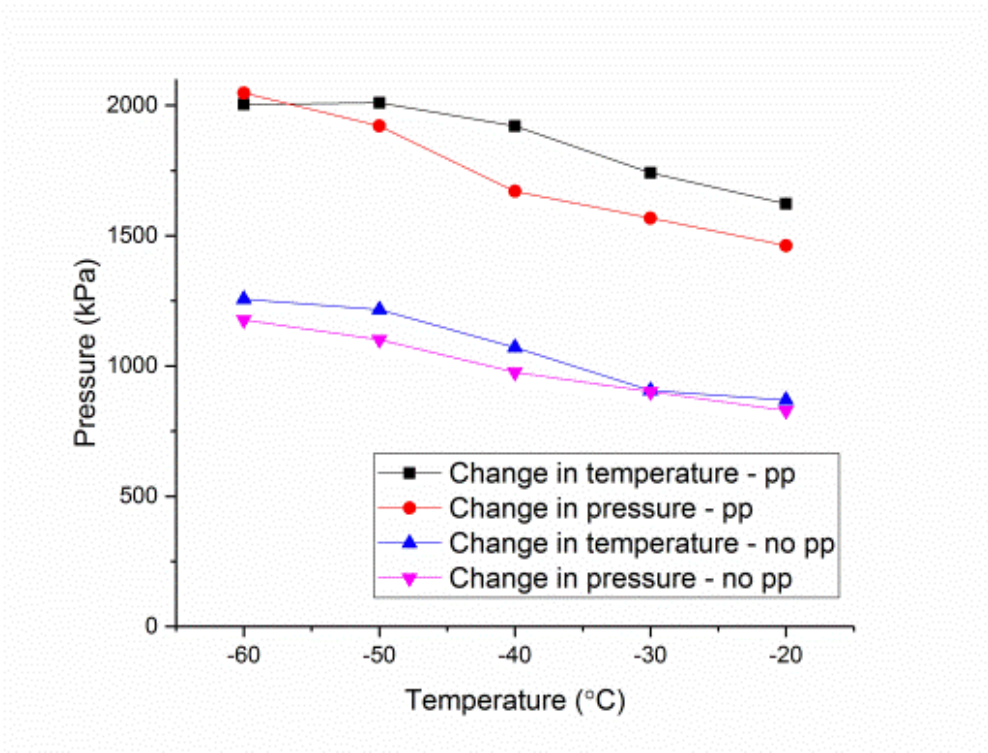


Figure 26 – Graphs of average pressure - Hydrogen - Revised formula

The percentage differences are as shown in TABLE 32. These show percentage differences ranging from a low (in difference) of 0.4 % to a high of 13.1 %, noting that in one case the difference is -2.2 %. These are again an improvement on the results with the original formula.

TABLE 32 – PERCENTAGE DIFFERENCES FOR AVERAGE PRESSURES - HYDROGEN - REVISED FORMULA

Temperature, °C	Percentage difference, %	
	For pressure piling (Chamber A)	For no pressure piling (Chamber B)
-20	9.9	4.6
-30	9.9	0.4
-40	13.1	8.9
-50	4.4	9.4
-60	-2.2	6.3

6.4.2 Discussion of results

The above results are plotted in Figure 27 and Figure 28 below, together with the original results shown on the left to allow a comparison to be made.

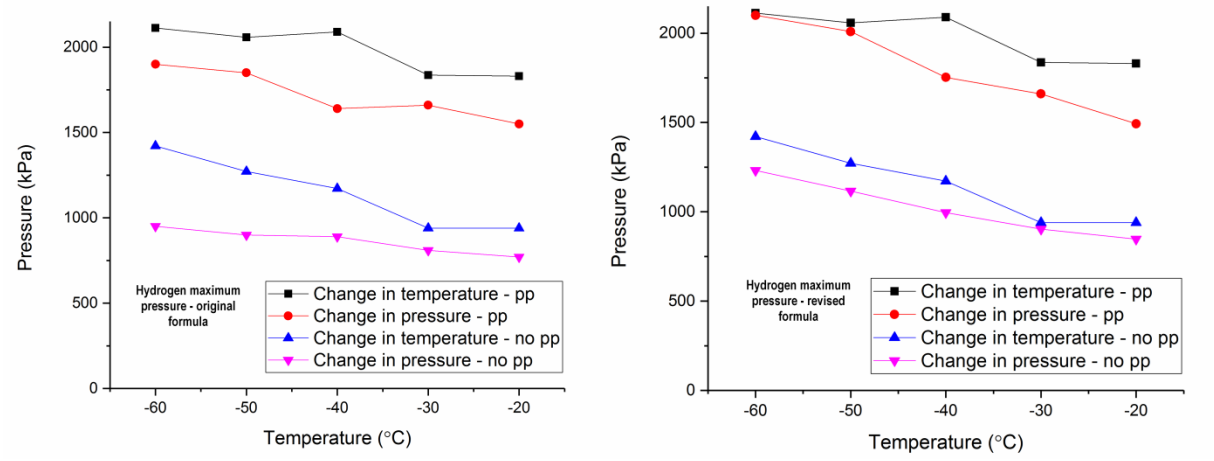


Figure 27 – Graphs of maximum pressure - Hydrogen - Original and revised formula

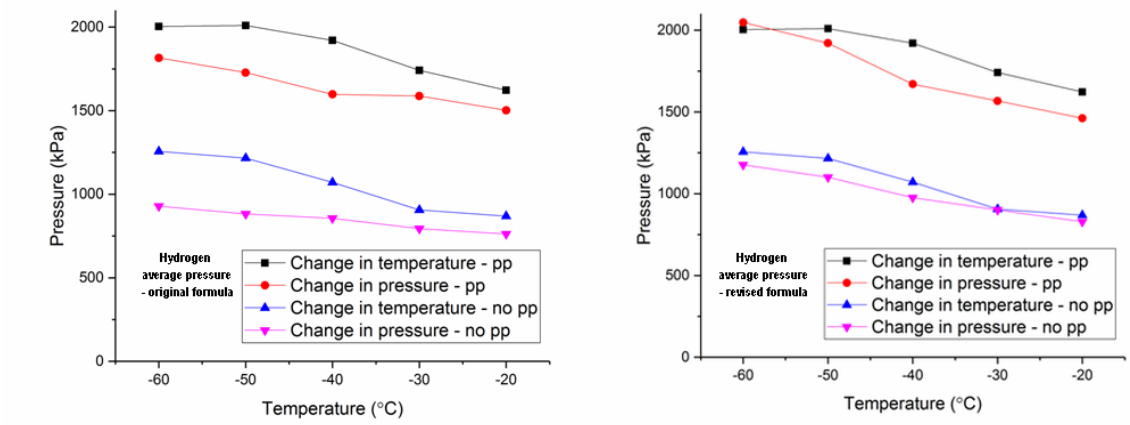


Figure 28 – Graphs of average pressure - Hydrogen - Original and revised formula

The results from using the revised formula do indicate an improvement in the correlation between testing at actual temperatures and testing using increased initial pressures.

6.5 Conclusions - revised pressure formula - hydrogen

The results using the revised formula do show an improvement on the existing formula when testing with hydrogen, based on the testing carried out under this project as reported in Chapter 4. However, most pressures remain higher when testing is done in actual temperature. So while the new formula does indicate improvement and it does appear it may take better account of the actual scenarios, it is likely that more test results will be needed to provide confidence or otherwise in its use. However, subsequent to this testing, testing with methane was carried out and also the check testing by PTB with hydrogen. As indicated elsewhere, these demonstrated better correlation with the existing formula when pressure piling was not present (ie in Chamber B). So further discussion on the possible revised formula is deferred until the next chapter and the overall thesis conclusions in Chapter 11.

7 Validity of using increased pressures at ambient temperatures for pressure determination for low temperatures - check testing at PTB

7.1 Introduction

In view of the potential significance of the findings of this work investigating the use of the formula for pre-pressurisation of flameproof equipment to simulate low temperatures and the potential impact on the standard, it was decided to seek independent verification of the work. PTB agreed to carry out the same work that was done using hydrogen for this testing. PTB did the work using the same range of temperatures. I provided PTB with a test plan for carrying out the work.

The work at PTB was carried out after the project work reported in Chapters 4, 5 and 6, regarding testing with hydrogen, testing with methane and testing the revised formula for hydrogen. The papers relevant to Chapter 4 were also published prior to the PTB work.

7.2 Experiments - PTB testing

PTB performed their low temperature testing in a freezer capable of achieving -60 °C. Their pre-pressurised testing was done in an autoclave, see Figure 29. I was present for the testing in the autoclave. Pressure measurements were made using Kistler transducers with associated charge amplifiers and pressure recording system.

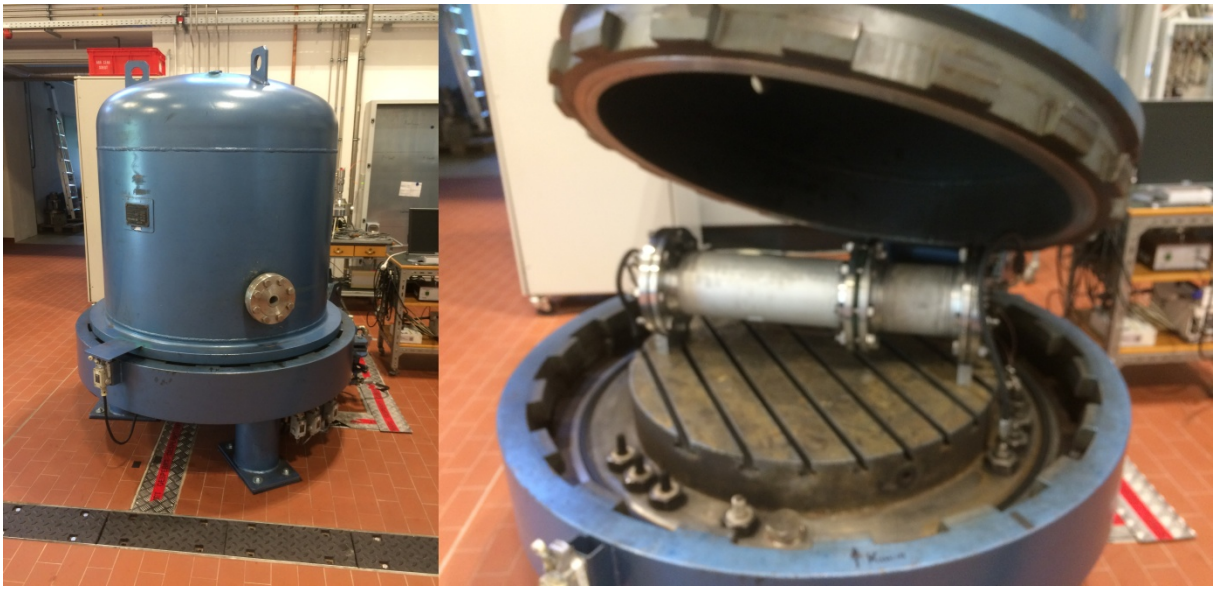


Figure 29 – PTB autoclave with pre-pressurised test

7.3 Results and discussion - PTB testing

The results of the PTB testing, are shown in Figure 30 and include comparison with the earlier results shown in Chapter 4. PTB have indicated that a major part of the results was comparable to those shown in Chapter 4, except for some differences in statistics. However, as can be seen from the graphs, there were some differences in the scenarios for the pressures in Chamber B (ie with no pressure piling) between those shown in Chapter 4 and those obtained by PTB. PTB achieved quite good correlation between the results when testing with lower temperatures, and with the pre-pressurisation for this scenario. However, the results when testing with the lower temperatures did provide slightly higher results in each case.

PTB did agree in an email (personal communication, 27 June 2017) that:

> The results from this experiment using hydrogen-air for pressure determination testing indicate that the use of the formula as currently shown in IEC 60079-1 for pre-pressurization for pressure determination for equipment intended for use in extremely low temperatures provides consistently, and at times significantly, lower pressure figures in comparison to testing with the actual temperatures <u>in the event that pressure piling occurs.</u>

They also stated:

> Generally, it is recommended to perform further test series with a higher number of explosions to increase the confidence of the results from a statistical point of view. Furthermore, experiments with different gas-air mixtures and different geometries would be worthwhile to investigate the validity of the conclusion for different scenarios.

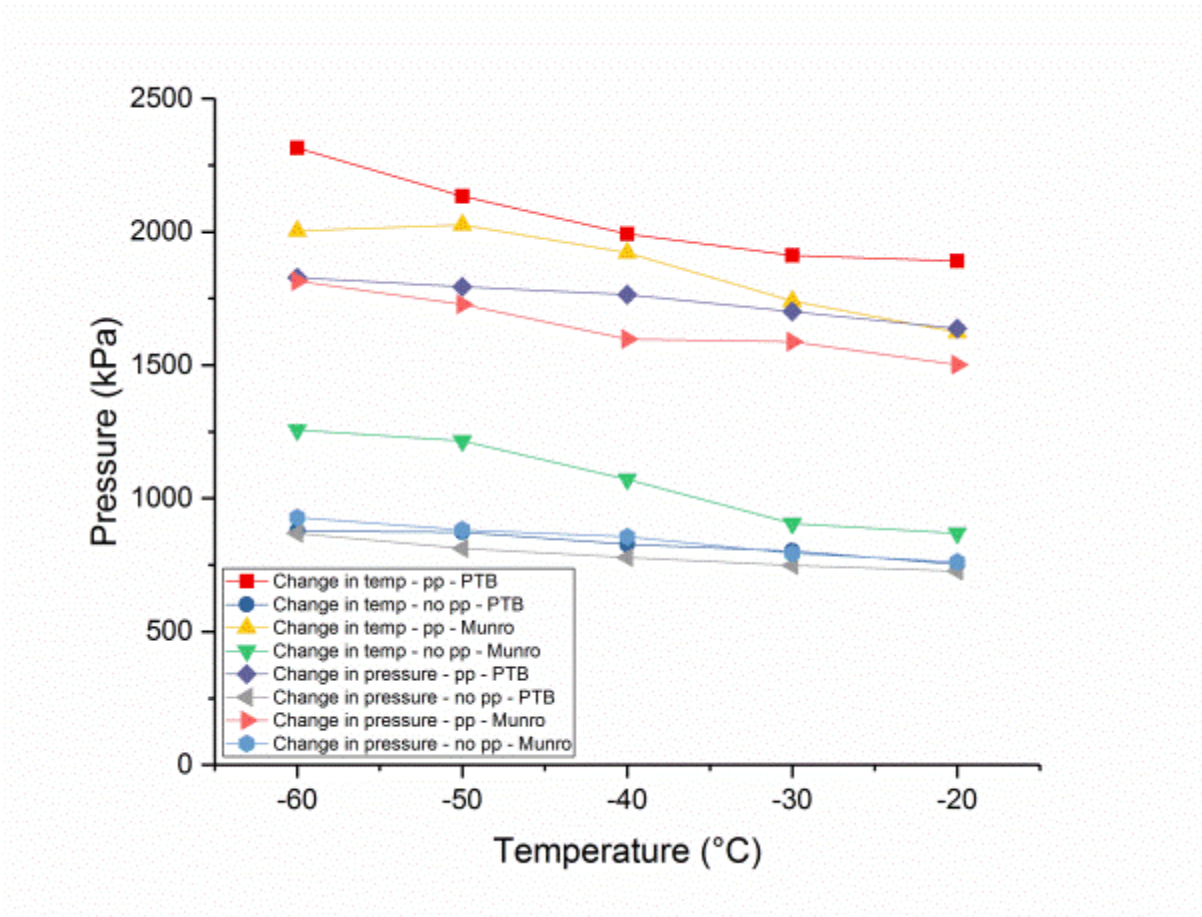


Figure 30 – Comparison of PTB results with earlier results

7.4 Conclusions - PTB testing

The results of the PTB testing confirm the concern raised earlier in this thesis regarding the change from IEC 60079 – 1 Edition 5 to Edition 6. Edition 5 only permitted the use of the formula for Groups I, IIA, or IIB, or IIC with internal free volume < 2 l. It did not permit its use for "rotating electrical machines (such as electric motors, generators and tachometers)" and only allowed it to be used for equipment that involved "simple internal geometry such that pressure piling is not considered likely". The latest two editions permit the formula to be used for any equipment with no restrictions.

However, while the testing in Chapter 4 suggested that using the formula in the situation where no pressure piling is involved might also be an issue, this was not supported by the PTB testing with a difference in pressures between the testing with low temperatures and the testing with pre-pressurisation being much less. Similarly, the testing with methane (Chapter 5) gave similar results in the chamber where there was no pressure piling.

The PTB results and the testing with methane introduce doubt as to whether the revised formula tested for hydrogen, as shown in Chapter 7, would be of value in regards to trying to take better account of the effect of the increase in moles in a gas at low temperature on explosion pressure for the situation with no pressure piling.

Figure 31 shows the graphs for testing with hydrogen using the revised formula previously shown in Chapter 6 of this thesis for average pressures, with testing by PTB for average pressures added. The results for the pressure piling situation produced results that are better in comparison to the PTB results only at the lower temperatures, and hence this was

inconclusive. For the situation with no pressure piling, the results with the revised formula are above those obtained when testing at actual temperatures and hence do not seem to provide any advantage for that situation.

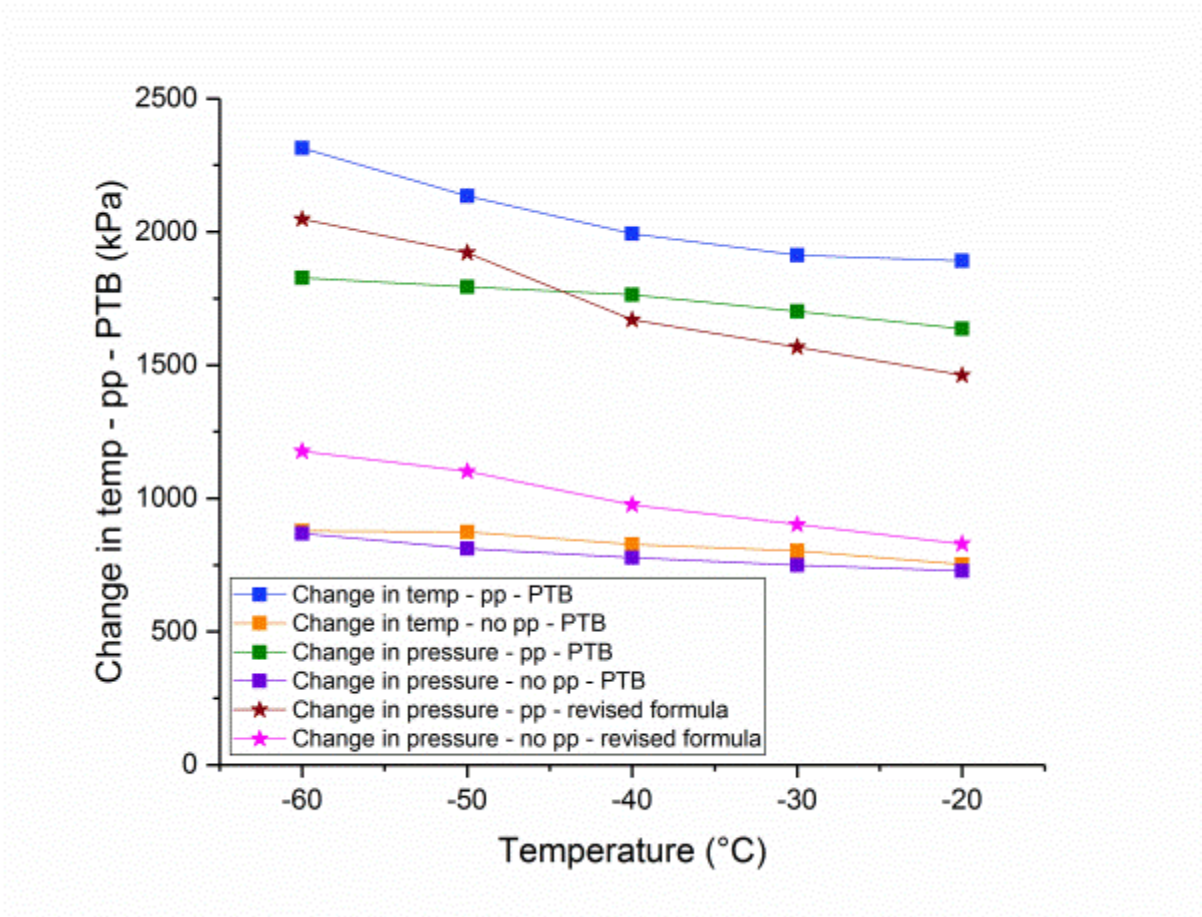


Figure 31 – Revised pressure formula compared to PTB results - average pressure

Further conclusions on this work, including recommendations for further work on this subject, are included in Chapters 11 and Chapter 12 of this thesis.

Further to the above, there is currently a program underway as part of the PTB Ex Proficiency Testing Scheme whereby participating laboratories will be providing explosion pressures that they obtain when testing with single and two chamber combinations of the same artefact using hydrogen and ethylene. These tests will be performed under the conditions of normal temperature and at -40 °C. For these tests either the actual temperature may be used for the lower temperature of -40 °C, or the test may be done with pre-pressurisation using the formula. So while these would not take the place of more extensive test programs, such as those recommended in this thesis, it is likely that they will provide some useful results in determining the comparison between using the formula and testing at actual temperatures.

8 Development of indicative pressures for flameproof motors - data mining project

8.1 Introduction

One of the issues facing manufacturers when they design flameproof motors is knowing the internal explosion pressures that the motors will have to withstand. The corollary is the challenge facing a testing and certifying body on how to test such motors to ensure the maximum possible pressure from an explosion is obtained (See Clause 15.2.3 of IEC 60079-1 and Chapter 2 of this thesis). This challenge for the testing body becomes even greater when a range of motors is involved, because of the need to select a representative range of motors to test. The majority of such motors are TEFC squirrel cage motors. Typically between 6 to 12 motors may be tested in the range. However, when major aspects, such as frame sizes (including whether short, medium or long) and the number of poles are considered, this sample can represent dozens of options to be included in the range that is certified. The other party facing a challenge is the body writing the international standards that define how such motors should be tested.

Finally, the above problems become further acerbated when the motors need to operate in extremely low temperatures where the explosion pressures can become significantly higher as indicated in Chapters 1 and 2.

8.2 Aims of this project in relation to flameproof motor information

One of the key aims as part of the overall PhD project was to provide motor manufacturers with design criteria that will enable flameproof motors to be manufactured for extremely low temperatures with greater confidence in their explosion protection properties, in particular their ability to withstand explosion pressures. The aim also extends to manufacture of flameproof motors designed for normal ambient temperatures. Three approaches that were taken to achieve this aim were:

1) Researching information regarding indicative pressures, based on existing information, as a data mining exercise;
2) Carrying out tests to establish explosion pressures for a motor at normal ambient and extremely low temperatures; and
3) Investigating the potential to make use of CFD as a tool to predict pressures in flameproof motors.

This chapter addresses 1) above, the data mining exercise. Approaches 2) and 3) will be addressed in the next Chapters 9 and 10. For the data mining project, the plan was to extract data on explosion pressures that have been obtained during type testing of electric motors, to investigate typical explosion pressures and to search for any patterns in the pressures obtained. While it was expected that most testing would have been done at ambient temperatures, it was also proposed to explore methods to apply this to extremely low temperatures.

As well examining scenarios from the data, it was also planned to use the data to help in development and validation of the use of CFD based on programs for prediction of pressures, which is addressed in 3) above and in Chapter 10.

As indicated above, this exercise started out as an attempt to help manufacturers understand the sort of pressures that their motors may need to withstand, based on frame size. However, when the data was analysed, and additional data was added through the testing of a flameproof motor at normal and extremely low temperatures (Chapter 9), it was realised the exercise should be extended to providing guidance to testing bodies, and recommendations for changes to the international standard IEC 60079-1. This extension of the exercise is addressed later in this chapter.

8.3 How electrical motor sizes are defined

The sizing of electrical motors is referenced in IEC 60072-1 and 60072-2 [74, 75] which define standard dimensions, commonly called "frame sizes", although the standards use the terms "frame numbers" for foot-mounted motors and "flange numbers" for flange-mounted motors. Most motors dealt with during this project were foot mounted. The term "Frame size" will be used here unless there is a need to refer specifically to something in the above standards.

Frame sizes covered by the two standards range from 56 to 1000 for foot mounted motors. These dimensions focus on outside dimensions such as shaft heights, and the distance between mounting holes, presumably to ensure compatibility in connection of motors to the equipment they are driving, although strangely, the standards do not seem to mention this. The size of the height from the base of a foot mounted motor to the centre of the shaft in mm is used to define the frame size. For example, a 160 frame motor has a height of 160 mm from the mounting base to the centre of its shaft and the overall height is approximately twice that, but more if the terminal box is mounted on the top. The letters "S", "M" and "L" (which are presumably short for Small, Medium and Large) are designated in relation to the length of the motor, which also impacts on the length of the stator and the corresponding rotor core length.

IEC 60072-1 in the scope claims to cover the majority of rotating electrical machines for industrial purposes within the dimension range of:

- Foot-mounted - shaft-heights: 56 mm to 400 mm
- Flange-mounted - pitch circle diameter of flange: 55 mm to 1080 mm

There is some overlap with IEC 60072-2, which has the smallest foot mounted frame number of 355. TABLE 33 shows the preferred "frame numbers" covered by the standard IEC 60072-1 for foot mounted motors. There is no comparable table in IEC 60072-2.

TABLE 33 – PREFERRED "FRAME NUMBERS" (SIZES) IN IEC 60072 – 1

Frame numbers		
56 M	160 S	250 M
63 M	160 M	280 S
71 M	160 L	280 M
80 M	180 M	315S
90 S	180 L	315 M
90 L	200 S	355 S
100 S	200 M	355 M
100 L	200 L	355 L
112 S	225 S	400 S
132 S	225 M	400 M
132 M	250 S	400 L

There is also a US-based NEMA system of specifying motors. However, for this project the IEC system will be addressed A paper by G. Arce et al on global standards for rotating machinery [76, 77], which was presented at a PCIC conference in 2015 and subsequently published in the IEEE Industry Applications Magazine, provides some comparisons of the IEC and NEMA standards.

8.4 Design of flameproof motors

Flameproof motors need to be manufactured strong enough to withstand an internal explosion of a gas or vapour that might occur in the hazardous area where the motor is installed. See Chapter 1 for more information regarding the flameproof technique, which also requires that no explosion can be transmitted to the surrounding atmosphere. This chapter will concentrate mainly on the need to withstand an explosion. The international requirements for testing of flameproof equipment, which includes flameproof motors, are contained in IEC 60079-1[8] with some requirements also in the General Requirements document IEC 60079-0 [49]. Earlier chapters have talked about how the tests are specified for all types of flameproof equipment. However, the standard also contains specific requirements relevant to electrical motors. To put these requirements in perspective, relevant aspects of flameproof motors are discussed below.

Flameproof motors include the conventional design of a rotor running within a stator with both encased in an enclosure and the rotor supported at each end by bearings. Figure 32 below shows a typical flameproof motor with part of the motor cut away to show the construction.

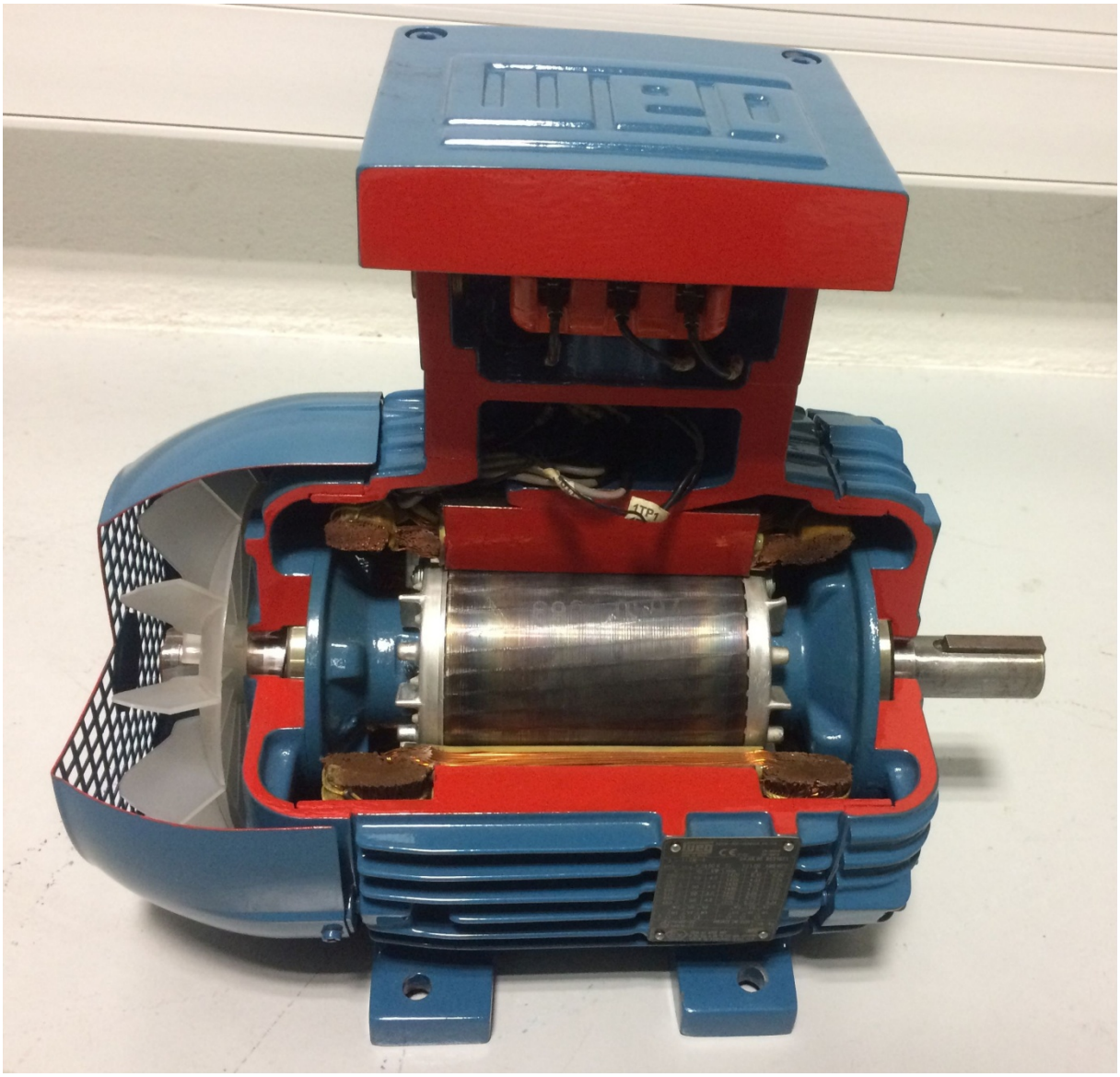


Figure 32 – Flameproof motor with cut-away section

8.5 Testing of flameproof motors

The main areas that have a volume that could contain gas are at the drive end (DE) and the non-drive end (NDE). There may also be a volume under the terminal box (TB) as shown in Figure 32 and in some cases, the whole terminal box may be open to the motor. A likely scenario for pressure piling is through the air gap between the drive end and the non-drive end. However, pressure piling may also occur between the section under the terminal box and any connection to the drive end and non-drive end. IEC 60079-1 contains some specific requirements about the testing of flameproof motors. These are as follows:

> 15.2.2.3 Rotating electrical machines shall be tested at rest and running. When they are tested running, they may be driven either by their own source of power or by an auxiliary motor. The minimum test speed shall be at least 90 % of the maximum rated speed of the machine.
>
> NOTE If the motor is intended to be converter driven, manufacturer specified rated speed often covers both present and future converter applications.
>
> All motors shall be tested with at least two transducers, with one located in the end-turn area at each end of the motor. Ignition shall be initiated at each end of the motor, in turn, with the motor both at rest and running. This will result in at least four series of tests. If a termination compartment is provided that is interconnected to the motor and is not sealed, a three transducer setup and additional test series is to be considered.

The reference to "termination compartment" above is widely interpreted to be the part of the terminal box where the incoming tables are terminated when a motor is installed. It does not clearly address the scenario that commonly occurs with terminal boxes where there is a compartment under the terminal box for termination of the wires coming from the stator of the motor. This situation can be seen in Figure 32 above. There is generally sealing between that compartment and the upper compartment where the external cables are terminated. For some motor designs, the compartment under the terminal box can have a significant volume that impacts on the pressures that may occur in the motor. There may also be a constriction between this compartment and the motor This can lead to pressure piling between this compartment and the motor. For large motors, in addition to the main terminal box, there are often auxiliary terminal boxes which are used for other electrical connections to the motor. These may, for example, be for temperature sensors or anti-condensation heaters. So for larger motors, the scenario can become even more complex. It is believed to be quite common for testing bodies not to test the scenarios associated with measurement of pressure and ignition in the compartment under the terminal box. This is not surprising because the standard implies that testing with two transducers and two ignition sources would be the norm. It will be demonstrated in this chapter and the following two chapters that omission of consideration of the compartment under the terminal box may have a significant impact on the maximum pressure measured for a motor.

8.6 The data mining exercise

8.6.1 Data mining exercise approach

The data mining exercise involved looking at a range of anonymised data from a few different testing stations and from manufacturers to indicate likely explosion pressures that might be obtained in relation to each frame size, taking into account the various scenarios regarding design and testing. A methodology was developed to ensure that the data would be completely anonymous with no connection to manufacturers or the models of their motors. Where deemed necessary by the testing body involved, specific agreements were obtained from manufacturers to access their data and report on it.

A unique "Motor Identifier" was used for this exercise so that the data source, including the manufacturer, could be kept anonymous. A cross-reference between the body's file/job number and the Motor Identifier has been kept separately from the results. So when the results are considered, there is no link back to that data source. However, for traceability to check data the cross-reference document could be used. It was also necessary to identify if a motor was part of a series and so there was also a "Series Identifier". In addition, there is a "Body Identifier". This is normally the testing body, but for information provided by a manufacturer then an identifier for the manufacturer is used. The complete Motor Identifier is assembled as follows:

- First, there is the Body Identifier followed by a dash, then the Series Identifier with numbers commencing at 01 followed by a dash and finally a number commencing at 001 for each motor in a series, eg CQST-01-001.
- Where there is no series, the Series Identifier is replaced by 00 with the final number again commencing at 001. For each non-series motor tested within a body, the Series Identifier remains at 00 and final number increments to 002, 003 etc.

The above Motor Identifier has been used with all data but is omitted from this report, so there is no a public link to the body or manufacturer concerned. This has been done to preserve the anonymity of the testing body as well as the manufacturer.

Metric units were used for the exercise, with kPa being used for pressure and cm^3 used for volume. This latter unit of measure seems to be industry practice, and so it was used instead of L.

8.6.2 Information sought

A form was developed to record the data for each motor. The information that was included in the form is outlined below.

8.6.2.1 Information for testing body/manufacturer

The following information was recorded for the testing body/manufacturer:

- Name

- Location
- Contact person

8.6.2.2 Motor information

The following information was recorded for the motor, where available:

- Equipment Group
- Motor type - eg induction motor. In practice, almost all data collected was from TEFC squirrel cage induction motors
- Motor parameters, voltage (including AC or DC), frequency, power, number of poles, speed
- Frame size, including if short, medium or long version (S, M, L)
- If part of motor series, frame sizes in series
- Basic dimensions, particularly if not standard frame size
- Mounting (particularly if it changed inside of enclosure) - eg foot or flange
- Motor construction - eg cast, fabricated - and the materials used
- Information about main and any auxiliary terminal boxes
- Internal volume
- Air gap width
- Air gap length (stator length)
- Rotor diameter
- Air paths via outside of stator
- Air paths to below terminal box from inside motor
- Air path into terminal box from inside motor
- Cooling system - where possible specified to IEC 60034-16
- Internal cooling ducts (numbers, cross-sectional area and length) - plus other relevant information on geometry
- Anything else in interior geometry that might impact on pressure, eg an internal fan

8.6.2.3 Testing configuration

A diagram of the testing configuration was included in the form to show the position and identification of pressure transducers and ignition sources, with an example shown below in Figure 33.

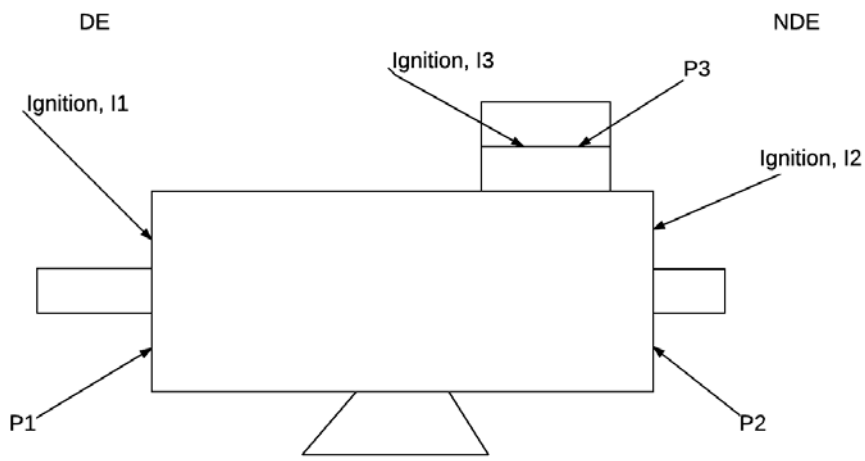


Figure 33 – Example of recorded testing configuration

8.6.2.4 Pressure testing results

TABLE 34 is an extract from the form for the pressure testing results, showing the results that were recorded, where available.

TABLE 34 – FORM FOR PRESSURE TESTING RESULTS

Date(s)	Ambient temperature(s) or the season (eg summer, winter)	Humidity (if known)	Ambient pressure or height above sea level	Comments

Gas used	Percent-age	Position of ignition	Initial pressure if not ambient	Explosion pressure, kPa			Rotating Y/N	Comments
				P1	P2	P3		

8.7 Results and discussions

8.7.1 Source of data and Groups covered

Results were collected from three different testing bodies located in three different countries. Some information was also received direct from manufacturers. Most of the results related to Groups IIB and IIC with some for Group I. The number of motors in each group is shown below:

- Group I – 7 motors – frame sizes 160 to 680
- Group IIB – 31 motors – frame sizes 90 to 560
- Group IIC – 22 motors – frame sizes 71 to 450

In doing this exercise, it was found that data was not readily available for Group IIA motors. It appears it may be unusual for manufacturers to seek certification of a range of motors that are solely for Group IIA. It was noted, however, that in some cases motors are tested and certified for both Group I and Group IIA. However, it is assumed that in many cases manufacturers offer their Group IIB certified motors when Group IIA motors are specified for an application.

8.7.2 Group I motors

The maximum explosion pressures for the Group I motors, together with information regarding the scenario for the maximum pressure, are shown for each motor in TABLE 35.

TABLE 35 – MAXIMUM PRESSURES FOR GROUP I MOTORS

Frame size	Power kW	No poles	Maximum pressure					
			Value kPa	Ignition point	Transducer Position	Rotating (Y/N)	Gas	Pressure Piling?
160M	11	2	262	Under TB	NDE	N	Methane	No
326	26	2	910.3	NDE	In TB	Unknown	Methane	Y
350J	80	Unknown	485.5	NDE	Under TB	N	Methane	Unknown
440J	Unknown	Unknown	600	Unknown	Unknown	Unknown	Methane	Unknown
500J	Unknown	Unknown	790	Unknown	Unknown	Unknown	Methane	Unknown
580J	Unknown	Unknown	660	Unknown	Unknown	Unknown	Methane	Unknown
680J	275	4	643.4	TB	DE	N	Methane	Y

The above results are also shown graphically in Figure 34 below.

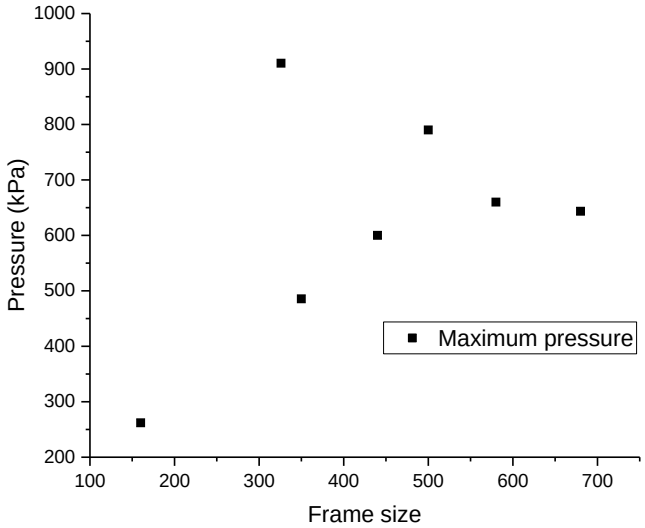


Figure 34 – Graph of maximum pressures for Group I motors

Some trending can be seen in the data, and in the graph, for six of the motors, but the explosion pressure for the 326 frame motor does not follow the trend of the other motors. However, an analysis of the scenario for this explosion shows that the ignition took place at the non-drive end of the motor and there was pressure piling through a connection at the same end of the motor to the terminal box where the pressure was measured. For some of the motors the detail was not available for the explosion scenarios, and so it was not known even whether the pressure was measured at the terminal box for those scenarios. Given the above, and the small sample numbers, it is difficult to draw conclusions from the data for Group I. But it does illustrate how critical pressure piling can be for Group I. Information in earlier chapters of this thesis has shown how significantly the explosion pressure can rise when there is pressure piling involving methane.

8.7.3 Group IIB motors

For Group IIB there is a much larger sample of motors tested, and in fact nearly every frame size is covered from 90 to 560.

The maximum explosion pressures for the Group IIB, together with information regarding the scenario for each maximum pressure, are shown for each motor in TABLE 36. There are some aspects of pressure figures shown that need to be understood and that may have impacted on some of the spread in the pressure figures. There was not consistent testing of motors from the three test bodies that provided the major amount of the data. In one test body one of the motors was only tested at rest. In another test body there was no measurement of explosion pressure or the use an ignition source under the terminal box. While these scenarios do not always give the maximum explosion pressures, it is quite common, and so it is likely that some of the figures are a bit low. For many of the motors, the hydrogen/methane mixture with air was not used. But if it had been used, it may not have produced higher pressures than those for ethylene (see 2.5).

It is interesting to note that in the majority of cases the maximum pressure was obtained when the motor was rotating. As noted earlier, the presence of turbulence will often produce higher explosion pressures. So when a motor is rotating, even if there is no internal fan, there will be turbulence induced by the rotation of the motor. The presence of an internal fan is likely to make this turbulence even higher, although an internal fan is normally only used in very large flameproof motors. However, in some cases, the rotation of the rotor can affect the transmission through the air gap and so reduce or eliminate the presence of pressure piling for that scenario. It was also noted, that in some cases, the maximum pressure was obtained when there is a pressure piling scenario between the end of the motor and the space under the terminal box at the same end. It is likely that turbulence associated with a rotating motor would increase the explosion pressure for the scenario. In such a situation the air gap ceases to be a factor in the explosion pressure.

TABLE 36 – MAXIMUM PRESSURES FOR GROUP IIB MOTORS

Frame size	Power, kW	No poles	Maximum pressure						
			Value, kPa	Ignition point	Transducer Position	Rotating (Y/N)	Gas	Pressure Piling?	In TB
90	1.1	4	310	NDE	DE	Y	Ethylene	Y	
90S	1.1	4	273.1	Under TB	DE	Y	Ethylene	N	
90L	2.2	2	627.6	NDE	TB	N	Ethylene	Y	581.6
100L	3	2 and 4	400.0	NDE	DE	Y	Ethylene	Y	320
			400.0	NDE	DE	Y	Ethylene	Y	
112M	5.5	4	375.0	NDE	DE	Y	Ethylene	Y	
112M	2.2	6	304.8	Under TB	DE	Y	Ethylene	N	711.4
112M	4	4	597.7	DE	Under TB	Y	Ethylene	Y	684.5
132S	5.5	4	480.0	NDE	DE	Y	Ethylene	Y	420
160L	15	4	620.0	NDE	DE	Y	Ethylene	Y	
160M	5.5	8	484.8	Under TB	DE	Y	Ethylene	Y	729.5
160M	11	2	691.4	DE	Under TB	Y	Ethylene	Y	602.2
180L	22	4	620.0	DE	NDE	Y	Ethylene	Y	320
200L	30	4	540.0	NDE	DE	Y	Ethylene	y	
200L	30	4	651.8	NDE	DE	N	Ethylene	Y	750.8
200L	30	4	656.5	DE	NDE	Y	Ethylene	Y	602.2
225M	22	8	460.0	NDE	DE	Y	Ethylene	Y	520
225M	30	6	810.0	DE	NDE	N	Ethylene	Y	
			532.0	DE	NDE	N	H_2/CH_4	N	
250M	55	4	545.0	DE	NDE	Y	Ethylene	Y	
250S/M	55	4	1,329.0	NDE	DE	N	Ethylene	Y	733.2
			1,399.0	NDE	DE	Y	H_2/CH_4	Y	
250M	55	4	600.4	NDE	DE	N	Ethylene	N	760.4
280S	75	4	750.0	DE	DE	Y	Ethylene	Y	455.0
280M	55	6	920.0	NDE	DE	Y	Ethylene	Y	
			463.0	NDE	NDE	N	H_2/CH_4	N	
280 S/M	75	2	1,423.0	NDE	DE	Y	Ethylene	Y	
			1,237.8	NDE	DE	Y	H_2/CH_4	Y	
280M	45	6	834.0	NDE	DE	Y	Ethylene	Y	
315L	160	3	950.0	NDE	DE	Y	Ethylene	Y	
315S/M	132	2	1,837.0	DE	Under TB	y	Ethylene	Y	744.0
			1,286.0	DE	Under TB	y	H_2/CH_4	Y	
355M	160	2 and 4	1,030.0	NDE	DE	Y	Ethylene	Y	530.0
355M/L	250	2	4,107.4	DE	NDE	Y	Ethylene	Y	
			1,151.4	DE	NDE	Y	Propane	Y	
			1,505.4	NDE	Under TB	Y	Ethylene	Y	
			1,070.6	NDE	Under TB	Y	H_2/CH_4	Y	
355M/L	260	4	1,335.0	DE	Under TB	Y	Ethylene	Y	776.5
			729.5	DE	NDE	y	H_2/CH_4	N	
560	1250	4	3,298.0	NDE	NDE	Y	Ethylene	Y	663.0
			1,013.0	DE	NDE	N	H_2/CH_4	N	

The above results are also shown graphically in Figure 35 below, but with only the maximum figure out of ethylene and hydrogen/methane shown. Ethylene had the highest pressure in all but one case. The high figure for the 355M/L frame motor is also omitted since the design was changed to prevent the high explosion pressure occurring.

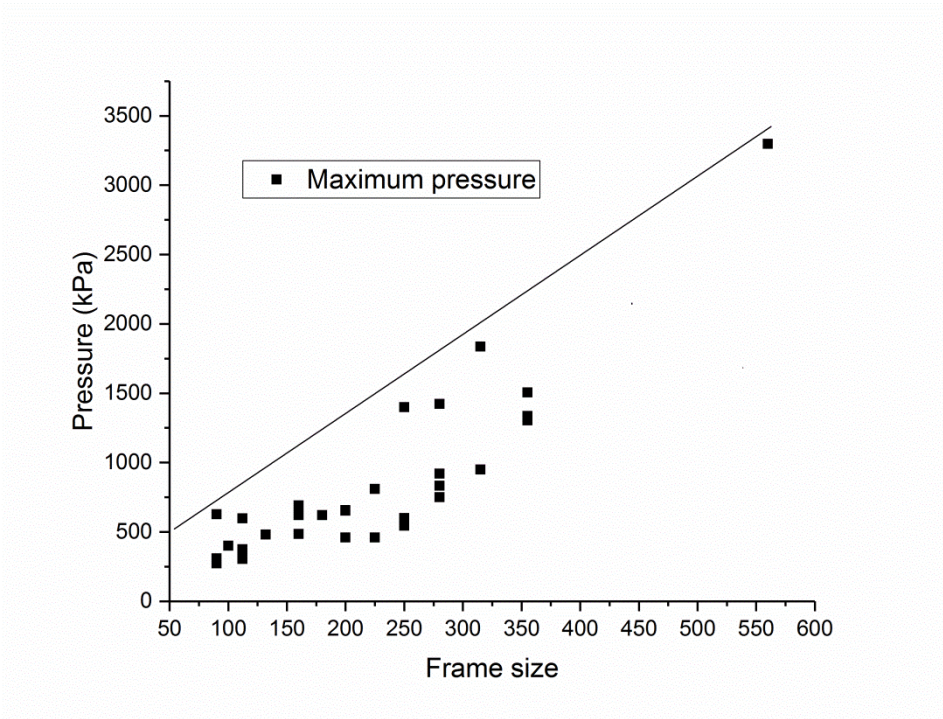


Figure 35 – Graph of maximum pressures for Group IIB motors

These results now show a much clearer trend, and it is possible to identify a maximum as shown by the straight line, under which all the results fall. Hence it is possible to derive an equation that can be used to estimate the likely worst case maximum pressure for any frame sizes in the range above, based on the data shown. The derivation of that equation is shown below.

Two points can be used on the line as follows, assuming "Frame size" is the x-axis and "Pressure" is the y-axis:

$(x_1, y_1) = (90, 627.6) -$ *the maximum pressure point for the smallest frame size*

$(x_2, y_2) = (560, 3298) -$ *the maximum pressure point for the largest frame size*

The slope of the line then becomes:

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{3298 - 627.6}{560 - 90} = 5.68$$

Thus equation then becomes:

$$y - 627.6 = 5.68(x - 90)$$

Which can be simplified as:

$$y = 5.68x + 116.25$$

Now, if x is replaced by the frame size, y will provide the likely maximum explosion pressure that could occur for that frame size for a Group IIB motor. It should be noted, however, that if the quantity of data is expanded to incorporate testing of other motors some higher explosion pressures might be introduced that would vary the equation. But it should provide a very useful starting point when looking at the maximum explosion pressure for which a motor needs to be designed. The results are shown in tabular form later in this chapter in TABLE 38. Of course, the factor that will be applied for overpressure testing will also need to be factored into the final figure. It would also make sense to include a margin on the initial explosion pressure figure.

Should be noted from the data in TABLE 36 in the last column, that for smaller frame sizes the maximum pressure may occur in the terminal box, separate to the motor. Presumably,

this is because of volume in the terminal box is significantly larger than the volume in the motor and so may produce higher pressures even when pressure piling is not present. So some care should be taken when using the above formula for smaller frame sizes, as the overpressure test for the terminal box may apply more pressure to the motor frame than the overpressure test applied to the motor itself. It would be possible to derive a revised formula that took into account the size of terminal boxes on smaller motors, but that would require a closer look at the likely maximum size of terminal boxes on smaller motors. So for the moment, it should be assumed that the formula is only applicable for explosion pressures inside the motor casing (including under the terminal box).

8.7.4 Group IIC motors

For Group IIC there was also a large sample of motors tested with most frame sizes covered from 71 to 450. The maximum explosion pressures for the Group IIC, together with information regarding the scenarios for the maximum pressure, are shown for each motor in TABLE 37.

Again there are some impacts on the confidence that the maximum figures were obtained. The majority of lower explosion pressure figures were obtained from two testing stations. One of those testing stations only tested the motors at rest but did look at the scenario of pressures occurring under the terminal box. The other testing station tested most motors both at rest and running (but in some cases only running). But it did not measure pressures or create ignition under the terminal box. So it is possible that scenarios involving the motors running and the inclusion of the compartment under the terminal box for ignition and pressure measures could lead to higher maximum pressures.

The above results are also shown graphically in Figure 36 below but with only the maximum pressures out of hydrogen and acetylene shown. It can be seen that the spread of results below is wider than for the Group IIB results. The reason for this is not immediately apparent, but there could be a few factors. These factors could include the difference in configurations, the difference in internal volumes, the difference in the air gap size and the difference in testing practices as outlined earlier.

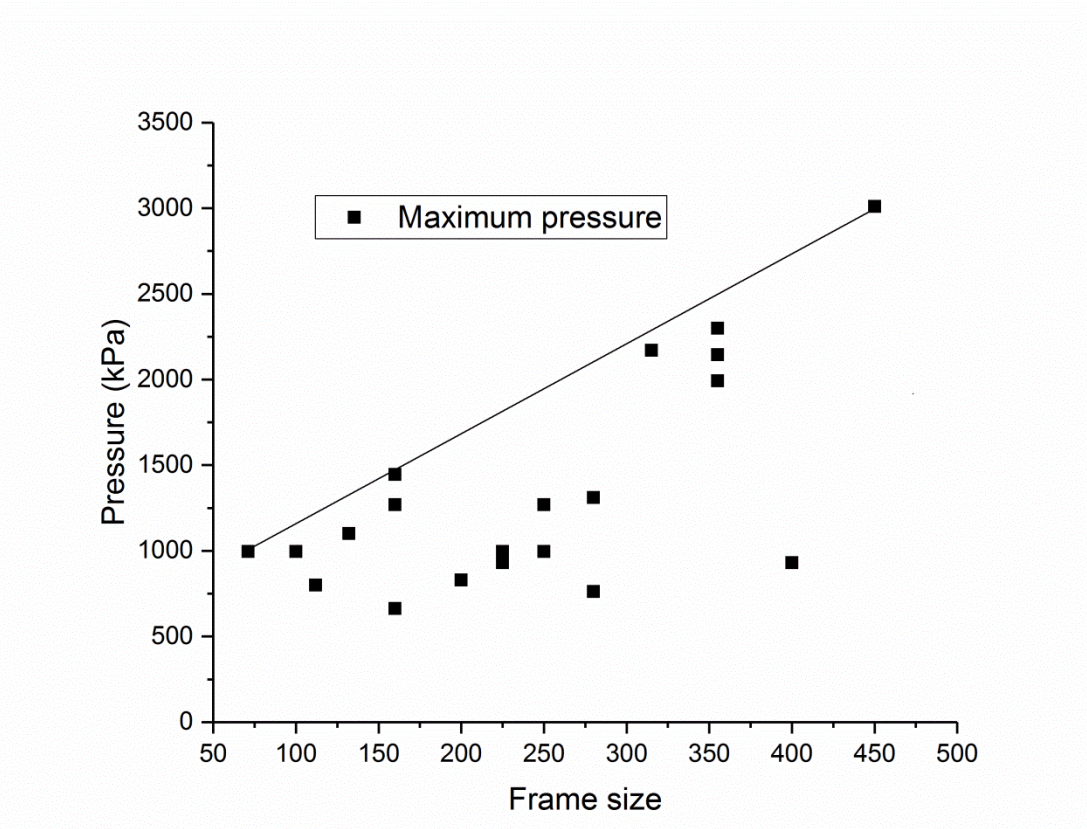


Figure 36 – Graph of maximum pressures for Group IIC motors

TABLE 37 – MAXIMUM PRESSURES FOR GROUP IIC MOTORS

Frame size	Power, kW	No poles	Maximum pressure						
			Value, kPa	Ignition point	Transducer Position	Running (Y/N)	Gas	Pressure Piling?	In TB, kPa
71	0.23	2	551	NDE	In TB	N	Hydrogen	N	
			996	NDE	In TB	N	Acetylene	Y	
100	1.5	4	996	Under TB	DE	N	Hydrogen	Y	578
			805	NDE	TB	N	Acetylene	Y	594
112M	4	2	640	NDE	DE	N	Hydrogen	N	
			800	DE	NDE	Y	Acetylene	Y	
132M	7.5	4	690	DE	NDE	N	Hydrogen	Y	
			1100	DE	NDE	N	Acetylene	Y	
160L	15	4	650	DE	NDE	Y	Hydrogen	N	
			1270	DE	NDE	Y	Acetylene	Y	
160	Unknown	Unknown	602	NDE	TB	N	Hydrogen	Y	602
			664	TB	NDE	N	Acetylene	Y	758
160M	11	2	813	NDE	TB	N	Hydrogen	Y	
			1,445	NDE	TB	N	Acetylene	Y	
200L	30	3	560	NDE	DE	Y	Hydrogen	N	
			830	DE	NDE	Y	Acetylene	Y	
225M	45	4	570	DE	NDE	Y	Hydrogen	N	
			930	DE	NDE	Y	Acetylene	Y	
225S	18.5	8	996	DE	Under TB	N	Hydrogen	Y	590
			996	DE	Under TB	N	Acetylene	Y	730
225M	30	6	528	DE	NDE	Y	Hydrogen	Y	
			947.5	DE	NDE	Y	Acetylene	Y	
250M	55	4	1270	NDE	DE	Y	Hydrogen	Y	
			1270	DE	NDE	Y	Acetylene	Y	
250	55	2	625	NDE	DE	N	Hydrogen	Y	
			625	DE	TB	N		Y	
			996	TB	NDE	N	Acetylene	Y	
			996	DE	TB	N		Y	
250M	Unknown	2	996	NDE	TB	N	Hydrogen	Y	
			996	DE	TB	N		Y	
			535	DE	NDE	N	Acetylene	Y	
280M	90	4	745	DE	NDE	Y	Hydrogen	Y	
			1310	DE	NDE	Y	Acetylene	Y	
280M	55	6	539	DE	NDE	Y	Hydrogen	N	872
			762	DE	NDE	N	Acetylene	N	
			762	NDE	NDE	Y		N	
315S	110	4	1810	NDE	DE	Y	Hydrogen	N	
			2170	DE	NDE	Y	Acetylene	N	
355S	185	4	2030	NDE	DE	Y	Hydrogen	N	
			2300	NDE	DE	Y	Acetylene	N	
355			996	TB	DE	N	Hydrogen	Y	
			1,992	DE	TB	N	Acetylene	Y	
355L	355	2	1,999	DE	NDE	N	Hydrogen	Y	
			2,144	NDE	DE	N	Acetylene	Y	
400S	Unknown	4	930	DE	NDE	N	Hydrogen	Y	
			930	NDE	DE	Y	Acetylene	Y	
450L	800	4	2,483	DE	NDE	Y	Hydrogen	Y	
			3,010	NDE	DE	Y	Acetylene	Y	

The results do not show quite as clear a trend as Group IIB because of their spread. However, it is still possible to identify a maximum, as shown by the straight line, under which

all the results fall. So similarly to Group IIB, it is possible to derive an equation for Group IIC that can be used to estimate the likely worst case maximum pressure for any frame sizes in the range above, based on the data shown. The derivation of the equation is shown below.

Again two points can be used on the line as follows:

$(x_1, y_1) = (71{,}996) - \ the\ maximum\ pressure\ point\ for\ the\ smallest\ frame\ size$

$(x_2, y_2) = (450, 3010) - \ the\ maximum\ pressure\ point\ for\ the\ largest\ frame\ size$

The slope of the line then becomes:

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{3010 - 996}{450 - 71} = 5.31$$

Thus equation then becomes:

$$y - 996 = 5.31(x - 71)$$

Which can be simplified as:

$$y = 5.31x + 618.71$$

So again, if x is replaced by the frame size, y will provide the likely maximum explosion pressure that could occur for that frame size for a Group IIC motor. However, in this case, as indicated above, it appears that none of the motors have been tested for the potentially worst case scenario and so it would be very useful to derive additional data for Group IIC motors to check whether the formula that some modification. However, even with the data used here the formula should provide a useful starting place for predicting the likely maximum pressures that will be experienced in Group IIC motors. Again the results are shown in tabular form later in this chapter in TABLE 38.

As indicated for group IIB, the factor to apply for overpressure testing will also need to be factored into the final figure. Similarly, as for Group IIB, it would also make sense to include a margin on the initial explosion pressure figure as well.

There was not enough information on the terminal box pressures to make a similar comment to that for Group IIB regarding the impact of the terminal box on smaller motors. However, it should be noted that the maximum pressure figure for the 71 frame size motor occurred within the terminal box with the ignition at the non-drive end of the motor. So it can be inferred that in this case there was a path between the motor and the main termination compartment of the motor. Thus for this scenario, the terminal box pressure has been taken into account for an almost worst case scenario. But it is possible that a higher pressure figure would have been obtained if the motor was running.

8.8 Conclusions on the data mining project

As indicated at the beginning of this chapter, the main aim of the data mining project was to provide manufacturers with explosion pressure data that would assist them in the design of flameproof motors. The data that has been presented for Group IIB and Group IIC flameproof motors, together with the derived equations for calculating maximum pressure, should provide manufacturers with a good starting point in this regard. The data for Group I may provide some indication.

This data mining project has also delivered a significant amount of information about the various scenarios that can occur when testing flameproof motors to determine maximum explosion pressures and the most important scenarios that should be applied when carrying out those tests. A couple of these are discussed below.

IEC 60079-1 requires motors to be tested running and at rest. A recent paper by Magyari et al [23] concluded that:

> Although from the theoretical point of view, as shown in the paper, the turbulence of the testing explosive mixture was supposed to have generated higher explosion pressures, still, the tests carried out on various motor samples, tested as part of this project, both at rest and while running, have shown that either the pressure differences are neglijible

(sic), or, on the contrary, higher explosion pressures have been recorded in the case of motors tested at rest.

The data that has been presented in this chapter contradicts that finding. When motors were tested both running and at rest, the maximum figures were more often achieved with the motor running. This was more evident when testing with ethylene for Group IIB, which does not appear to have been used as part of the Magyari investigation. So, although not stated in the paper, it appears the conclusions have been drawn for Group IIC testing. However, even the data for Group IIC testing that was examined as part of this project found that higher pressures were often found when motors were running, but perhaps not to the same extent as for Group IIB. The occurrence of the maximum pressure for the running condition is consistent with various studies that have established that turbulence will often lead to higher pressures and why, even for equipment other than motors, the need to consider testing with turbulence when testing is included in the standard. So it is recommended there be no change in the standard in this regard.

The standard is currently unclear about the need to measure pressure and to provide an ignition source under the terminal box where there is a chamber open to the motor. This lack of clarity has led to inconsistencies in testing and the likelihood that the maximum pressures occurring in the motors have not been found by bodies who are not applying this scenario. So it is recommended that the guidance in IEC 60079-1 on testing of motors should clarify the need to carry out testing in this way.

It should be noted that the approach presented in this chapter of estimating the likely maximum explosion pressure is only intended as a tool for manufacturers designing motors and not as a substitute for testing of motors. Notwithstanding this, it can be seen from the data that it is likely in some cases the pressures obtained when testing motors may not be the highest possible pressures. The likelihood of this might be reduced by ensuring the worst case scenarios for pressures are always measured, for example, always measuring pressure and providing ignition under the terminal box. However, since testing motors is a sampling exercise when ranges are involved, it is always possible that the sample being tested is not the one which will give the worst case explosion pressure. So it may make sense to include minimum explosion pressure requirements in IEC 60079-1 to ensure motors in the range are not overpressure tested at an inappropriately low pressure. It would be possible to derive such as lower pressure from the data shown in Figure 35 and Figure 36. This could be done, for example, by deriving the best fit curve from the data.

All the data presented here so far, however, has only been for motors tested at ambient temperatures. Later chapters will explore the impact of extremely low temperatures on explosion pressures in flameproof motors. However, based on the equations derived in this chapter for Groups IIB and IIC, and the factors for low temperatures shown in IEC 60079-1 Edition 7.0 Table 7 – *Test factors for reduced ambient conditions*, it is possible to make some rough estimations of pressure at low temperatures.

TABLE 38 has been compiled using the equations for Groups IIB and IIC and the above factors to provide indicative pressures at normal and low temperature conditions. It should be noted, however, that the factors above are intended for equipment where pressure piling does not take place. So their application to motors for this situation is, as suggested, only indicative.

The data presented in this chapter, along with additional information that came through the testing and simulations in the following chapters, has provided some interesting insights into how the design of flameproof motors can significantly impact on the likelihood of higher explosion pressures occurring. These situations are exacerbated when motors are tested at extremely low temperatures, and not only lead to the possibility of a motor needing to be stronger, but can also lead to flame transmission occurring. Consideration is being given to publishing information separately to this thesis on some of the findings that have emerged on methods can be used to improve the design of flameproof motors, with particular emphasis on avoiding high explosion pressures.

TABLE 38 – INDICATIVE PRESSURES FOR FLAMEPROOF MOTORS AT NORMAL AND LOW TEMPERATURE CONDITIONS

	Group IIB Temperature, ºC					Group IIC Temperature, ºC				
	Normal	**-30**	**-40**	**-50**	**-60**	**Normal**	**-30**	**-40**	**-50**	**-60**
	Factors					**Factors**				
	1	**1.37**	**1.45**	**1.53**	**1.62**	**1**	**1.37**	**1.45**	**1.53**	**1.62**
Frame size	**Pressure, kPa**					**Pressure, kPa**				
56	434	595	630	665	704	915	1,254	1,327	1,401	1,483
63	474	650	687	725	768	953	1,305	1,381	1,457	1,543
71	520	712	753	795	842	995	1,363	1,443	1,522	1,612
80	571	782	827	873	924	1,043	1,429	1,512	1,595	1,689
90	627	860	910	960	1,016	1,096	1,501	1,589	1,677	1,775
100	684	937	992	1,047	1,108	1,149	1,574	1,666	1,758	1,861
112	752	1,031	1,091	1,151	1,219	1,213	1,661	1,758	1,855	1,965
132	866	1,186	1,256	1,325	1,403	1,319	1,807	1,912	2,018	2,137
160	1,025	1,404	1,486	1,568	1,661	1,468	2,011	2,128	2,245	2,378
180	1,139	1,560	1,651	1,742	1,845	1,574	2,156	2,282	2,408	2,550
200	1,252	1,716	1,816	1,916	2,029	1,680	2,302	2,436	2,570	2,722
225	1,394	1,910	2,022	2,133	2,259	1,813	2,483	2,628	2,774	2,937
250	1,536	2,105	2,228	2,350	2,489	1,946	2,665	2,821	2,977	3,152
280	1,707	2,338	2,475	2,611	2,765	2,105	2,884	3,052	3,220	3,410
315	1,905	2,610	2,763	2,915	3,087	2,291	3,138	3,321	3,505	3,711
355	2,133	2,922	3,092	3,263	3,455	2,503	3,429	3,629	3,830	4,055
400	2,388	3,272	3,463	3,654	3,869	2,742	3,757	3,976	4,195	4,442
450	2,672	3,661	3,875	4,089	4,329	3,008	4,120	4,361	4,601	4,872
500	2,956	4,050	4,287	4,523	4,789	3,273	4,484	4,746	5,008	5,302
560	3,297	4,517	4,781	5,044	5,341	3,592	4,920	5,208	5,495	5,818

9 Development of indicative pressures for flameproof motors - testing motor at low temperatures

9.1 Introduction

Much of the research reported earlier in thesis looked at the impact of extremely low temperatures on explosion pressures and flame transmission in flameproof equipment in general, particularly where there was a possibility of pressure piling. The previous chapter, Chapter 8, looked at the likely pressures that would be developed in flameproof motors based on results from testing bodies and manufacturers. This chapter now looks at providing information specifically relevant to flameproof motors when tested at a range of temperatures from ambient down to extremely low temperatures.

9.2 Experiments - 160 frame motor

9.2.1 Choice and set up of motor

For this exercise, a 160 frame flameproof motor was chosen. This motor was designed for use in a normal range of ambient temperatures, and so it was decided that it would not be appropriate to try to run the motor at extremely low temperatures. This was because, at extremely low temperatures, it was likely that the bearing grease would not be suitable and may freeze, plus there might also be a problem with the insulation of the windings at extremely low temperatures. So all tests were carried out with the motor at rest. Pressure transducers were installed in the motor at the drive end, the non-drive end and the wall of the chamber under the terminal box. Ignition sources were installed adjacent to the pressure transducer positions on the end shields, and on the opposite side of the terminal box to where the terminal box pressure transducer was placed. Figure 37 shows the motor in the environmental chamber with all the instrumentation in place and the gas supplies connected.

Figure 37 – 160 frame motor in environmental chamber

9.2.2 Testing of the 160 frame motor

The motor was tested at the temperatures of +20, -20, -40 and -60 °C. The following gases and their concentrations with air, as defined by IEC 60079-1 for pressure determination, were used for the testing:

1) Hydrogen with air at (31 ± 1) %
2) Acetylene with air at (14 ± 1) %
3) Ethylene with air at (8 ± 0.5) %
4) Hydrogen/methane (85/15) with air at (24 ± 1) %

These are essentially the stoichiometric mixtures for those gases. To make allowance for experimental error and other factors such as the paramagnetic effect of the oxygen analyser, the tolerance in each case was halved. 1) and 2) are used for pressure determination testing for Equipment Group IIC, and 3) and 4) are used for pressure determination testing for Equipment Group IIB. The hydrogen/methane mixture is only for use in cases where pressure piling may be present. This was discussed in 2.5.

For each gas ignition position of drive end, non-drive end and under the terminal box, the pressure was measured at each of the three pressure transducers, also placed at drive end, non-drive end and under the terminal box. For each test condition of gas/air mixture, ignition position and temperature, the test was carried out twice. The maximum pressure was noted for each combination of gas/air mixture and temperature.

9.3 Results and discussions - 160 frame motor

The maximum pressures for testing of the 160 frame motor at each temperature point for each gas are shown in TABLE 39.

TABLE 39 – MAXIMUM PRESSURES FOR TESTING OF 160 FRAME MOTOR

Gas	% with air	Initial temp, °C	Pressure from testing		
			Ignition	Transducer	Max pressure, kPa
Hydrogen	31	20	DE	NDE	563
		-20	TB	TB	762
		-40	TB	DE	724
		-60	DE	NDE	891
Acetylene	14	20	TB	NDE	655
		-20	TB	NDE	928
		-40	TB	NDE	963
		-60	TB	NDE	1,098
Ethylene	8	20	NDE	TB	844
		-20	NDE	TB	873
		-40	NDE	TB	1,102
		-60	NDE	TB	1,026
Hydrogen/ Methane (85/15)	24	20	NDE	TB	422
		-20	TB	NDE	501
		-40	TB	NDE	581
		-60	TB	NDE	256

The results for the maximum pressures are also plotted in Figure 38. Below is an analysis of the results, initially by each gas and then looking for common issues or themes.

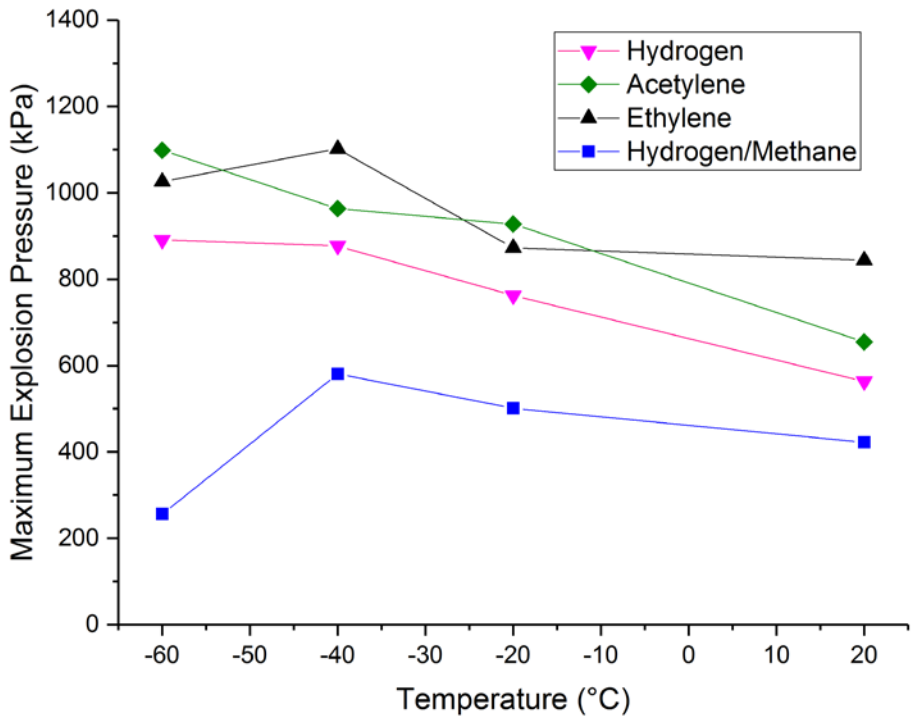


Figure 38 – Maximum explosion pressure figures for 160 frame motor

9.3.1 Results for hydrogen

An interesting outcome of the testing with hydrogen was the change in maximum pressure scenario for each change in temperature for the testing, as shown in TABLE 39 above. The following examines that outcome:

a) At +20 °C, the scenario producing the maximum pressure was with the ignition at the drive end and pressure measurement at the non-drive end

b) At -20 °C, the scenario producing the maximum pressure was with ignition under the terminal box and pressure measurement also under the terminal box, but with the ignition and pressure measurement on opposite sides of the compartment under the terminal box

c) At -40 °C, the scenario producing the maximum pressure was with the ignition under the terminal box and pressure measurement at the drive end

d) At -60 °C, the scenario producing the maximum pressure was with ignition under the terminal box and pressure measurement at the non-drive end, which was the same as for +20 °C

All results indicated there was flame transmission through the air gap involving pressure piling. However, for maximum pressures, only scenarios a) and d) above involved transmission through the air gap.

The above shows that the transmission scenario producing maximum pressure at normal ambient temperature is not an indication of the scenario that will produce maximum pressures at lower temperatures.

The graph shows the linear increase in pressure from 20 °C to -40 °C but the increase to -60 °C is not as large as might be expected. There is no clear reason for this. It may just be a result of a low number of tests for the scenario or some effect due to ice within the motor forming from the water, which is a by-product of the explosions.

9.3.2 Results for acetylene

An initial round of tests for acetylene produced lower explosion pressures for tests below zero than would be expected. It was decided to repeat these tests, and the new results are shown in TABLE 39 and Figure 38 above, clearly indicating an increase in explosion pressure as the temperatures fall. It is possible the initial low-pressure results were the result of ice formation within the motor at the low temperatures, particularly when the motor was cooled from positive to negative temperatures.

In contrast to the explosions with hydrogen, acetylene and the same scenario at each temperature point. This involved ignition under the terminal box and the maximum pressure occurring at the non-drive end. Thus, pressure piling involving the air gap was a significant feature. However, this was the only scenario that provided clear evidence of pressure piling through the air gap, and it would appear that the pressure developed with the combination of terminal box and drive end volumes was sufficient to produce ignition through the air gap. However, this was not obviously a direct result of increased pressures near the drive end. The pressures near the drive end were higher after ignition at the drive end than for ignition under the terminal box. So there is some more complex situation occurring here regarding the combustion.

Of particular interest is the obvious difficulty in achieving flame transmission through the air gap with acetylene, even though it occurred with hydrogen. A likely reason for this is the significant difference between the acetylene stoichiometric mix used for this testing (14 %) and the mixture specified for flame transmission testing in IEC 60079-14 acetylene (7.5 %). In contrast, the corresponding mixtures for hydrogen 31 % and 27.5 %, which are reasonably close. This provides evidence that it may be necessary to test with mixtures other than the stoichiometric mix where pressure piling is involved, and will be discussed further in the conclusions in Chapter 11.

9.3.3 Results for ethylene

Similarly to acetylene, ethylene showed a consistent scenario is for the production of maximum pressures. The scenarios were ignition at the non-drive end and pressure measurement under the terminal box. Interestingly this scenario occurred in the opposite direction to the scenario with acetylene. However, for ethylene, flame transmission continued to occur through the air gap, producing pressure piling for all scenarios. The fact that flame transmission continued to occur at low temperatures, even though the air gap was only 1 mm, looks consistent with the results shown in Chapter 3, indicating that the likelihood of flame transmission for ethylene is similar or higher at lower temperatures. There is some variation on the linear increase in pressure as temperatures fall, but similarly for hydrogen, this is likely to be due to an insufficient number of tests, or the presence of ice affecting pressures.

9.3.4 Results for hydrogen/methane

The testing with hydrogen/methane again showed some variation in the scenarios that produced the maximum pressure as follows:

a) At +20 °C scenario that produced the highest explosion pressure was ignition at the non-drive end and pressure measurement under the terminal box which was the same scenario for ethylene at all temperatures

b) At the temperatures of -20, -40 and -60 °C, the scenario that produced the highest pressure was ignition under the terminal box and pressure measurement at the non-drive end

An analysis of the results show that at the lower temperatures flame transmission no longer occurred through the air gap for the scenario in a), that is there was no transmission through the air gap for ignition at the non-drive end and pressure measurement under the terminal box. However, flame transmission continued to occur creating a higher explosion pressures due to pressure piling for -20 and -40 °C for ignition under the terminal box and pressure measurement at the non-drive end. However, at -60 °C, of the two tests carried out for the scenario one showed no transmission through the air gap and the other show apparently marginal transmission, as there was no significant explosion pressure produced at the non-drive end. This resulted in significantly lower maximum explosion pressure at -60 °C, as can be as clearly shown in Figure 38.

Thus the premise of using hydrogen/methane because of more likely transmission through small gaps producing pressure piling does not appear to hold true for lower temperatures. In Chapter 3, it was shown that flame transmission with hydrogen becomes less likely as lower temperatures. Hence it is likely that the high percentage of hydrogen used in this mix is responsible for the lack of flame transmission at lower temperatures.

9.4 Conclusions regarding testing of the 160 frame motor

From the above results and discussions, some general conclusions can be drawn as shown below.

For pressure determination in flameproof motors, the scenario that produces the highest explosion pressure at normal ambient temperatures may not be the same as the one that will produce the highest explosion pressures at lower temperatures. This further indicates that pre-pressurisation of equipment that may be subject to pressure piling is not a suitable method for determining maximum explosion pressures; a topic that was discussed in Chapters 4, 5, 6 and 7.

A significant contributor to the likely scenarios that will produce maximum pressures at low temperatures is whether flame transmission will occur through the air gap. How this may occur is very dependent on the gas that is used for testing and may also be affected by the composition of the gas/air mixture if the stoichiometric mix is not close to the mixture that will be most likely to produce flame transmission. It is also dependent on the size of the air gap and length of the path through the air gap. For some motors the air gap may be large enough the transmission will occur with any gas at any temperature.

This testing as highlighted an additional issue. For reference pressure testing, IEC 60079-1 has the option for electrical equipment intended for use at an ambient temperature below -20 °C, of determining the reference pressure at a temperature not higher than the minimum ambient temperature. However, the application of this clause means that the equipment need only be tested at that low temperature. It can be seen from the testing of the 160 frame motor that, if it were tested for use in -60 °C for group IIB, the reference pressure would be lower than if tested at -40 °C. It might even be feasible, looking at the explosion pressure for hydrogen/methane and the first round of testing for acetylene, for the explosion pressures at low temperatures to be lower than those at ambient temperatures. Therefore it may be necessary to test at other temperatures. In addition to the minimum ambient temperature. For example, it might be necessary to test at normal ambient temperature and also at a point roughly midway between normal ambient temperature and the minimum ambient temperature.

For this research, only two tests were done at each temperature point for each gas. It would be useful to carry out additional testing to gather more data to provide better statistical confidence in the figures. It might then be possible to make estimations of the factors that could be applied at each temperature point for testing at low temperatures and to apply these factors to the ambient figures derived from the equations. This is unlikely to be adequate for type testing of electric motors for the purpose of certification, but it would provide indicative figures for manufacturers. This would be an alternative approach to that shown in the previous chapter of making use of the factors that are shown in IEC 60079-1 for use in non-pressure piling situations.

10 Investigations into the use of CFD to determine explosion pressures

10.1 Introduction

As indicated earlier, the investigation here aimed at considering the potential to use CFD for the prediction of explosion pressures in flameproof equipment, in particular in flameproof motors. This investigation also addresses the potential to predict explosion pressures in flameproof motors at extremely low temperatures. It was known when starting this exercise that there would be some potential limitations, particularly with regard to the grid size, that impact on the modelling of explosions in flameproof motors.

Chapter 1 looked at some relevant work that has been done in relation to the use of CFD. A recurring theme in the publications was the potential for CFD to predict explosion pressure in flameproof equipment including, in one paper, in flameproof motors. These predictions go back a long way, for example to a paper in 1997 [32] which has been talked about earlier and as recently as 2016 [78] where the statement is made:

> Interactions between flame front, pressure waves and combustion-generated flow are important for hydrogen flame propagation under confinement. Generally, it is difficult to measure these interactions and the consequent turbulence generation during hydrogen explosions using experimental methods, especially when they involve high-speed, compressible reacting flow. Computational fluid dynamics (CFD) calculation can help to gain more details of these interactions, but only relatively small-scale or simplified 1D/2D problems. Thanks to the rapid advance in both numerical techniques and computer performance, CFD computation will, in future, allow us to solve problems of scales that currently seem prohibited.

But, I have been unable to find evidence that those predictions about predicting explosions have become a reality for the case of flameproof motors. However, the use of CFD to predict explosions and related phenomena in other scenarios such as oil rigs or internal combustion engines has progressed significantly, assisted by improved computational powers of computers and, presumably, appropriate financial investment to support foster the development.

10.2 What is CFD?

So what is CFD? CFD is referred to in the book by Tu et al [79] as "derived from the disciplines of fluid mechanics and heat transfer". Gexcon, similarly, in their training describe it as "a branch of fluid mechanics that solves fluid flow problems by numerical methods and algorithms".

CFD has been used for many years to predict scenarios in hazardous areas such as offshore oil production rigs and oil refineries. Many of its developments have been inspired by major accidents, such as those in the UK at Flixborough in 1974 and the Piper Alpha oil rig in 1998. The nature of these accidents has tended to focus developments on large-scale installations rather than at the equipment level for explosion-protected equipment. CFD also has widespread use in fields other than hazardous areas.

CFD uses algorithms to solve the relevant governing Navier-Stokes equations. These equations are based on conservation of mass, conservation of momentum and conservation of energy. Tu et al [79] talk about these as the physical laws:

- Mass is conserved for the fluid
- Newton’s second law: The rate of change of momentum equals the sum of forces acting on the fluid
- First law of thermodynamics: The rate of change of energy equals the sum of the rate of heat addition to the fluid and the rate of work done on the fluid

These equations are presented in slightly different ways, depending on which publication is consulted. The FLACS course training manual shows the formulas used for FLACS are as shown below:

- Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

- Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\underbrace{\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \left(\mu_B - \frac{2}{3}\mu\right)\frac{\partial u_k}{\partial x_k}\delta_{\mathrm{ij}}\right]}_{\tau_{\mathrm{ij}}} + \rho a_i$$

- Conservation of energy:

$$\underbrace{\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho h u_j)}_{\rho\frac{Dh}{Dt}} = \underbrace{\frac{\partial p}{\partial t} + u_j\frac{\partial p}{\partial x_j}}_{\frac{Dp}{Dt}} + \frac{\partial}{\partial x_j}(J_{h,j}) + S_h$$

However, it did not define the elements in the equations. Other versions can be found In publications on CFD.

With limited exceptions, the Navier-Stokes equations cannot be solved analytically. In CFD the use of a grid is used to convert the equations to algebraic equations that can be solved. The grid used can be one-dimensional, two-dimensional or three-dimensional.

10.3 Use of CFD to predict explosion pressures

The use of CFD, either from first principles or when using commercially available computer packages, still seems to be mainly the role of experts in CFD. But my interest lies in the possibility of manufacturers being able to use a commercial package to predict the explosion pressures that may occur in their motors. When I started this exercise, I had no knowledge of CFD, and so I have relied on CFD experts for some of my decisions in my process of investigation.

I have since developed some basic knowledge and understanding of CFD during the research by means of a four-day training course at Gexcon in Norway, reading books and papers on the subject, and my discussions with experts. A number of these experts work at the University of Sydney. I have also had excellent support from the engineers at Gexcon.

10.4 Consideration of available CFD packages

There is a wide range of CFD packages available, but I quickly reduced the potential field down to two. For the research, given the other significant research elements related to flameproof motors, I decided the best approach was to concentrate on one potential package rather than try to do a wide review with my limited knowledge of CFD.

FLACS was a package that featured in publications I had reviewed and appeared to focus on creating an interface for practising engineers, rather than CFD specialists. I found the thesis by Rogstadkjernet [34] of particular interest with the more recent papers by Middha and Skjold [33, 35] providing supporting evidence of its potential. But the university did not hold a licence for this package and so I had to purchase one.

ANSYS FLUENT was the other package I considered. It did have the advantage that the university held a licence for it and I also met with the ANSYS Sydney agents to discuss its possible use. But this package seems to need significantly more in-depth knowledge of CFD to use it effectively than does FLACS.

I was fortunate to be able to obtain advice from Adjunct Professor David Fletcher at the University of Sydney who is very familiar with both packages. He indicated that he thought FLACS would hold the best promise for my investigation. Another circumstance validated this approach. While at a PCIC Europe conference in Berlin, Germany in 2016 I met a design engineer, Pedro Maia (personal communication, 16 June 2016), from the motor manufacturing company WEG, based in Portugal. He said that he was planning to try ANSYS FLUENT to try to predict explosion pressures in flameproof motors to assist them with their motor designs. We decided to collaborate to examine the respective merits of the two packages using one of their motor designs. This approach was finalised during a trip I made to their factory in November 2016, where it was decided to focus on a 355 frame motor size. At a follow-up visit

in June 2017, we were able to compare the results we were obtaining and to look at a more complex design of the motor incorporating the terminal box.

Hence I am in the position to comment on the use of two quite different CFD packages. We are planning to prepare a joint paper for a conference or journal comparing our results. A tentative title for the paper is:

> Potential for computational fluid dynamics (CFD) to predict explosion pressures in flameproof motors

10.5 Summary of FLACS capabilities and approach

10.5.1 FLACS basics

I can draw on five separate areas to consider the capabilities and approach of FLACS in addition to adding my own experience. These areas are:

- The Gas Explosion Handbook [80]
- The FLACS manual, currently for Version 10.6
- The Gexcon training notes for their training course - FLACS I
- Publications detailing studies using FLACS

The Gas Explosion Handbook, which has its latest version online at http://www.gexcon.com/article/gas-explosion-handbook (September 2017), describes FLACS as:

> The FLACS code is a three-dimensional gas explosion and gas dispersion simulation tool. The model takes account of the interaction between the gas flow and complex geometries such as structures, equipment and pipework (sic). The FLACS code produces quantitative information, e.g. in the form of pressure-time curves. By performing sensitivity studies alternative scenarios and layouts can be tested and their explosion hazard potential can be identified.

FLACS can address more than just explosions. Some key applications include:

- Dispersion of flammable or toxic gas
- Gas and dust explosions
- Propagation of blast and shock waves
- Pool and jet fires

But the only aspect being examined as part of this research is the pressure from gas explosions inside flameproof equipment.

A feature of FLACS is the extensive validation experiments, often on full-scale models, which have contributed to the development of the code.

FLACS can be run on Windows and UNIX platforms. For this investigation, I was using a Windows laptop computer with an i7 processor.

10.5.2 RunManager

FLACS is started by opening the "RunManager". This gives access to some of the main tasks in FLACS, including:

- Starting the pre-processor CASD which is used to build geometries and to develop scenarios
- Running CFD simulations based on the geometries and scenarios above
- Starting the "postprocessor" Flowvis which provides information on the results of simulations in graphical form
- Providing access to the Command Window which can be used as an alternative means to initiate actions within FLACS.

For this research, I have only used the RunManager and not the command line approach, and so I will restrict my comments to the approach.

10.5.3 The pre-processor CASD

10.5.3.1 Building the geometry

Geometries are developed using the CASD pre-processor. FLACS is designed to develop geometries in three dimensions. Producing good representative geometry is critical to achieving accurate dispersion and explosion analyses. Objects in FLACS are mostly built from box or cylinder "primitives". The use of "left difference" operations can be used to create holes. It is also possible to use a CAD input utility which, depending on the file may be two or three-dimensional. The computational space is defined using a Cartesian grid. The geometry is mapped to the grid using a distributed porosity concept. In addition to porosities, sub-grid turbulence factors are calculated.

Simple models can be built directly using the "Add" tab and then normally "box" or "cylinder". In the same tab "left difference" is used to create holes. More complex models can be built using the "Geometry" tab. Within this scenario a geometry database is used to build and store the geometry, to create "objects" for inclusion in the geometry and, if needed, to define "materials" for use in the objects and geometry.

As part of the geometry building process, the computational domain and the computational grid are specified. This is a critical part of the process and the one that has provided some of the most difficult issues in this research for the application of FLACS to flameproof enclosures and motors. The manual states that "one should not use grid cells of 1-2 cm or less, because for very small grid cell sizes, the subgrid (sic) model for premixed combustion (explosions) is not applicable: the burning velocities tend to be severely overpredicted (sic)". However, the geometries inside the equipment used for the scenario included critical geometries on which this impacted. This is discussed in more detail for the various geometries later in this chapter.

Once the model has been completed and saved, the porosities are calculated and verified. This proved a critical step to find out whether walls of enclosures were treated as solid (and hence <u>not allowing</u> an explosion to pass through), and if holes, such as motor air gaps, were open (and hence <u>allowing</u> an explosion to pass through). This step normally required some adjustment to the geometry and the grid size to come up with a model that could reasonably simulate the required explosion.

The FLACS manual states that:

> In FLACS, the computational mesh is composed of cubic or rectangular grid cells defined by grid lines arranged in vertical or horizontal directions, i.e. a single-block Cartesian grid. It is possible to vary the mesh resolution in any of the Cartesian directions. However, it is not possible to fit the mesh to curved or inclined walls or objects. Instead, these are modelled using stepped walls.

Since motors and the artefact being used in this investigation, together with many of their components, are essentially cylindrical in nature, this limitation in FLACS became a significant issue. Sufficient thickness needs to be built into the walls of any cylindrical object to ensure there is no porosity. It was found that the smaller the diameter of the cylinder the thicker it needed to be to ensure it was not porous. Some porosity situations for the motors and the artefact will be demonstrated below.

An example of the CASD screen with the model for the 255 frame motors is shown later in this chapter in Figure 39.

10.5.3.2 Defining the scenarios

The scenarios are also defined within CASD. For the purpose of this research, the main scenarios that need to be addressed are:

- Simulation type - for this exercise the types of "Gas explosion" and "Gas explosion (DDT)" were considered - these set a number of default parameters for the rest of the scenario setting below
- Monitor points - these require the locations and output variables, which in this case involved the simulation of the positions of pressure transducers similar to those used in testing

- Single point 3D output - for this exercise, information about the combustion product before and after combustion, pressure, and temperature was selected
- Simulation and output control - critical features here were the maximum time for the simulation and the plotting of time steps
- Initial conditions - critical features here were initial turbulence and temperature
- Gas concentration and volume - establishes the extent of the gas cloud which needs to cover all the equipment, and the gas(es) to be used
- Ignition - the position of the ignition source

Once the job has been saved, complete with the scenario, the scenario information is saved in a file commencing with "cs" and then the CASD job number. This file can be read by a text reading program such as WordPad.

10.5.4 Simulations

After defining the scenario, the next step is to run the actual FLACS simulations. These are done using the RunManager. The run time is very dependent on the grid size. The smaller the grid size, the longer the run time.

Jobs can only be run after the porosity calculation has been done. This can be initiated either in CASD or in the RunManager. After the porosity calculation has been done, the job will show as "READY" in the RunManager and then "FINISHED" at the end of the simulation.

Two features help to make processing faster and more efficient:

- The use of the "Parallel run" in the "Parameters" facility; or in "Options", "Preferences", "Default". This allows parallel processing by increasing the number of threads to take account of computers with more than one CPU core in a shared memory configuration. For my laptop it was possible to run with four threads, leading to a significant reduction in processing time.
- Serial processing using the "Batch Run" facility allows more than one job to be queued which is very useful when running multiple scenarios. This means there is no time lost between each simulation and large numbers of simulations can be run unattended or while doing other activities.

10.5.5 Postprocessor Flowvis

Flowvis is a postprocessor program for visualising results from simulations of gas explosions, gas dispersion and multiphase flow carried out in the FLACS RunManager. It has extensive capabilities for displaying what has happened during the simulation. But it is dependent on the necessary information being specified in the simulation scenarios so that it will be logged during the simulation.

It is capable of producing several different types of plots. It can display several plots on the one page or utilise a "Page" function to provide plots on different tabbed pages. A plot can include information from only one simulation or from several simulations.

The types of plots that can be displayed are:

- Scalar time plot: variable plotted along time axis
- Scalar line plot: variable plotted along a grid line
- 2D cut plane plot: variable contours plotted on a plane
- 3D plot: variable contours plotted in 3D

Examples of the Scalar time plot and the 2D cut plane plots appear later in this chapter, for example, Figure 40 shows a 2D cut plane plot at the top of the figure and a scalar time plot at the bottom of the figure. These are the two plots that have been used in this research and displayed many times throughout this chapter as part of the analysis of various investigations undertaken.

10.6 Approach for simulation of pressure - preliminary studies

During a visit to Gexcon in November 2016 to undergo FLACS training, I also spent time with one of their engineers developing an initial FLACS model for simulating explosion pressures

in a flameproof motor. The version of FLACS being used for this was FLACS_v10.5. For this, a 255 frame motor was used. This model was built using the CASD facility with the simple approach of adding primitives to build the motor. It was possible to add an end-shield, motor casing, stator, rotor and shaft. No terminal box was used in this simple approach. The scenarios were then developed for the motor within the CASD facility. Simulations using both "Gas explosion" and "Gas explosion (DDT)" were used. The gas used for these simulations was a stoichiometric mix of hydrogen and air. This simulates one of the tests used for determining explosion pressure for IIC motors in IEC 60079-1. The ignition and pressure measurement scenarios were also set up to follow the methods used for pressure determination. Pressure transducers were simulated on the end-shields at both ends of the motor, and an ignition source was introduced into one end. Since this model was built symmetrically, there was no need to simulate ignition sources at either end.

Some immediate problems were found. These mainly related to the issues of grid size and porosity as handled by the FLACS program. It was found that with a grid size within the range recommended for FLACS, the porosity of the motor allowed gas and explosions to propagate through the walls of the motor. In contrast, the porosities in the air gap prevented transmission of the explosion from one end of the motor to the other. Trying to solve this by using a smaller than recommended grid size leads to long processing times and was not within the recommended grid size validated for the FLACS code. It was decided that the best solution at this time was to thicken the walls of the motor artificially and to increase the size of the air gap. Using this approach, it was possible to get an explosion scenario and pressures that looked reasonable. The main result of this exercise was that it proved that the approach could work, but in this case only using a model that was modified from the real scenario.

Figure 39 shows the model of the 255 frame motor in CASD, with the scenario settings shown on the right-hand side.

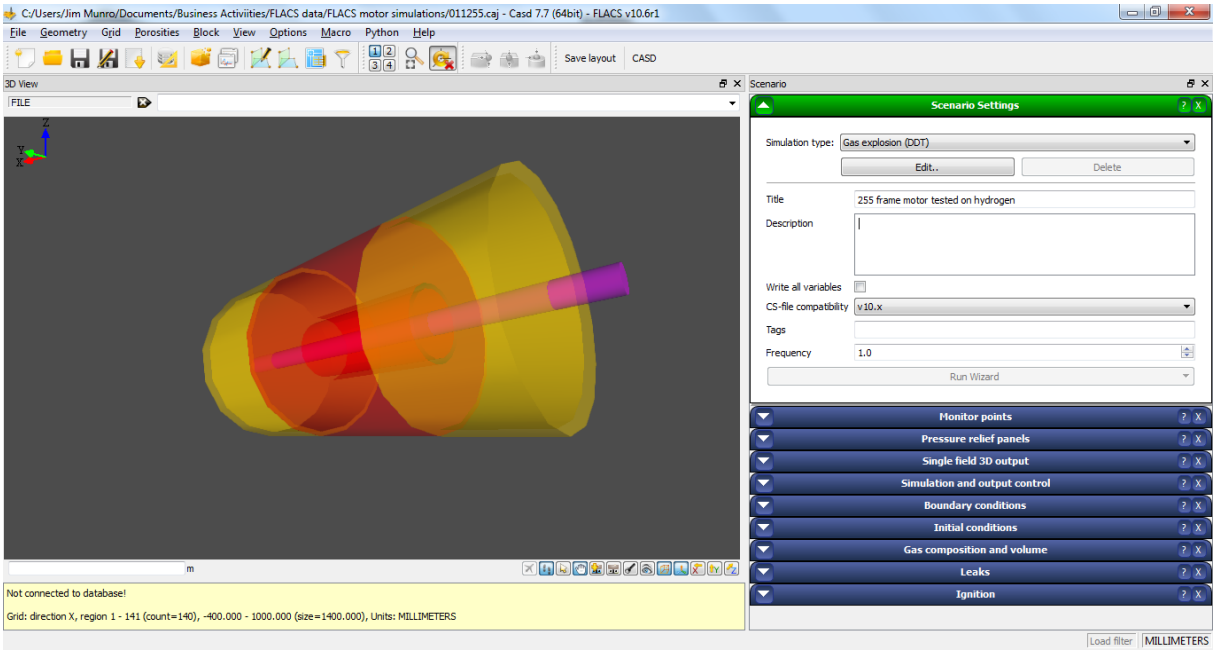


Figure 39 – 255 frame motor in CASD

Figure 40 shows an example of the results for the 255 frame motor using the Flowvis simulation program. The top of the figure is a 2D cut plane plot showing the product (hydrogen/air) partially consumed by the explosion. The lower part of the figure shows the scalar time plot pressure curves from the two pressure transducers.

The maximum pressure figure at the non-drive end, with the ignition at the drive end, shows a maximum pressure of 859 kPa. Maximum figures for hydrogen from the data mining project for different motors, as shown in Chapter 8 are 570, 996 and 528 kPa. So the explosion pressure figures shown from this test appear to be in the right pressure range.

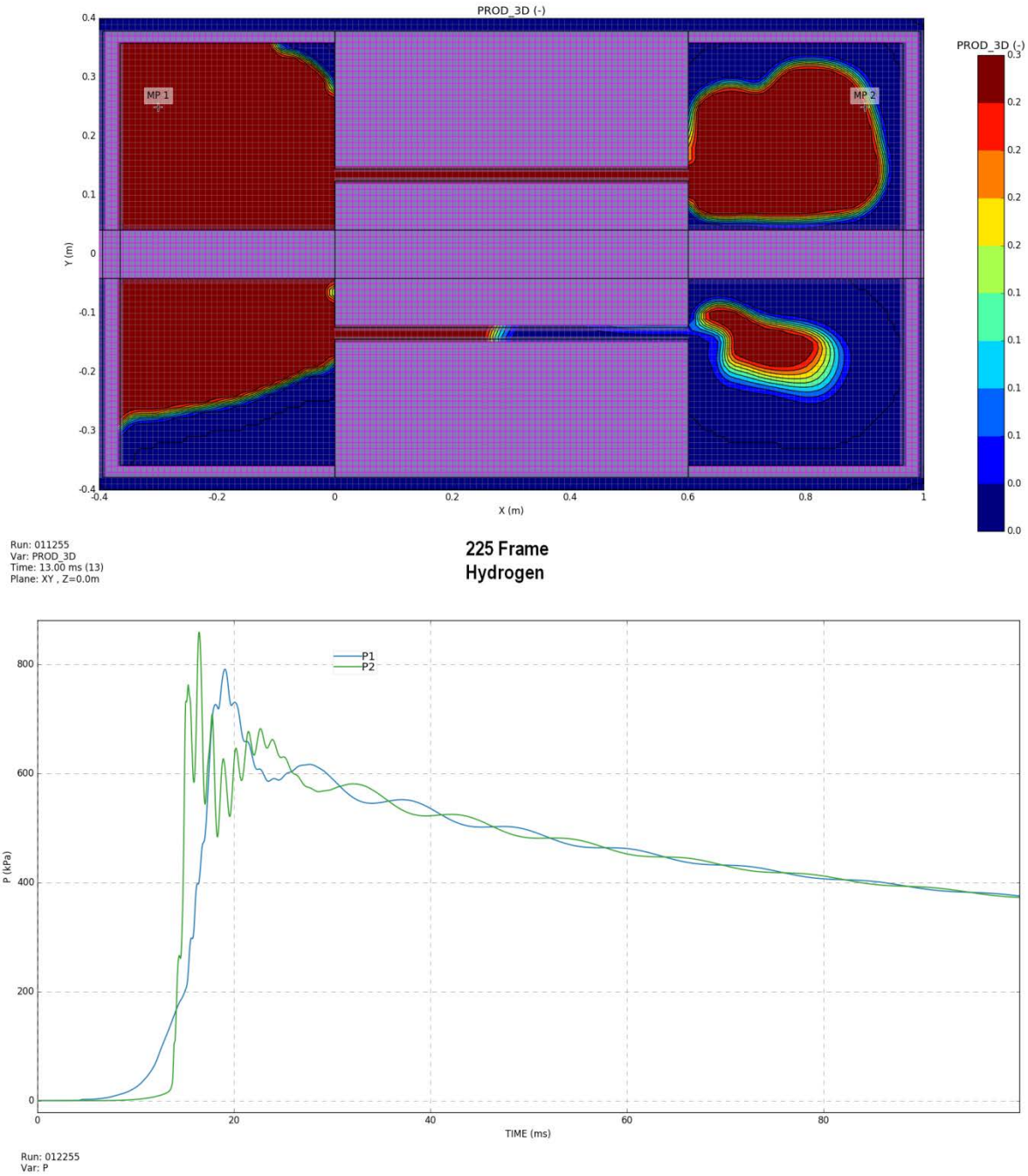


Figure 40 – Example of 255 frame results in Flowvis

10.7 Simulation of 355 frame motor

10.7.1 Basic build geometry without terminal box

As noted earlier, it was decided to collaborate with an engineer from WEG to produce simulations using both FLACS and ANSYS FLUENT, and for this exercise, a 355 frame motor was chosen as shown in Figure 41. Again for this initial exercise, a motor geometry without a terminal box was chosen. The previous exercise of using a 255 frame motor was done without knowledge of the actual motor dimensions except for some of those defined by IEC 60072–1 [74]. This time it was possible to use actual motor dimensions. But for this new exercise, it was again necessary to make some modifications to take account of porosity. The end-shields were thick enough to avoid leakage, but the motor case had to be made thicker. This could be done by increasing the outside thickness and hence preserving the internal geometry, as was done for the 255 frame. However, it was again necessary to increase the size of the air gap.

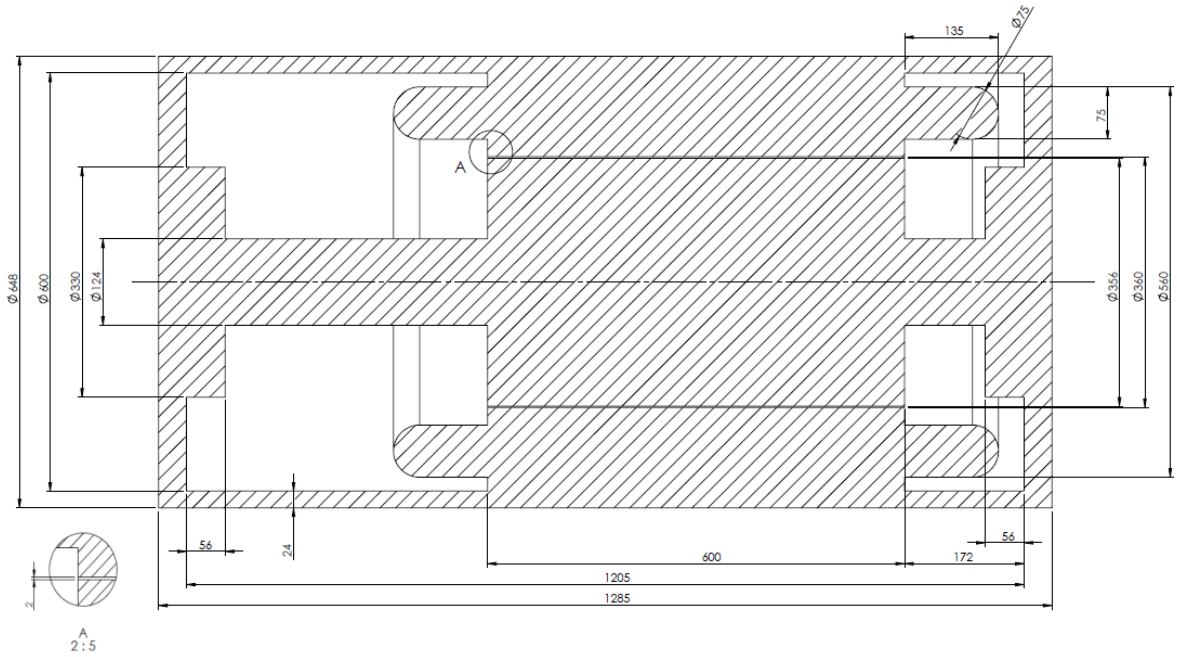


Figure 41 – Simplified design of 355 frame motor without terminal box.

Again a simple build was done using primitives using the CASD pre-processor. The design produced in CASD is shown in Figure 42 with the gridlines included. The figure is shown in semi-transparent mode to show the drive end ignition position and the positions of the two pressure transducers.

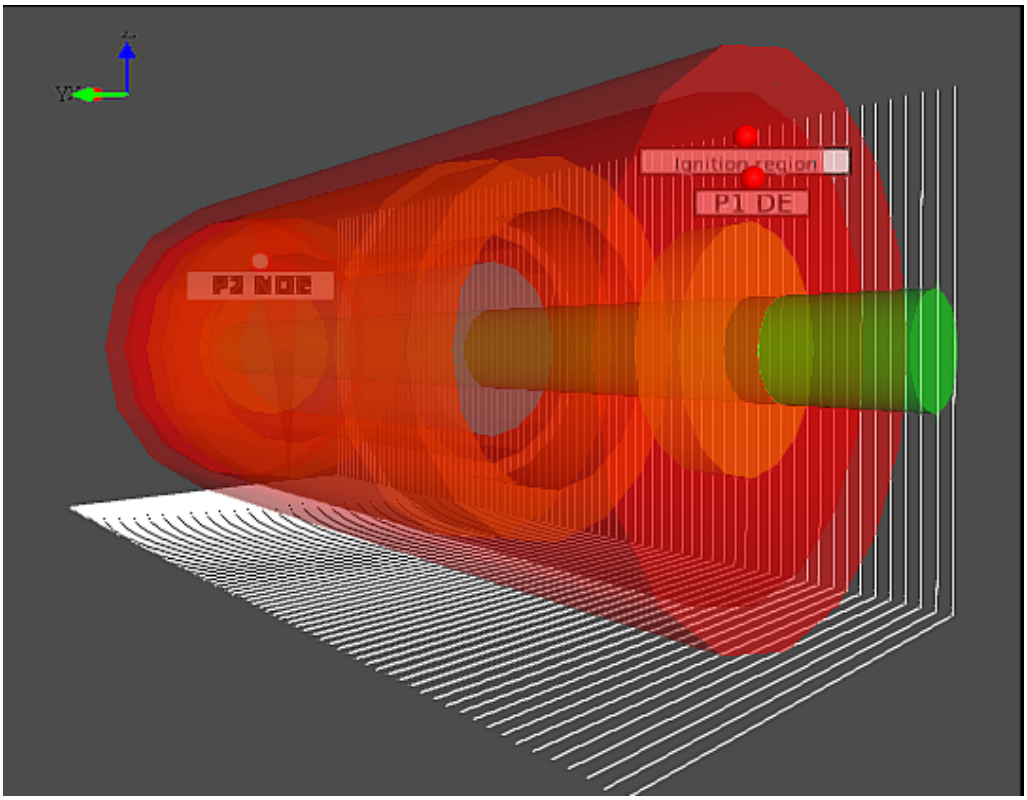


Figure 42 – Simplified design of 355 frame motor in CASD

The detail of this process was recorded in an Excel spreadsheet to enable possible future modifications to be readily made for the rebuild or to extrapolate this approach for use on other frame sizes to be built without including terminal box. This spreadsheet is shown in TABLE 40.

TABLE 40 – SPREADSHEET FOR 355 FRAME WITHOUT TERMINAL BOX

Step	Part	Action	Position, mm			Diameter, mm	Length, mm	Hue	
			x	y	z			No	Colour
1	Motor case and DE end shield	Cylinder external diameter plus extra 16 mm	0	0	0	680	1285	0	Red
2		Cylinder motor internal diameter	40	0	0	600	1285		
3		Left difference							
4	DE bearing cap	Cylinder	40	0	0	300	56	60	Yellow
5		Union							
6	DE winding	Cylinder outside of winding	338	0	0	560	135	30	Orange
7		Cylinder Inside winding diameter	328	0	0	410	155		
8		Left difference							
9	Stator	Cylinder stator outside diameter	473	0	0	600	600	30	Orange
10		Stator internal diameter	468	0	0	360	620	120	Green
11		Left difference							
12	NDE winding	Solid cylinder NDE winding	1073	0	0	560	135	30	Orange
13		Left difference	1073	0	0	410	155		
14	NDE bearing cap	Solid cylinder NDE bearing cap	1189	0	0	300	56	60	Yellow
15		Solid cylinder NDE end shield	1245	0	0	600	40	0	Red
16		Union							
17	Shaft	Shaft	-150	0	0	124	1485	120	Green
18		Union							
19	Rotor	Cylinder outside of rotor minus 80 mm	473	0	0	276 (356)	600	180	Cyan
20		Union							

10.7.2 Scenarios for 335 frame without terminal box

Scenarios were then developed using the CASD pre-processor. For this, the "Gas explosion" scenario was used. For such a scenario FLACS includes a number of default parameters. Any additional information, or parameters that needed changing, are shown in TABLE 41. These have been extracted from the "cs" file for the exercise. Simulations were done using hydrogen, acetylene and ethylene. Since pressures were measured and reported in kPa for the experiments done for this research project, it was necessary to change the default pressure measurement parameter from "barg" to kPa for this and all subsequent simulations.

Turbulence is a significant issue in applying CFD. According to the FLACS training, there are three major turbulence models evolving in the field:

- Direct Numerical, or DNS: calculates the entire range of turbulent length scales directly from the Navier-Stokes equations - this approach requires very high grid resolution
- Large Eddy Simulation, or LES: calculates the large-scale motions of the flow, and models sub-grid scales
- Reynolds-averaged Navier-Stokes RANS: solves the time-averaged Navier-Stokes equations - this group includes the k-ε model used FLACS

Turbulence is a particular issue for flameproof motors because when running there is significant turbulence created inside the motor. This turbulence can become even higher for

larger motors incorporating internal fans. The turbulence model in FLACS to simulate turbulence within motors was applied for the 355 frame motor. This was done just for the purpose of simulating rotation, as this motor does not have an internal fan. The values chosen are shown in TABLE 41. These are just preliminary figures to indicate the impact of turbulence and to show the potential to demonstrate pressures for scenarios when motors are at rest and running. Some later research may be useful to try to establish the best figures to use (see 12.4).

TABLE 41 – PARAMETERS FOR SCENARIOS FOR 335 FRAME WITHOUT TERMINAL BOX

Information/parameters		Data (dimensions in m)
TEMPLATE_NAME (Scenario)		Gas explosion
MONITOR_POINTS (Pressure transducer coordinates: x, y, z)	P1 DE	0.041, 0, 0.2
	P2 NDE	1.244, 0, 0.2
POSITION_OF_IGNITION_REGION (Ignition source coordinates: x, y, z)	DE	0.05, 0, 0.25
	NDE	1.244, 0, 0.25
SINGLE_FIELD_3D_OUTPUT		NP, NPROD, NFMOLE, NT
SIMULATION_AND_OUTPUT_CONTROL	TMAX	0.04 for hydrogen and acetylene, 0.1 for ethylene
	KEYS	“RADIATE=04”
	DTPLOT	0.001
	HEAT_SWITCH	On (Set to 1)
INITIAL_CONDITIONS (when initial turbulence included.	RELATIVE_TURBULENCE_INTENSITY	0.1
	TURBULENCE_LENGTH_SCALE	0.002
GAS_COMPOSITION_AND_VOLUME	POSITION_OF_FUEL_REGION	0, -0.35, -0.35
	DIMENSION_OF_FUEL_REGION	1.285x0.7x 0.7

10.7.3 Geometry build using "objects" including terminal box

Figure 43 shows the CAD drawing of the 355 motor with one terminal box. Only the cavity in the underside of the motor is shown. This is open to the motor. The upper part of the terminal box is used for connection of the electrical supply cables to the motor, but this part of the junction box is sealed from the lower part. If there were openings, the standard also requires the test to include this upper part. There is also an option of having two terminal boxes, but this option was not included in this investigation. The presence of the terminal box introduced more complex geometry and hence the need to use the features of the geometry tools in FLACS to produce a version of the 355 frame motor with the terminal box. In addition, it was possible to include the cableway that runs the length of the stator under the terminal box when using this method.

The possibility of using the CAD input facility was considered. However, noting that it was a two-dimensional drawing and that FLACS works in three dimensions, it was decided to build the motor using the CASD geometry tools. This approach involved the construction of objects for the various components of the motor. The motor was then built using those components using the "Instance" function in the geometry tab of CASD. When the Instance command is used, there is provision to insert the coordinates for the position where the object is to be placed. The coordinates used will depend on whether the object is built with the base x, y, z coordinates of 0, 0, 0 or the actual coordinates for the geometry. For this exercise, it was found to be convenient to use a mix of these approaches.

Again, it was found necessary to thicken some parts of the motor construction and to provide a larger air gap. The introduction of the cableway meant that the motor casing had to be made even thicker than for the scenario without the terminal box. The terminal box introduced some complex operations to build it due to the need for the lower part of the terminal box to fit the round shape of the motor casing, and for the hole between the terminal box and the motor to be only partially open. The cableway itself was altered to a rectangular shape to make the geometry simpler.

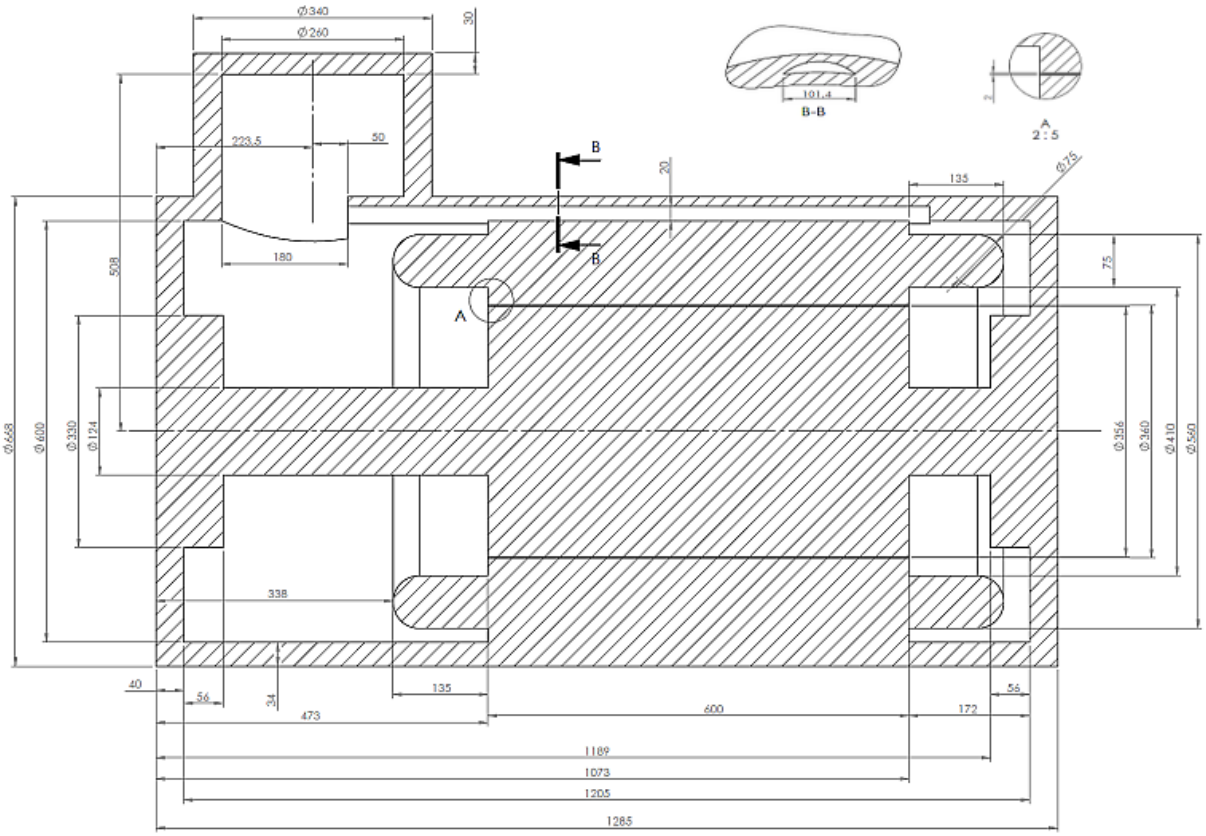


Figure 43 – Drawing of 355 frame motor with terminal box

Figure 44 shows the CASD design in semi-transparent mode and includes the pressure transducers and ignition source when at the drive end.

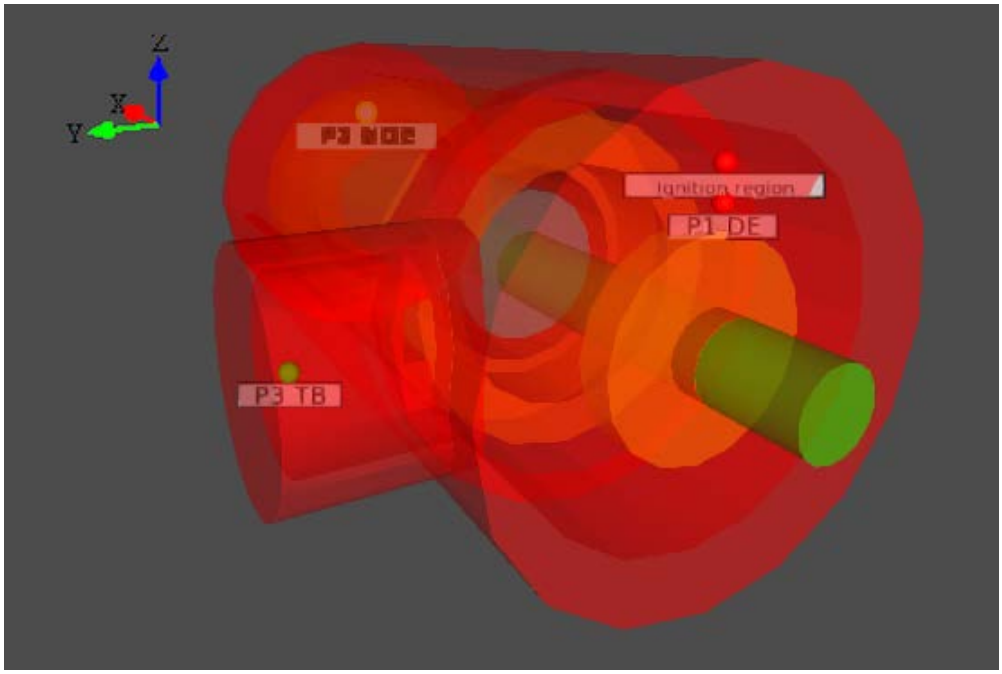


Figure 44 – 355 frame with terminal box in CASD

TABLE 42 shows the main steps involved in the construction of the motor. The colours in the table are those used in the CASD design for the various parts as shown in Figure 44. This template was designed in a way to allow it to be readily adjusted for other motor frame sizes. This concept was tested when building the 160 frame motor as shown later.

TABLE 42 – SPREADSHEET FOR 355 FRAME WITH TERMINAL BOX

Main step	Part	Object step	Object (name)	Information	Action	Position				Dimensions				Hue No
						x (ref 0)	x (object)	y	z	Diam/ x (rect)	y (rect)	Length	Dir'n	
1	Motor case	1	Motor_ casing	Motor case with DE endshield	Cylinder external diameter plus extra 80 mm	0	0	0	0	748		1285	x	0
		2			Hole of TB		223.5	150	0	260		300	y	120
		3			Left difference									
		4		TB hole	Cylinder motor internal diameter		40	0	0	600		1285	x	
		5			Left difference									
		6		Cut cableway	rectangle rod for hole		273.5	290	-45	1200	40	90	x	120
		7	End object		Left difference									
2	Terminal box	1	TBox	Terminal box	Vertical cylinder		223.5	200	0	340		364	y	0
		2			Make bottom semi-circular		0	30	0	600		500	x	120
		3			Left difference									
		4		Hole inside	TB internal diameter		223.5	200	0	260		324	y	120
		5	End Object		Left difference									
					Instance Tbox	0								
3	TB Fill	1	TB_hole_ring	Fill part of case under TB	Cylinder external motor diam	273.5	0	0	0	748 (708 initially)		78 (80?)	x	0
		2			Cylinder motor internal diam		40	0	0	600		1285	x	
		3			Left difference									
		4		Cut cableway	Rectangle rod for hole		250.0	290	-45	200	-10	90	x	120
		5	End object		Left difference									
		6			Instance TB_ring	273.5 (0?)		0	0				x	
4	DE bearing cap	1	Bearing_cap	DE bearing cap	Cylinder		0	0	0	120		40	x	60
		2	End object											
		3			Instance Bearing_cap	40		0	0				x	
5	Winding overhang DE	1	Stator_ winding_ overhang	For both winding overhangs	Cylinder outside of winding		0	0	0	560		135	x	30
		2			Cylinder Inside winding diameter		-20	0	0	410		155	x	120
		3	End of object		Left difference									
		4			Instance Stator_winding_ overhang	338		0	0				x	
6	Stator	1	Stator	Stator	Cylinder stator outside diameter		473	0	0	600		600	x	30
		2			Stator internal diameter		468	0	0	360		620	x	120
		3	End of object		Left difference									
		4			Instance Stator	0		0	0				x	
7	Winding NDE	1		Winding overhang	Instance Stator_winding_ overhang	1073		0	0					30
8	NDE bearing cap			Use earler object	Instance Bearing_cap	1189		0	0					60
9	Shaft	1		Shaft	Shaft		-150	0	0	124		1485		120
				End of object										
					Instance shaft	0		0	0					
10	Rotor	1	Rotor_winding	Rotor without shaft	Cylinder outside of rotor minus 80 mm		473	0	0	276 (356)		600		180
				End of object										
					Instance Rotor_winding	0		0	0					
11	NDE end shield	1		Endshield	Cylinder		1245	0	0	748		40		0
				End of object										
					Instance Endshield	0		0	0					

Figure 45 shows the porosities in the XY view.

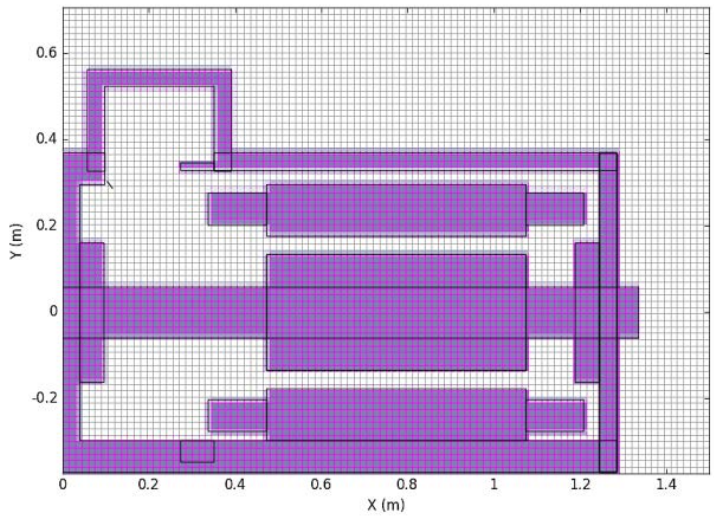


Figure 45 – Porosities of 355 frame with terminal box

10.7.4 Scenarios for 355 frame motor with terminal box

Most of the scenario settings that were defined for the 355 frame motor without the terminal box were reused for the 355 frame motor with the terminal box, but with the need to adjust for the new geometry. A third pressure transducer was added in the terminal box, and the scenario of ignition in the terminal box was also added. TABLE 43 shows the relevant parameters.

TABLE 43 – PARAMETERS FOR SCENARIOS FOR 335 WITH TERMINAL BOX

Information/parameters		Data (dimensions in m)
TEMPLATE_NAME (Scenario)		Gas explosion
Grid size		0.015
MONITOR_POINTS (Pressure transducer coordinates: x, y, z)	P1 DE	0.041, 0, 0.2
	P2 NDE	1.244, 0, 0.2
	P3 TB	0.2235, 0.507, 0
POSITION_OF_IGNITION_REGION (Ignition source coordinates: x, y, z)	DE	0.05, 0, 0.25
	NDE	1.244, 0, 0.25
	TB	0.15, 0.5, 0
SINGLE_FIELD_3D_OUTPUT		NP, NPROD, NFMOLE, NT
SIMULATION_AND_OUTPUT_CONTROL	TMAX	0.04 for hydrogen and
	KEYS	“RADIATE=04”
	DTPLOT	0.001
	HEAT_SWITCH	On (Set to 1)
INITIAL_CONDITIONS (when initial turbulence included.	RELATIVE_TURBULENCE_INTENSITY	0.1
	TURBULENCE_LENGTH_SCALE	0.002
GAS_COMPOSITION_AND_VOLUME	POSITION_OF_FUEL_REGION	0, -0.35, -0.35
	DIMENSION_OF_FUEL_REGION	1.285x0.7x 0.7

10.7.5 Results for 355 frame motor

10.7.5.1 355 frame without terminal box simulation results

The following figures show the results for the simulation of the 355 frame motor without the terminal box. The pressure-time curves show results with the ignition at the drive end on the left and ignition at the non-drive end on the right. Immediately below those are the corresponding 2D cut plane plots showing the product partially consumed by the explosion. Figure 46 is for hydrogen, Figure 47 is for acetylene and Figure 48 is for ethylene. It can be seen that in each case the explosion develops more quickly when the ignition is at the non-drive end. There is clear evidence of pressure piling for hydrogen and acetylene, but not for ethylene.

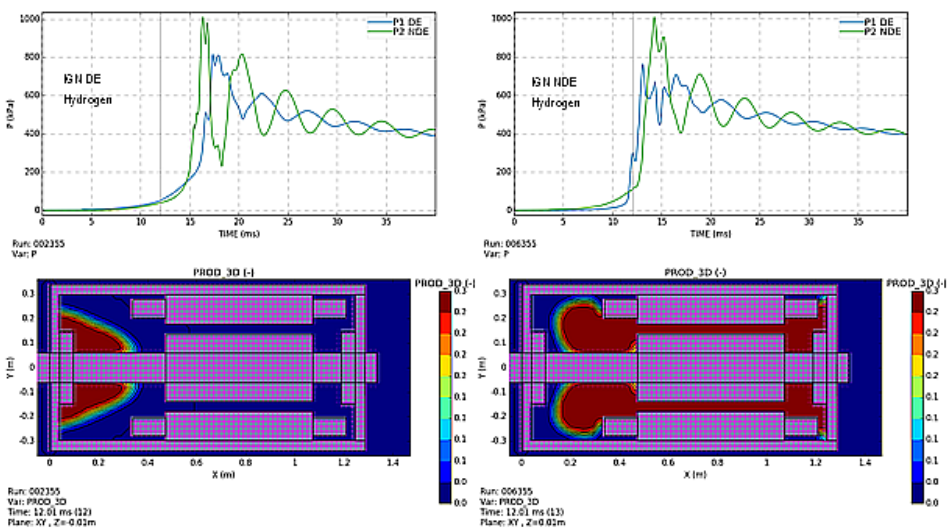


Figure 46 – 355 frame without terminal box - Hydrogen

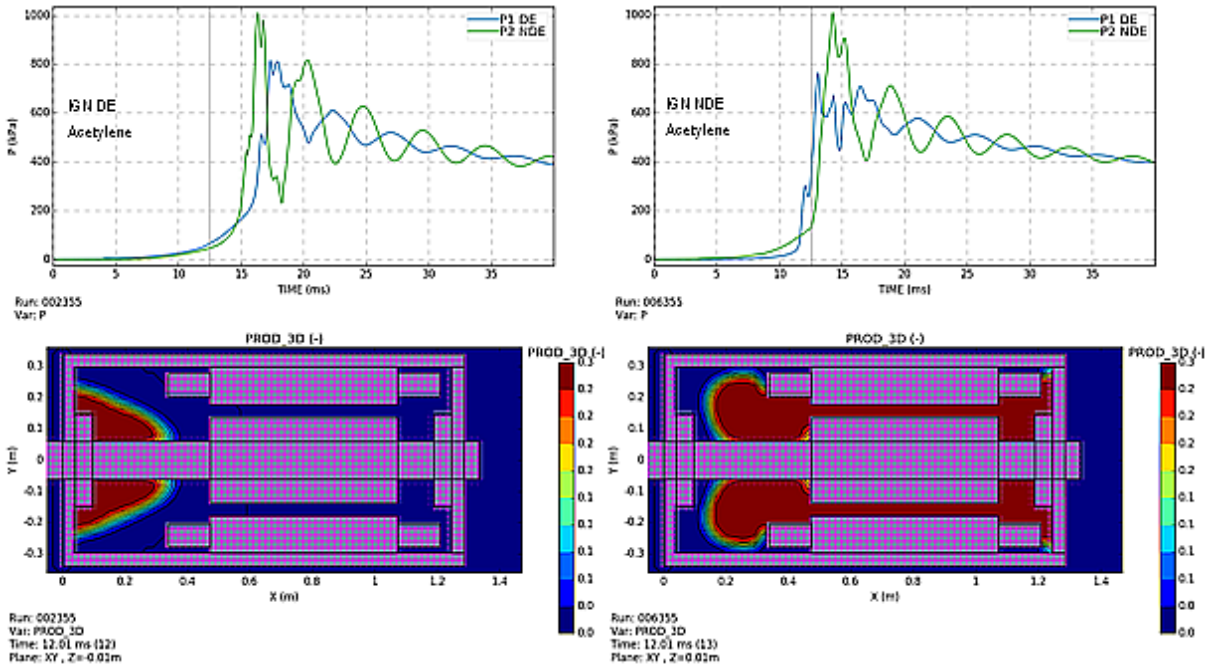


Figure 47 – 355 frame without terminal box - Acetylene

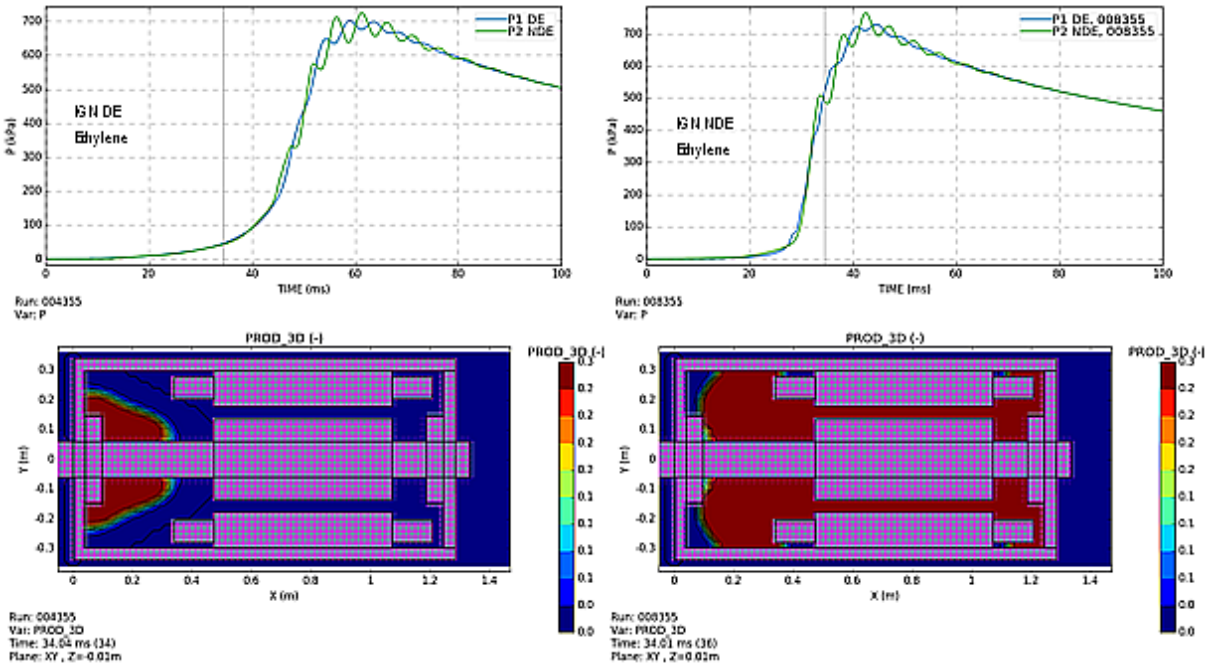


Figure 48 – 355 frame without terminal box - Ethylene

Simulations were also run to investigate the possibility of introducing turbulence into the initial conditions to simulate the situation where the motor is running. Figure 49 shows the results for the pressure-time curves. The solid lines are the pressures for the simulations where there is the initial turbulence, and the dashed lines are the original pressure figures with no initial turbulence. The figures on the left are for ignition at the drive end, and figures on the right are for ignition at the non-drive end. The figures on the first line are for hydrogen, the figures on the next line are for acetylene, and the figures on the last line are for ethylene. It can be seen that in five out of the six cases the presence of turbulence has resulted in higher pressures. In the case of ethylene with the ignition from the non-drive end, the curve is starting to resemble a pressure piling situation.

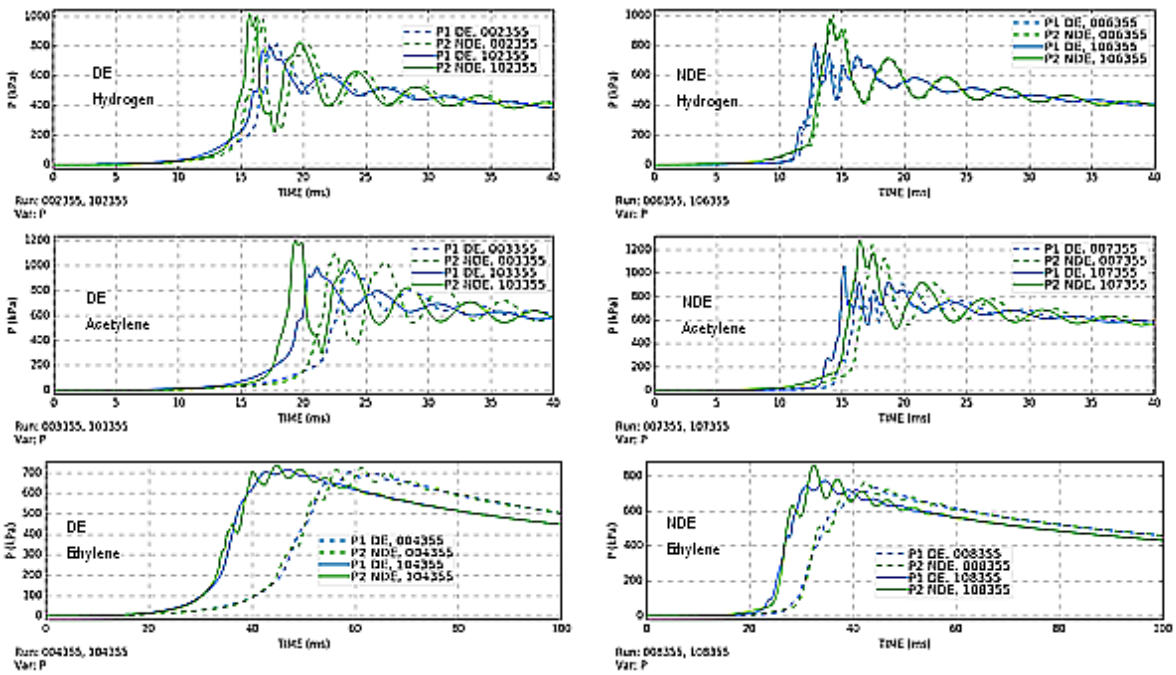


Figure 49 – 355 frame without terminal box - Pressure-time curves showing the effect of turbulence

TABLE 44 shows the maximum pressure figures for each of the above simulations.

TABLE 44 – PRESSURE FIGURES FOR 355 FRAME WITHOUT TERMINAL BOX

Gas	Ignition point	Turbulence?	Max pressure position	Max pressure, kPa
hydrogen	DE	No	NDE	1,009
		Yes	NDE	1,015
acetylene		No	NDE	1,092
		Yes	NDE	1,205
ethylene		No	NDE	724
		Yes	NDE	736
hydrogen	NDE	No	NDE	1,007
		Yes	NDE	976
acetylene		No	NDE	1,237
		Yes	NDE	1,283
ethylene		No	NDE	763
		Yes	NDE	859

10.7.5.2 355 frame with terminal box simulation results

The following figures show the results for the simulation of the 355 frame motor with the terminal box. The pressure-time curves show results with the ignition at the drive end on the left, ignition at the non-drive end in the middle and ignition in the terminal box on the right. Immediately below those are the corresponding 2D cut plane plots showing the product partially consumed by the explosion. Figure 50 is for hydrogen, Figure 51 is for acetylene and Figure 52 is for ethylene. It can be seen that in each case, the explosion develops more quickly when the ignition is at the non-drive end. As found in the simulation of the motor without the terminal box, there is clear evidence of pressure piling for hydrogen and acetylene, but not for ethylene.

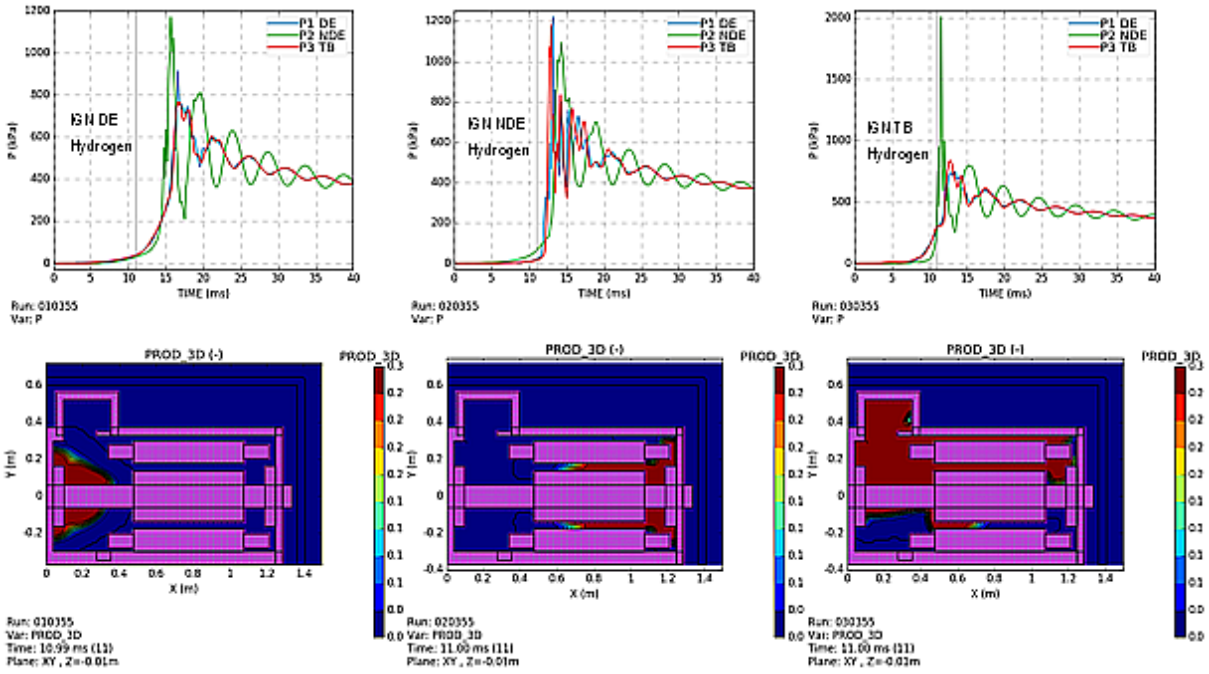


Figure 50 – 355 frame with terminal box - Hydrogen

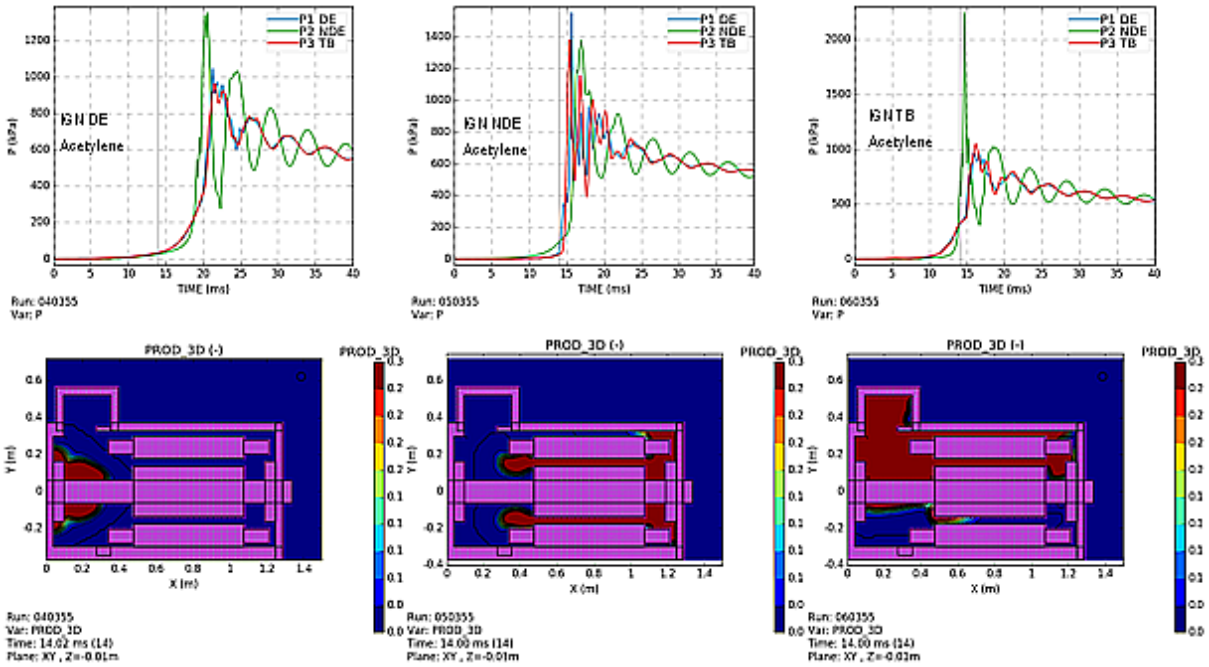


Figure 51 – 355 frame with terminal box - Acetylene

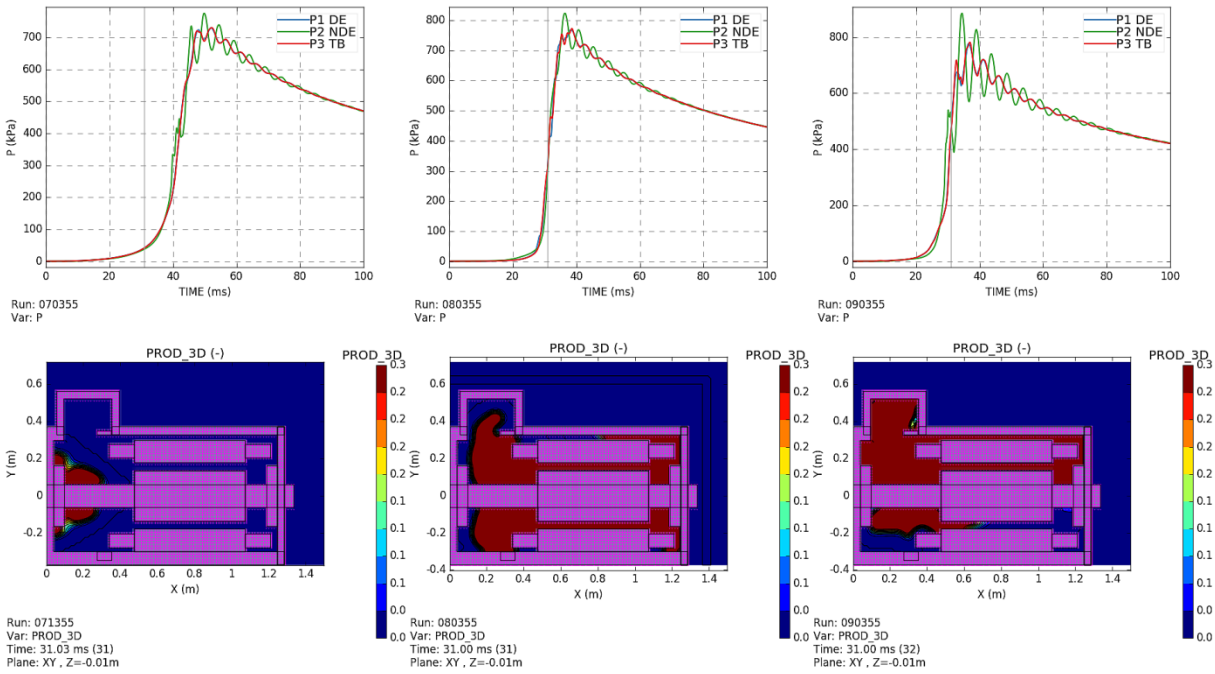


Figure 52 – 355 frame with terminal box - Ethylene

Simulations were again run to investigate the possibility of introducing turbulence in the initial conditions to simulate the situation where the motor is running. Figure 53 shows the results for the pressure-time curves. As before, the solid lines are the pressures for the simulations where there is the initial turbulence, and the dashed lines are the original pressure figures with no initial turbulence. The figures on the left are for ignition at the drive end, the figures in the centre for ignition at the non-drive end and figures on the right for ignition at the terminal box. As above, the figures on the first line are for hydrogen, the figures on the next line are for acetylene and the figures on the last line are for ethylene. In this case, however, the figures with initial turbulence are less than or about the same as those without initial turbulence. While this was not expected, it is not unusual, as can be seen from the data in Chapter 8. This is also reported by Magyari et al [23]. It is the reason that motors are tested at rest and running, because the worst-case situation cannot be predicted.

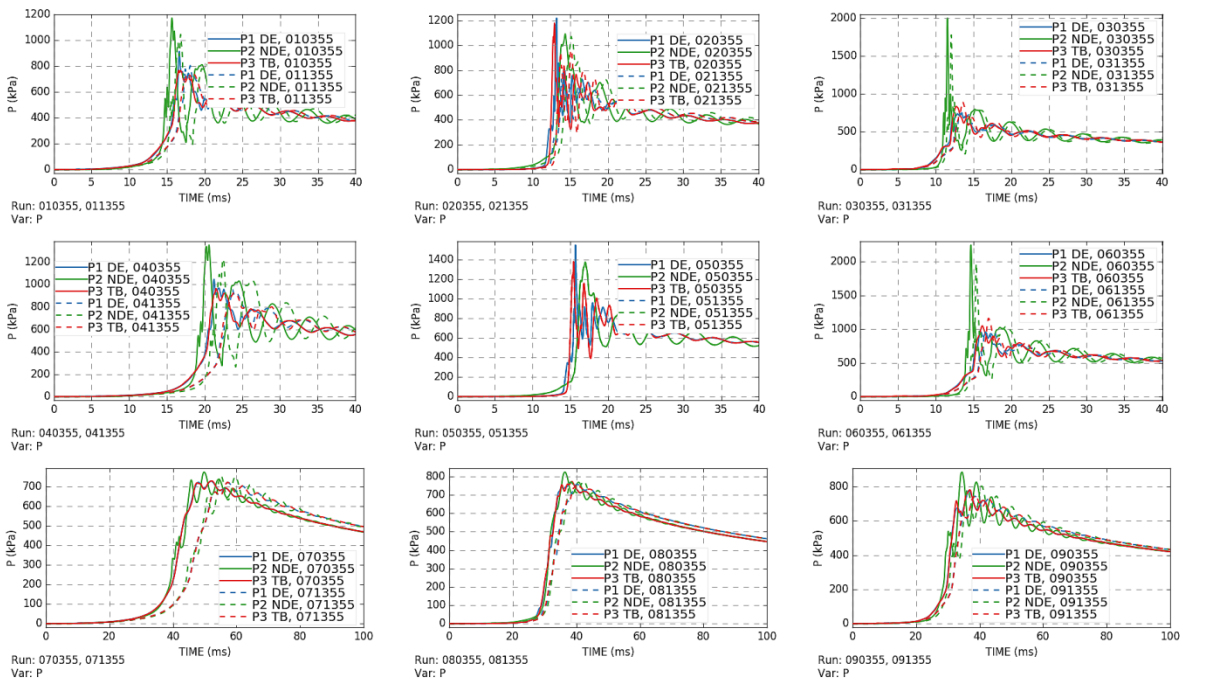


Figure 53 – 355 frame with terminal box - Pressure-time curves showing effect of turbulence

TABLE 45 shows the maximum pressure figures for each of the above simulations.

TABLE 45 – PRESSURE FIGURES FOR 355 FRAME WITH TERMINAL BOX

Gas	Ignition point	Turbulence?	Max pressure position	Max pressure, kPa
hydrogen	DE	No	NDE	1,169
	NDE		DE	1,218
	TB		NDE	2,004
acetylene	DE		NDE	1,351
	NDE		DE	1,547
	TB		NDE	2,243
ethylene	DE		NDE	775
	NDE		NDE	823
	TB		NDE	884
hydrogen	DE	Yes	NDE	1,044
	NDE		NDE	1,072
	TB		NDE	1,782
acetylene	DE		NDE	1,226
	NDE		DE	1,549
	TB		NDE	1,968
ethylene	DE		NDE	757
	NDE		NDE	770
	TB		NDE	803

10.7.5.3 Comparison of 355 frame motor with actual result data

Although this actual motor was not subject to testing, in Chapter 8 there is data for testing of other 355 frame motors. So it is possible to make some comparison with the maximum pressure figures for those motors. TABLE 46 shows the comparison with actual data for Group IIB (for ethylene only) and TABLE 47 show the comparison with actual data for Equipment Group IIC (for hydrogen and acetylene).

TABLE 46 – COMPARISON WITH ACTUAL DATA - IIB

Group IIB - Testing						
Frame size	Maximum pressure					Notes
	Value kPa	Ignition point	Transducer Position	Rotating? (Y/N)	Gas	
355M	1,303.0	NDE	DE	Y	Ethylene	Hydrogen/methane not used
355M/L	4,107.4	DE	NDE	Y	Ethylene	Before potting cable gallery
	1,505.4	NDE	Cable gallery	Y	Ethylene	After potting cable gallery
	1,070.6	NDE	Cable gallery	Y	H_2/CH_4	
355M/L	1,335.0	DE	Under TB	Y	Ethylene	
	729.5	DE	NDE	Y	H_2/CH_4	
Group IIB - FLACS						
With TB? (Y/N)	Maximum pressure					Notes
	Value kPa	Ignition point	Transducer Position	Turbulence? (Y/N)	Gas	
N	763	DE	NDE	N	Ethylene	
N	859	NDE	NDE	Y	Ethylene	
Y	884	TB	NDE	N	Ethylene	
Y	803	TB	NDE	Y	Ethylene	

TABLE 47 – COMPARISON WITH ACTUAL DATA - IIC

Group IIC - Testing						
Frame size	**Maximum pressure**					**Notes**
	Value kPa	**Ignition point**	**Transducer Position**	**Rotating? (Y/N)**	**Gas**	
355S	2,030	NDE	DE	Y	Hydrogen	
	2,300	NDE	DE	Y	Acetylene	
355	996	TB DE	DE TB	N	Hydrogen	Same in both scenarios
	1,992	DE	TB	N	Acetylene	
355L	1,999	DE	NDE	N	Hydrogen	
	2,144	NDE	DE	N	Acetylene	
Group IIC - FLACS						
With TB? (Y/N)	**Maximum pressure**					**Notes**
	Value kPa	**Ignition point**	**Transducer Position**	**Turbulence? (Y/N)**	**Gas**	
N	1,009	DE	NDE	N	Hydrogen	
N	1,015	DE	NDE	Y		
N	1,237	NDE	NDE	N	Acetylene	
N	1,283	NDE	NDE	Y		
Y	2,004	TB	NDE	N	Hydrogen	
Y	803	TB	NDE	Y		
Y	2,243	TB	NDE	N	Acetylene	
Y	1,968	TB	NDE	Y		

10.7.5.4 Discussion on results for 355 frame motor

For the Group IIB testing with ethylene, the maximum pressure was slightly higher when testing with the terminal box version and the scenario that produced the highest pressure involved ignition at the terminal box. However, for both versions, the pressures obtained with ethylene were at least 30% lower than those obtained with actual testing. But as noted earlier, there was little evidence of pressure piling in the FLACS scenarios for ethylene, but there was pressure piling in the actual testing. This appears to be an anomaly and would benefit from future investigation.

For the Group IIC testing with hydrogen and acetylene, the maximum pressures obtained provided very good correlation with those obtained from actual testing. The maximum figure for hydrogen from the three motors tested was 2,030 kPa, and the maximum figure for hydrogen from the simulation for the motor with the terminal box was 2,004 kPa. The maximum figure for acetylene from the three motors tested was 2,300 kPa, and the maximum figure for acetylene from the simulation of the motor with the terminal box was 2,243 kPa. The results are shown in TABLE 48. While the results are extremely encouraging, it should be noted that actual testing results with this particular design of motor is likely to have produced different results again. But it is encouraging to note that the results produced from the simulation correlate closely to the maximum of the figures from the testing of the three motors. This is likely to be the most useful pressure figure to ensure a manufacturer could be reasonably confident this is would cover different options in a particular frame size. It should be noted, however, that the artificial increase in air gap for the simulation means the actual air gap was not modelled. Using different sizes for this artificially large air gap might also produce some different results. It would be useful to explore this as part of further research.

So in summary, it appears that for a motor of this size, even with the current limitations within FLACS related to grid size, good correlations can be obtained for motors designed for Group IIC applications. But the results being obtained for Group IIB applications using ethylene indicate that further investigation will be required.

TABLE 48 – COMPARISON OF MAXIMUM FIGURES - IIC

Gas	Maximum pressure, kPa	
	Test data (from 3 models)	Motor with terminal box
Hydrogen	2,030	2,004
Acetylene	2,300	2,243

10.8 Simulation of proficiency testing artefact

10.8.1 Geometry build for artefact

10.8.1.1 Introduction

As shown in Chapters 4 and 5, the PTB proficiency testing artefact was used for testing with hydrogen and methane at extremely low ambient temperatures. Since this artefact has a less complex geometry than a motor, it was decided it might provide a good validation exercise to see whether correlation in pressures could be obtained with actual testing. As testing at normal ambient explosion pressures for the artefact had not been done at normal temperatures, only correlation for testing at low temperatures could be carried out.

The artefact is shown in Figure 16 but is reproduced here in Figure 54 for convenience.

Figure 54 – Exploded view of the artefact

Initially, the simple geometry build approach was used to build the artefact. However, when it was found that a range of options for the geometry would be necessary to deal with porosity and grid size, it was decided to use the more complex geometry building with the use of objects to make it easier to try variations for the orifice plate. It was found the orifice plate had two problems; the first was the thickness of the plate which, if too thin, could permit passage of gas and explosion from one chamber to the other, and the second the size of the orifice itself which, if too small, could prevent passage of an explosion. Hence simulations were run with different sizes of the orifice and different thicknesses of the orifice plate. The sizes used impacted on the grid sizes that could be used. The following were the three options used:

a) 40 mm orifice and 40 mm thick orifice plate - 15 mm grid size

b) 30 mm orifice and 40 mm thick orifice plate - 20 mm grid size

c) 15 mm orifice and 10 mm thick orifice plate - 10 mm grid size

For each, it was necessary to carefully centre one grid square in the orifice to ensure there was no blockage of the explosion. However, due to the partial porosities of the grid around the hole and the stepped nature of that hole, accurate representation of the hole was not possible for any of the scenarios. The three options are discussed in more detail below.

10.8.1.2 Option a) 40 mm orifice and 40 mm thick orifice plate - 15 mm grid size

Option a) above had two major compromises; the orifice was larger than in practice, and the grid size was smaller than recommended. However, it did produce an orifice that more closely represented a circle (albeit with stepped walls).

The following figures show the final geometry of that artefact with a 40 mm hole for the orifice, as follows:

- Figure 55 shows the XY view with the porosities and demonstrates that there is a clear hole through the orifice (grid cell is white, not grey).

- Figure 56 shows the orifice in a YZ view and also shows one grid cell through the centre of the orifice is clear (zero area blockage in each dimension).
- Figure 57 shows the porosity around the cylinder and the stepped walls that have resulted.

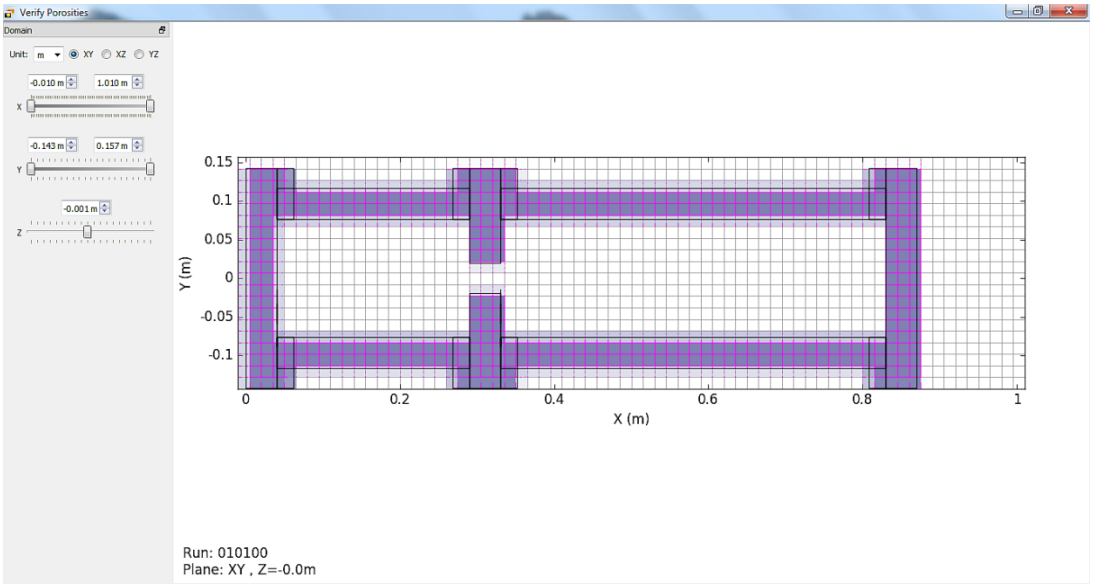


Figure 55 – Artefact XY view

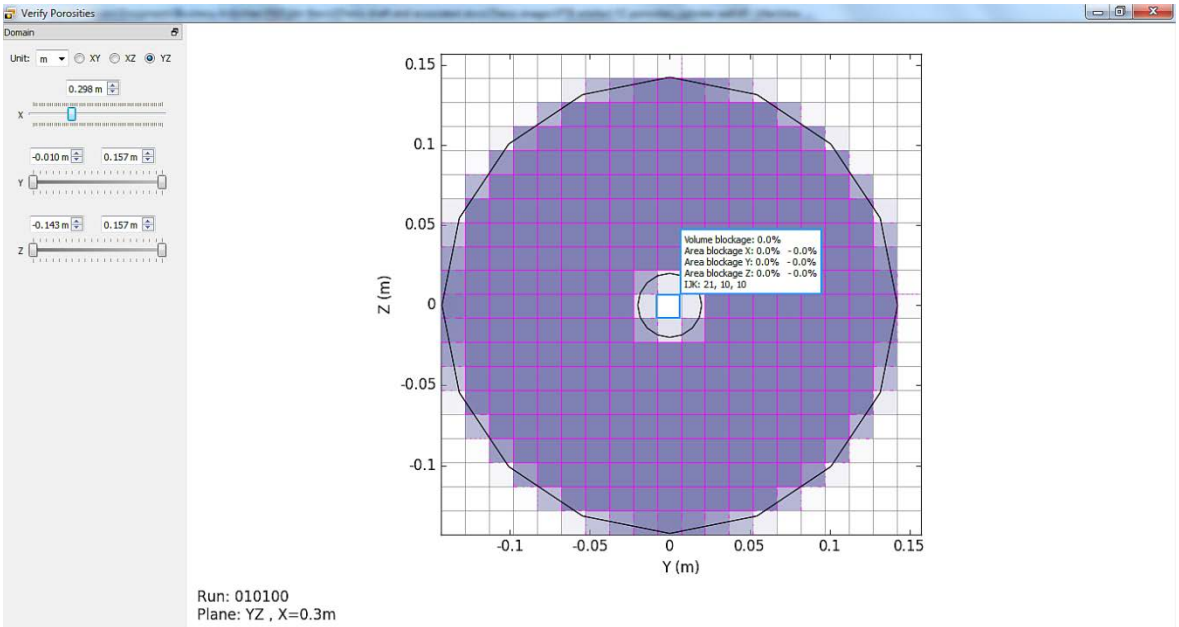


Figure 56 – Artefact YZ view - orifice

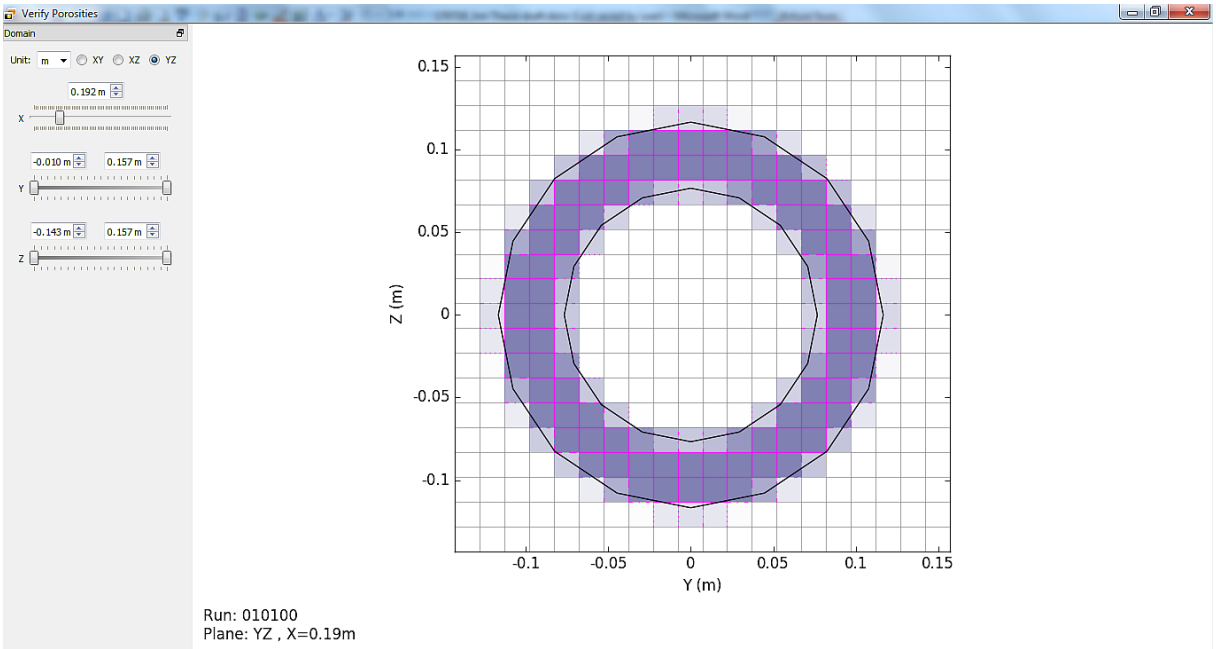


Figure 57 – Artefact YZ view - cylinder wall

10.8.1.3 Option b) 30 mm orifice and 40 mm thick orifice plate - 20 mm grid size

Figure 58 shows three of the porosity views for the option b) with the squares representing the grid. On the top left there is the YZ plane at the orifice plate showing grid centred on the orifice with zero blockage. The top right shows the YZ plane with the wall of the cylinder with dark grid cells having zero porosity, that is allowing no passage of gas or explosion. The bottom shows the XZ view again showing the open orifice.

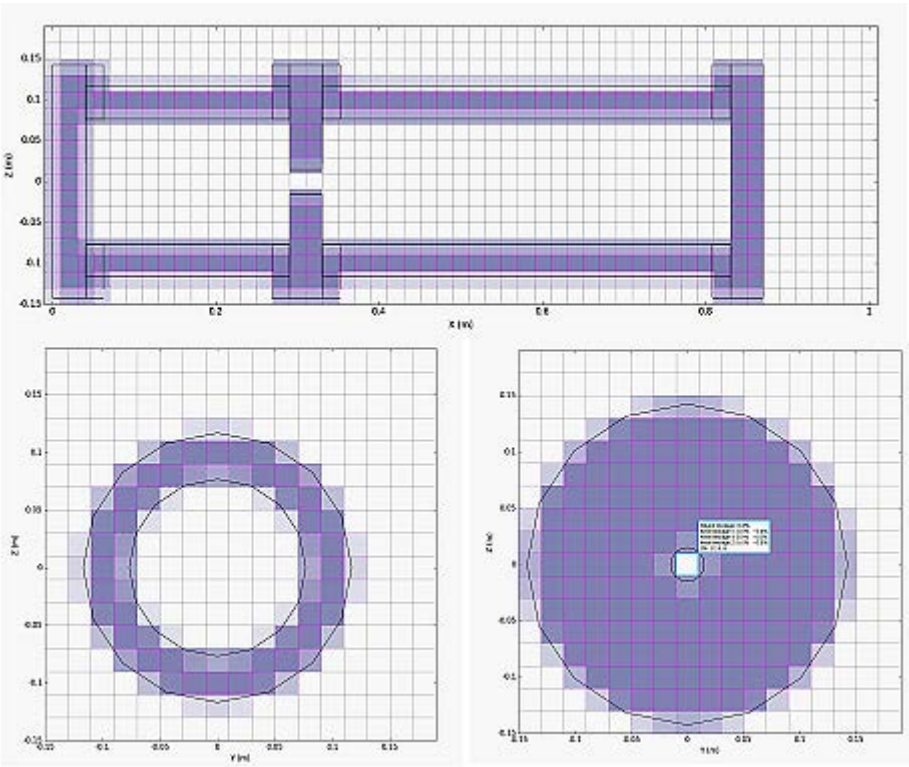


Figure 58 – 30 mm orifice & 40 mm thick orifice plate - 20 mm grid size

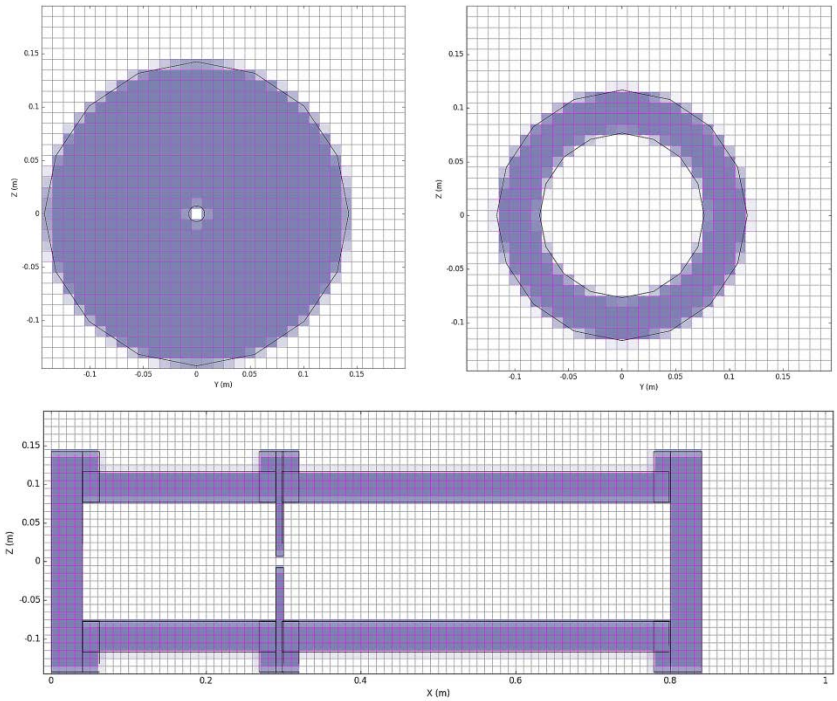


Figure 59 – 15 mm orifice & 10 mm thick orifice plate - 10 mm grid size

10.8.1.4 Option c) 15 mm orifice and 10 mm thick orifice plate - 10 mm grid size

Similar to option b) above, Figure 59 above shows three of the porosity views for the option c) with 15 mm orifice and 10 mm thick orifice plate. On the top left there is the YZ plane at the orifice plate showing the grid centred on the orifice with zero blockage. The top right shows the YZ plane with the wall of the cylinder with dark grid cells having zero porosity, that is allowing no passage of gas or explosion. The bottom shows the XZ view again showing the open orifice and blockage by the orifice plate.

10.8.2 CASD view of artefact with 40 mm orifice

Figure 60 shows the artefact with the 40 mm orifice as displayed in CASD in semi-transparent mode. Thus it is possible to see the orifice within the artefact.

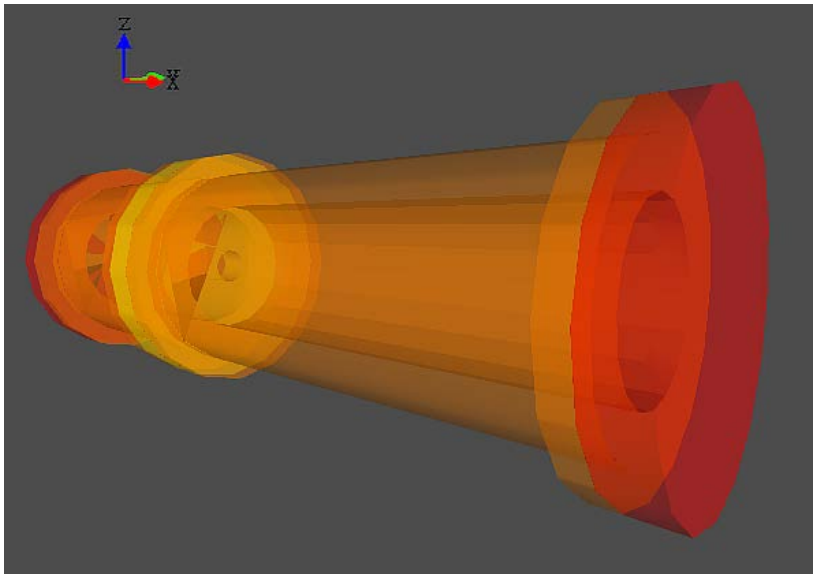


Figure 60 – PTB artefact in CASD

10.8.3 Scenarios for artefact

The "Gas explosion" scenario was used. The position of the pressure transducers and ignition source were the same as that used in the tests described in Chapters 4 and 5. The

rest of the scenario parameters were similar to those used for motors above with simulations being done with both hydrogen and methane. The simulations were carried out at temperatures of +20, -20, -40, -50 and -60 °C for each gas. The key parameters and locations of the ignition source and pressure transducers are shown in TABLE 49 below.

TABLE 49 – PARAMETERS FOR SCENARIOS FOR PTB ARTEFACT

Information/parameters		Data (dimensions in m)
TEMPLATE_NAME (Scenario)		Gas explosion
MONITOR_POINTS (Pressure transducer coordinates: x, y, z)	P-A on Chamber A	0.045, 0, 0
	P-B on Chamber B	0.825, 0, 0 (changed to 0.795 for 10 mm thick orifice plate)
POSITION_OF_IGNITION_REGION	Located at the end of Chamber B	0.825, 0.05, 0 (changed to 0.795
SINGLE_FIELD_3D_OUTPUT		NP, NPROD, NFMOLE, NT
SIMULATION_AND_OUTPUT_CONTROL	TMAX	0.04 for hydrogen and 0.1 for methane
	KEYS	“RADIATE=04”
	DTPLOT	0.001
	HEAT_SWITCH	On (Set to 1)
INITIAL_CONDITIONS		+20, -20, -30, -40, -50 and -60 °C
GAS_COMPOSITION_AND_VOLUME	POSITION_OF_FUEL_REGION	0, -0.13, -0.13
	DIMENSION_OF_FUEL_REGION	0.9x0.3x 0.3

TABLE 50 – RESULTS FOR 30 MM AND 15 MM ORIFICES

Grid size, mm	Orifice, mm	Gas	Maximum time, s	Initial temperature, °C	Pressure from simulation, kPa	
					Chamber A	Chamber B
0.02	30 diameter, 40 thick	Hydrogen	0.04	20	1,590	593
				-20	1,891	686
				-30	2,002	711
				-40	2,120	740
				-50	2,238	777
				-60	2,364	818
0.02	30 diameter, 40 thick	Methane	0.1	20	1,193	553
				-20	1,259	679
				-30	1,280	713
				-40	1,307	755
				-50	1,337	800
				-60	1,375	851
0.01	15 diameter, 10 thick	Hydrogen	0.04	20	1,580	653
				-20	1,770	759
				-30	1,804	795
				-40	1,846	830
				-50	1,869	867
				-60	1,884	918
0.01	15 diameter, 10 thick	Methane	0.1	20	897	652
				-20	1,080	749
				-30	1,135	778
				-40	1,193	806
				-50	1,263	813
				-60	1,335	840

10.8.4 Results for artefact

The most promising results were for:

- 30 mm hole and 40 mm thick orifice plate with 20 mm grid; and
- 15 mm hole and 10 mm thick orifice plate with 10 mm grid

The first used a grid size that did not violate the FLACS rules. But it had a hole larger than the actual artefact orifice and an orifice plate that was 22 mm thicker than the actual plate. The second had the actual diameter of the artefact orifice and the thickness only 2 mm larger than the thickness of the orifice plate. But had a grid size that was less than recommended for FLACS. So both were still a compromise.

The results for both scenarios are shown in TABLE 50 above and the figures below. A discussion of the results is provided in 10.8.5.

Figure 61 shows the separate traces for each temperature for the simulation with hydrogen for the 30 mm hole and 20 mm grid size.

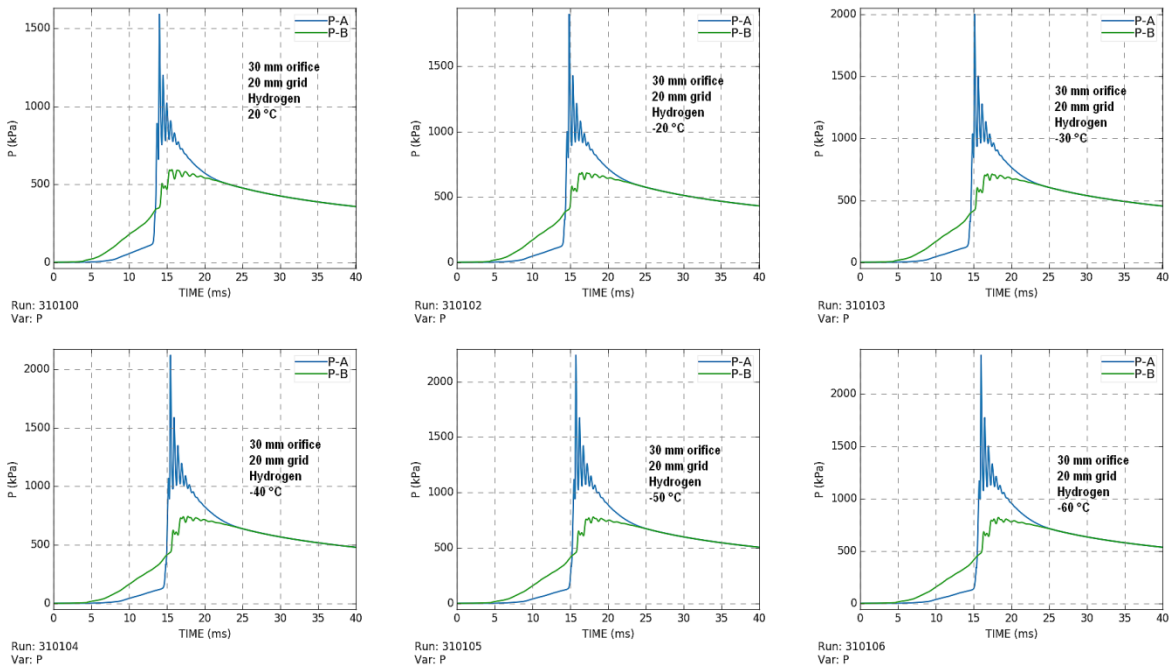


Figure 61 – 30 mm hole and 20 mm grid - Hydrogen (separate)

Figure 62 includes the same traces on the one chart, and the linear increase in pressure with decreasing pressure can be clearly seen. This is consistent with the published research and the research carried out under this PhD project.

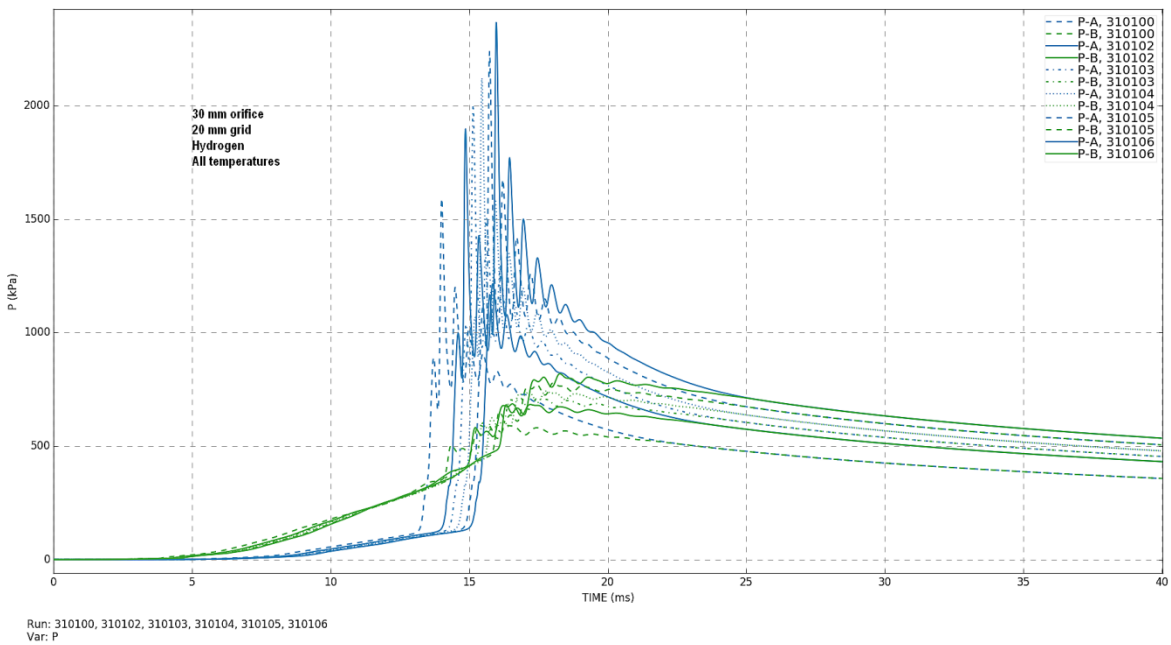


Figure 62 – 30 mm hole and 20 mm grid - Hydrogen (together)

Figure 63 shows the separate traces for each temperature for the simulation with methane for the 30 mm hole and 20 mm grid size.

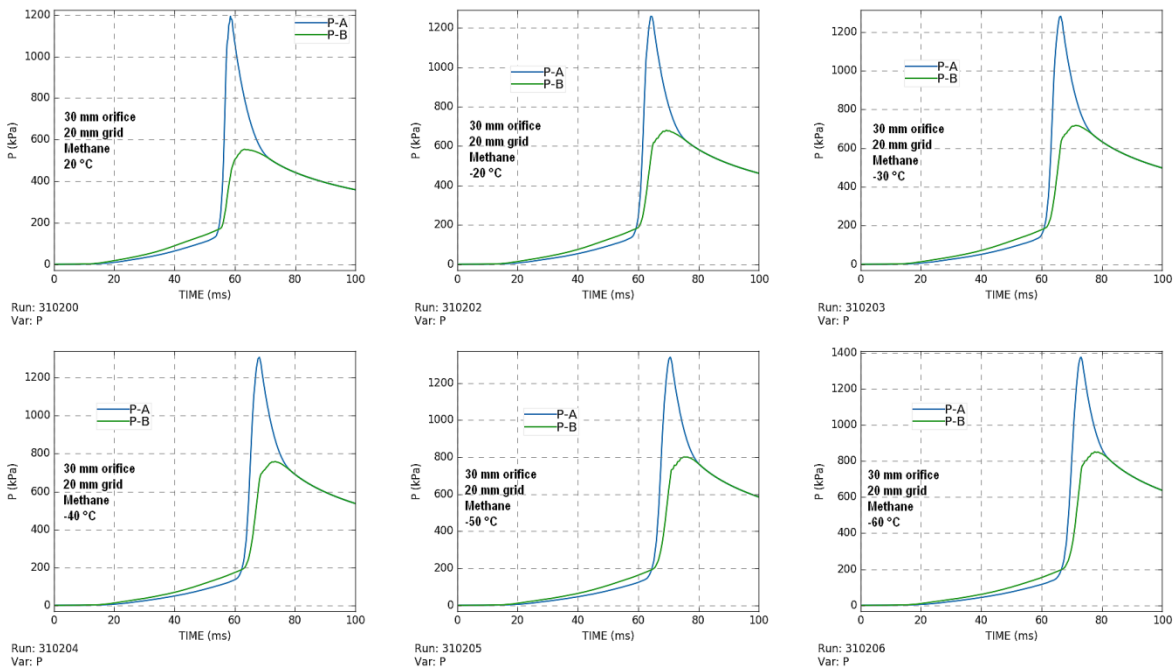


Figure 63 – 30 mm hole and 20 mm grid - Methane

Figure 64 shows the separate traces for each temperature for the simulation with hydrogen for the 15 mm hole and 10 mm grid size.

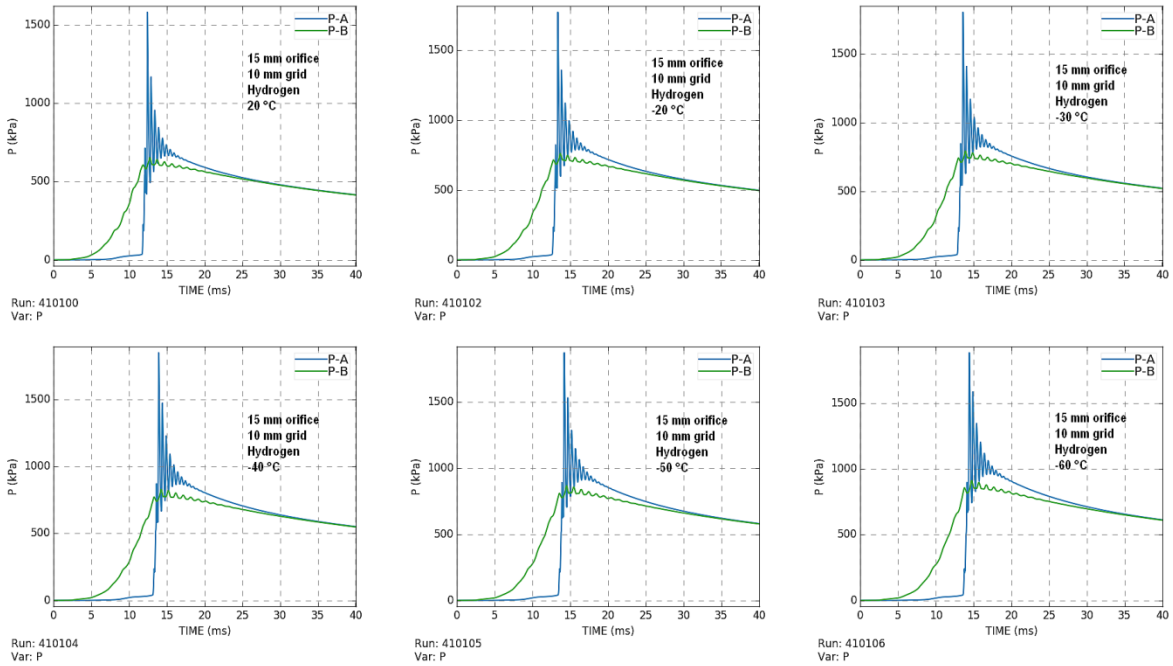


Figure 64 – 15 mm hole and 10 mm grid - Hydrogen

Figure 65 shows the separate traces for each temperature for the simulation with methane for the 15 mm hole and 10 mm grid size.

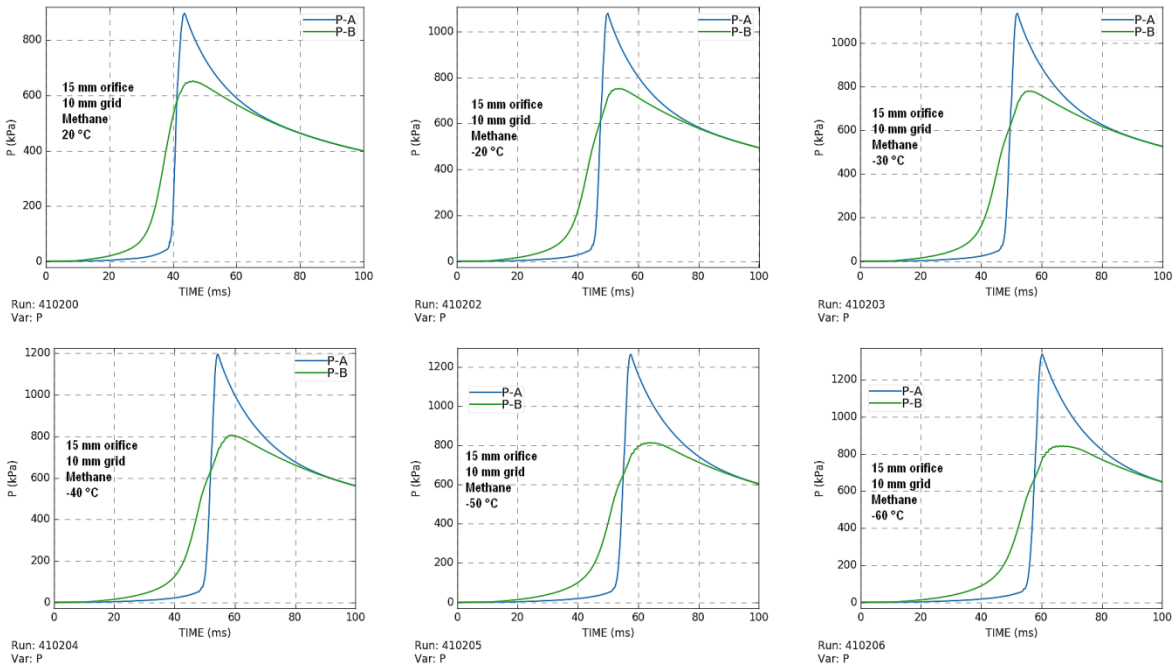


Figure 65 – 15 mm hole and 10 mm grid - Methane

TABLE 51 – RESULTS FOR 30 MM AND 15 MM ORIFICES COMPARED TO TESTING

Grid size, mm	Orifice, mm	Gas	Max time, s	Initial temp, °C	Pressure from simulation, kPa		Pressure from testing, kPa			
					Chamber A	Chamber B	Chamber A, Max	Chamber A, Ave	Chamber B, Max	Chamber B, Ave
0.02	30 diam, 40 thick	Hydrogen	0.04	20	1,590	593				
				-20	1,891	686	1,830	1,623	940	869
				-30	2,002	711	1,836	1,741	940	906
				-40	2,120	740	2,090	1,921	1,172	1,071
				-50	2,238	777	2,058	2,027	1,422	1,250
				-60	2,364	818	2,112	2,004	1,422	1,257
0.02	30 diam, 40 thick	Methane	0.1	20	1,193	553				
				-20	1,259	679	1,806	1,769	518	510
				-30	1,280	713	1,900	1,811	504	493
				-40	1,307	755	2,004	1,913	559	527
				-50	1,337	800	2,059	2,030	592	566
				-60	1,375	851	2,171	2,024	609	568
0.01	15 diam, 10 thick	Hydrogen	0.04	20	1,580	653				
				-20	1,770	759	1,830	1,623	940	869
				-30	1,804	795	1,836	1,741	940	906
				-40	1,846	830	2,090	1,921	1,172	1,071
				-50	1,869	867	2,058	2,027	1,422	1,250
				-60	1,884	918	2,118	2,004	1,422	1,257
0.01	15 diam, 10 thick	Methane	0.1	20	897	652				
				-20	1,080	749	1,806	1,769	518	510
				-30	1,135	778	1,900	1,811	504	493
				-40	1,193	806	2,004	1,913	559	527
				-50	1,263	813	2,059	2,030	592	566
				-60	1,335	840	2,171	2,024	609	568

TABLE 51 above compares the simulation results with the actual results obtained during testing.

Figure 66 shows the pressure waveforms for the actual testing with hydrogen at a temperature of -20 °C The wave-forms can be compared with those for the simulation results for the 30 mm and 15 mm orifices with hydrogen at the same temperature in Figure 67 and Figure 68 respectively.

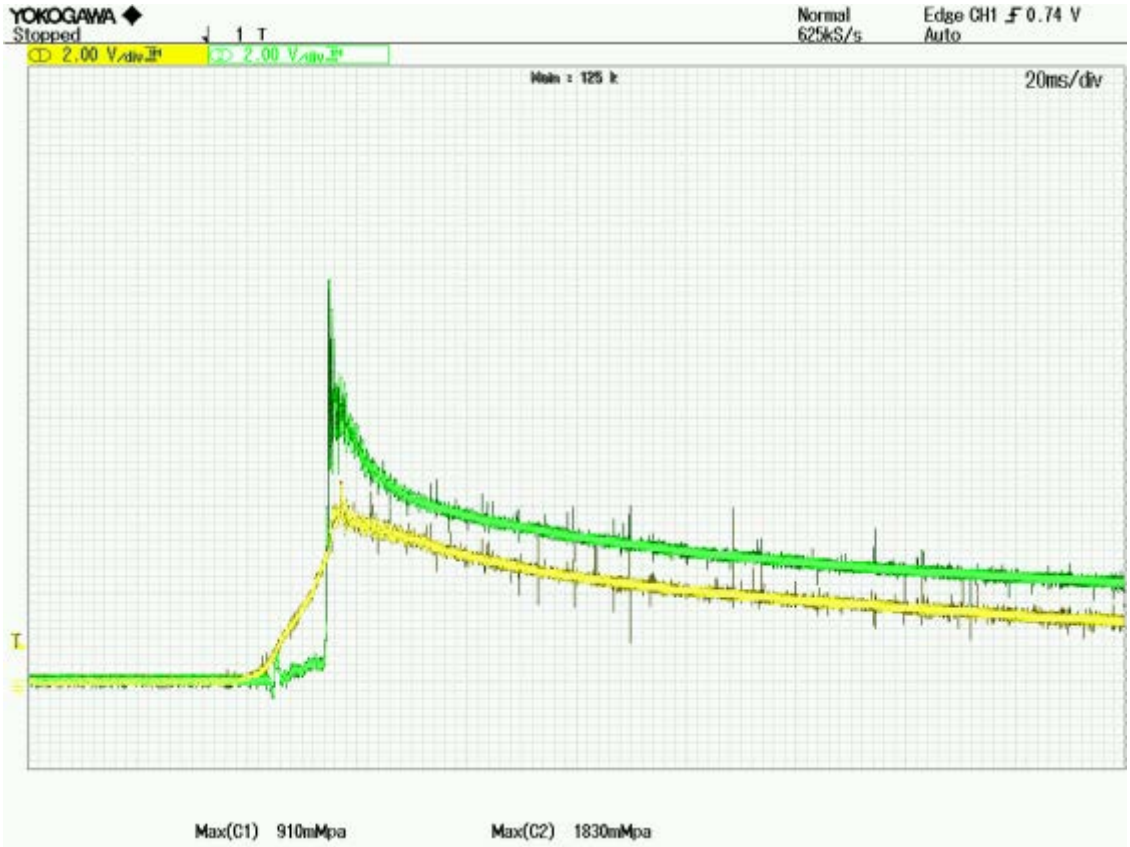


Figure 66 – Test of artefact with hydrogen at -20 °C

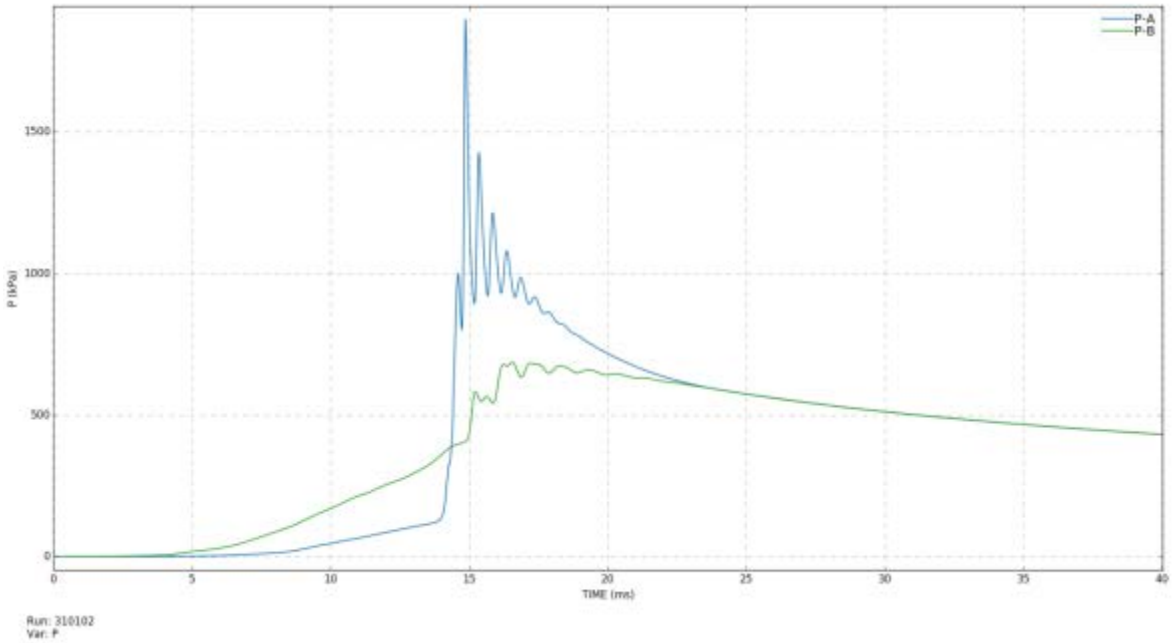


Figure 67 – Simulation with 30 mm orifice at -20 °C

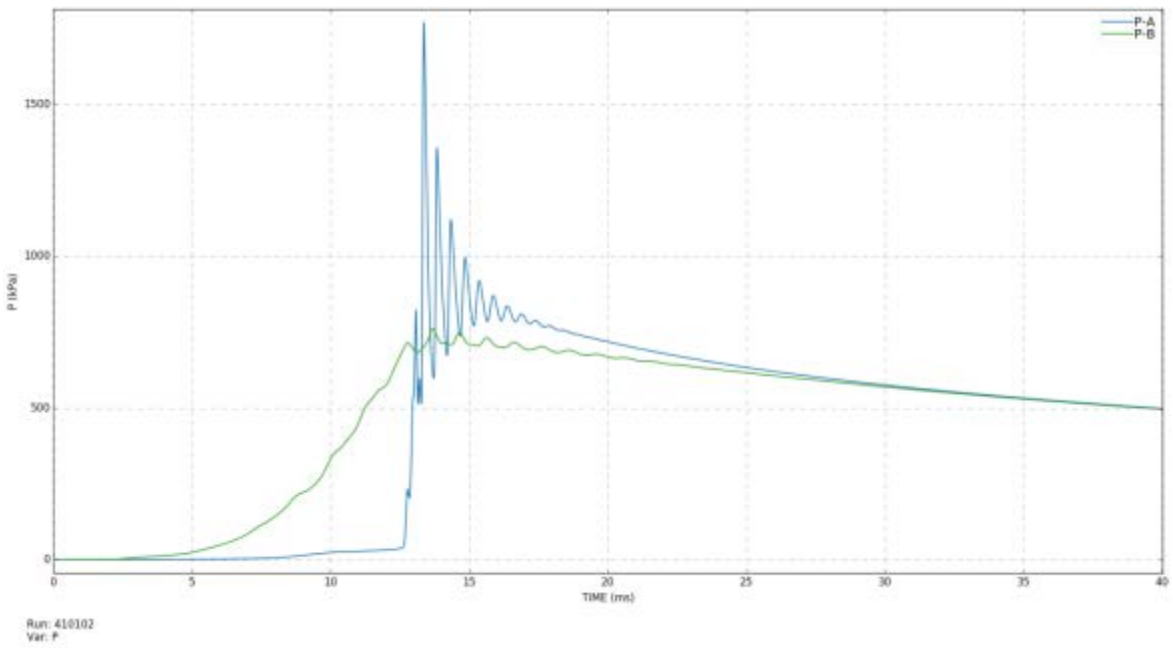


Figure 68 – Simulation with 15 mm orifice at -20 °C

It is also possible to view the correlation of the results graphically. Figure 69 shows the comparison of the test and simulation results for hydrogen and Figure 70 shows the comparison the test and simulation results for methane.

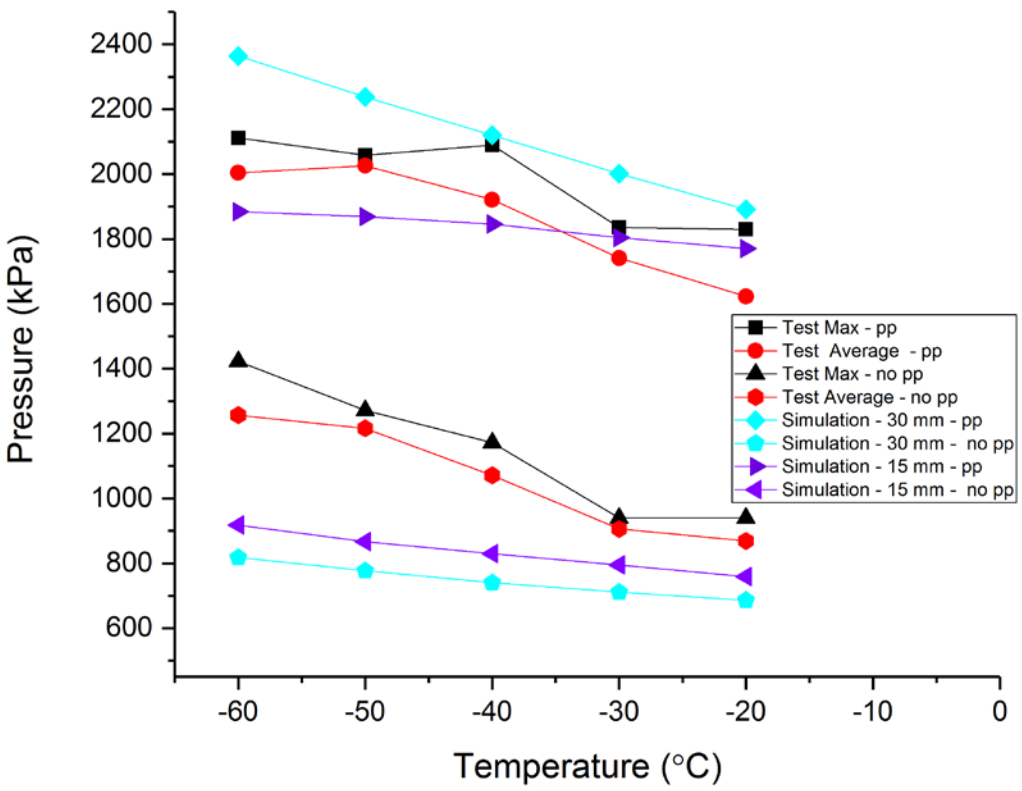


Figure 69 – Comparison of test and simulation results for hydrogen

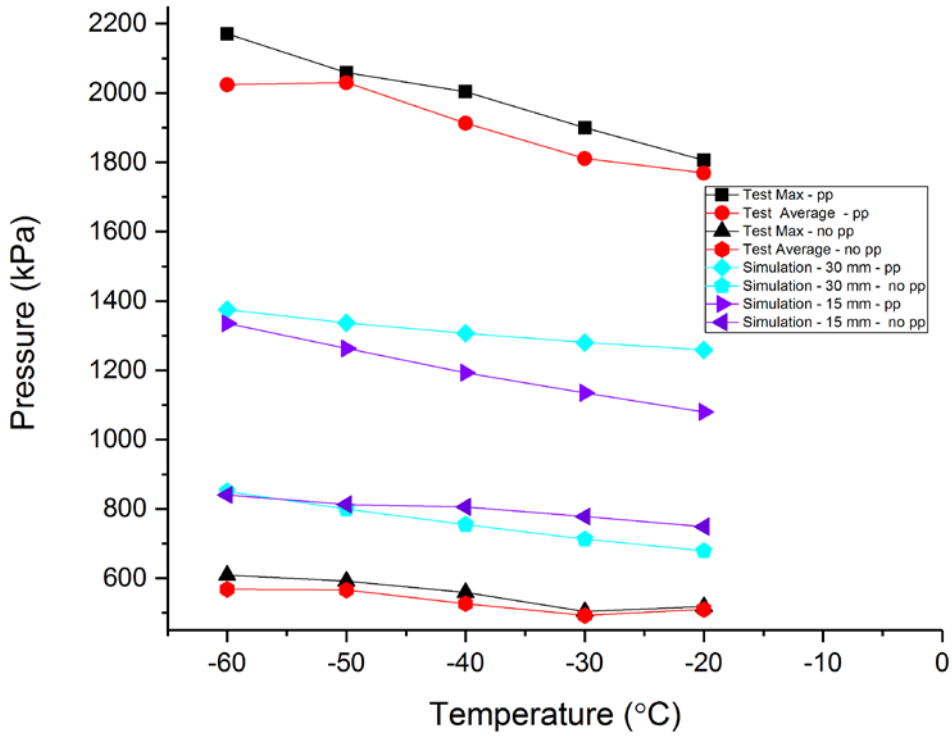


Figure 70 – Comparison of test and simulation results for methane

10.8.5 Discussions on artefact simulation results

It can be seen from the preceding results that there are some areas of reasonable agreement between the simulation results and those from actual testing. Some of the positive results include:

- The waveforms for hydrogen shown above in Figure 66, Figure 67 and Figure 68 show quite a good correlation in the shape for both orifice sizes.
- The pressure piling results using hydrogen were reasonably close to the experimental results with the 30 mm orifice providing higher pressures the 15 mm orifice.
- For most results, there was reasonable similarity between the two different orifice sizes with the 30 mm orifice giving higher results for the pressure piling scenario and mostly lower results for the no pressure piling scenario.

However, there were also some significantly different results, for example:

- The pressure piling results for methane were significantly less than those obtained when testing
- Conversely, the methane results for non-pressure piling situation were higher than those obtained when testing

It should also be noted that, based on the results from PTB for hydrogen with higher pressures for pressure piling and lower figures for no pressure piling, the results look even better.

It is of interest to compare the above results with those obtained by Lars Rogstadkjernet, as discussed in his PhD thesis [34]. His simulations were carried out using grid cells ranging from 5 to 20 mm. He found the 5 mm cells provided the fastest combustion. His results were also carried out using hydrogen and methane. The results he obtained with the double chamber look comparable to the results presented here. He did not show his results for methane with a double chamber. He also reported that 4 mm holes always provided quenching of methane. This was consistent with the results that were obtained in 3.8 when trying to obtain transmission through the nozzles using methane. I had the opportunity to

discuss Rogstadkjernet's research with him when I was visiting Gexcon in Norway (personal communication, 23 June 2017). He indicated there were problems with the flame speed when he produced his results and that one mechanism he used to adjust this in order to get better results was to vary the mixture from the stoichiometric mix to slow down the flame speed. This was not attempted for the simulations reported on here, but may well have provided improved results, particularly in the case of methane where there was pressure piling.

So in summary, probably the most accurate comment that can be made on the results is that they are promising. But it needs to be recognised in this exercise, as discussed earlier, that neither of the two scenarios reported on here fulfils all the requirements of compliant geometry and operation within the stated capabilities of FLACS.

10.9 Simulation of 160 frame motor (including terminal box)

10.9.1 Geometry build for 160 frame motor

In building the geometry of the 160 frame motor the template developed for the 355 frame motor was used with the dimensions adjusted appropriately. For this motor, there was a terminal box but no cableway. The resulting design is shown in CASD in Figure 71. The figure shows the design with the ignition at the drive end. Ignition was also done at the non-drive end and the terminal box. This model shows transducers in four positions as indicated in the figure. The reason for placing two transducers in the terminal box was to test the claim in the FLACS manual that the side-on transducer would not measure dynamic pressure as well as one that is facing the pressure wave. The results of this test indicated only slightly higher pressures for the pressure position P3-TOP at the top of the terminal box compared with P4 - TB SIDE on the side of the terminal box. This may have partly been due to the way the explosion propagated as shown in Figure 72. In view of this, it was decided to carry out all simulations with only the pressure transducer on the side of the terminal box to replicate the position that was used for actual testing. This transducer then became designated P3 – TB for the series of tests.

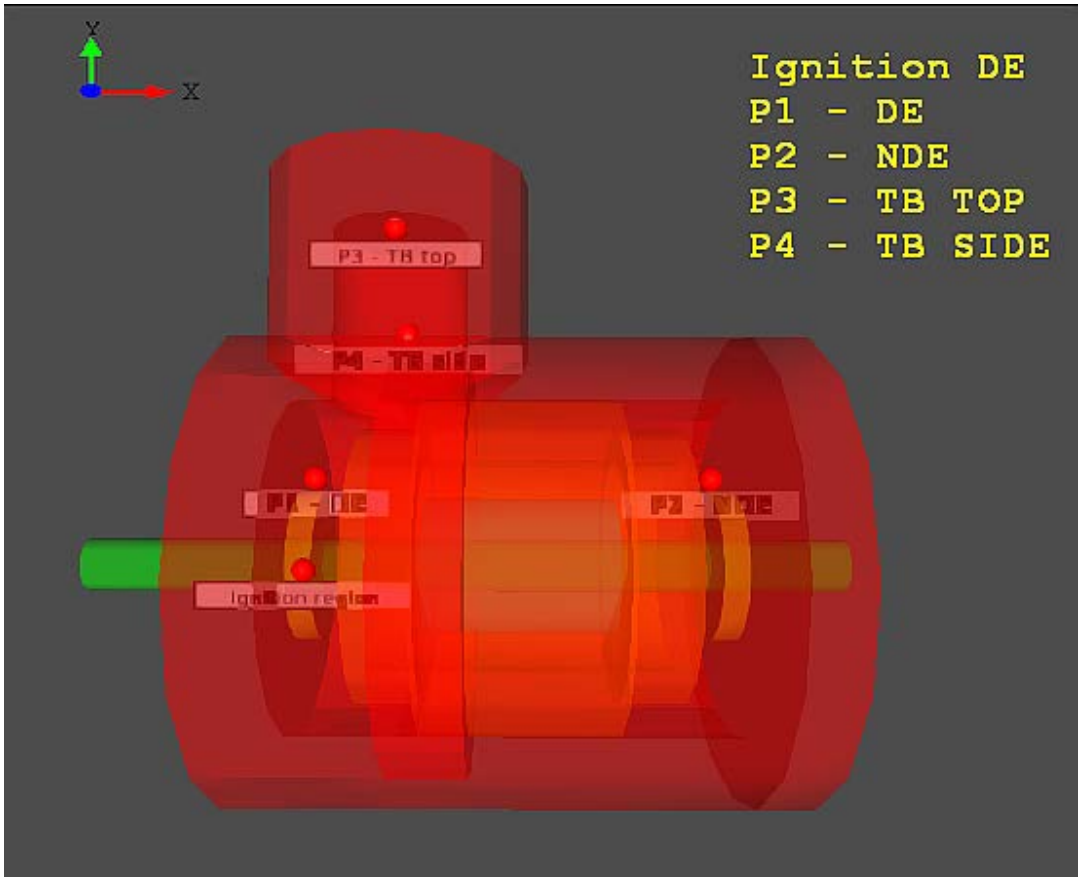


Figure 71 – 160 frame motor in CASD

The key parameters and locations of the ignition source and pressure transducers are shown in TABLE 52.

TABLE 52 – PARAMETERS FOR SCENARIOS FOR 160 FRAME MOTOR

Information/parameters		Data (dimensions in m)
TEMPLATE_NAME (Scenario)		Gas explosion
Grid size		0.015
MONITOR_POINTS (Pressure transducer coordinates: x, y, z)	P1 DE	0.041, 0.07, 0
	P2 NDE	0.37, 0.07, 0
	P3 TB	0.117, 0.22, -0.054
POSITION_OF_IGNITION_REGION (Ignition source coordinates: x, y, z)	DE	0.05, 0, 0.08
	NDE	0.371, 0, 0.0.08
	TB	0.117, 0.22, 0.05
SINGLE_FIELD_3D_OUTPUT		NP, NPROD, NFMOLE, NT
SIMULATION_AND_OUTPUT_CONTROL	TMAX	0.04 for hydrogen and acetylene, 0.1 for ethylene
	KEYS	“RADIATE=04”
	DTPLOT	0.001
	HEAT_SWITCH	On (Set to 1)
GAS_COMPOSITION_AND_VOLUME	POSITION_OF_FUEL_REGION	0, -0.185, -0.185
	DIMENSION_OF_FUEL_REGION	0.5x0.5x0.4

10.9.2 Scenarios for 160 frame motor

The initial scenarios for the 160 frame motor were the same as for the 355 frame motor. However, it was also possible to introduce scenarios for a range of temperatures covering the +20 °C, -20 °C, -40 °C and -60 °C as these had also been done with the testing. The simulations were also run for the same range of gases, ie with hydrogen, acetylene, ethylene, and in addition, a mix of hydrogen 85/methane 15, using all of the temperatures shown. As this motor had only been tested stationery, no turbulence was introduced into the initial conditions.

10.9.3 Results for 160 frame motor simulations

Results for the above simulations are discussed below.

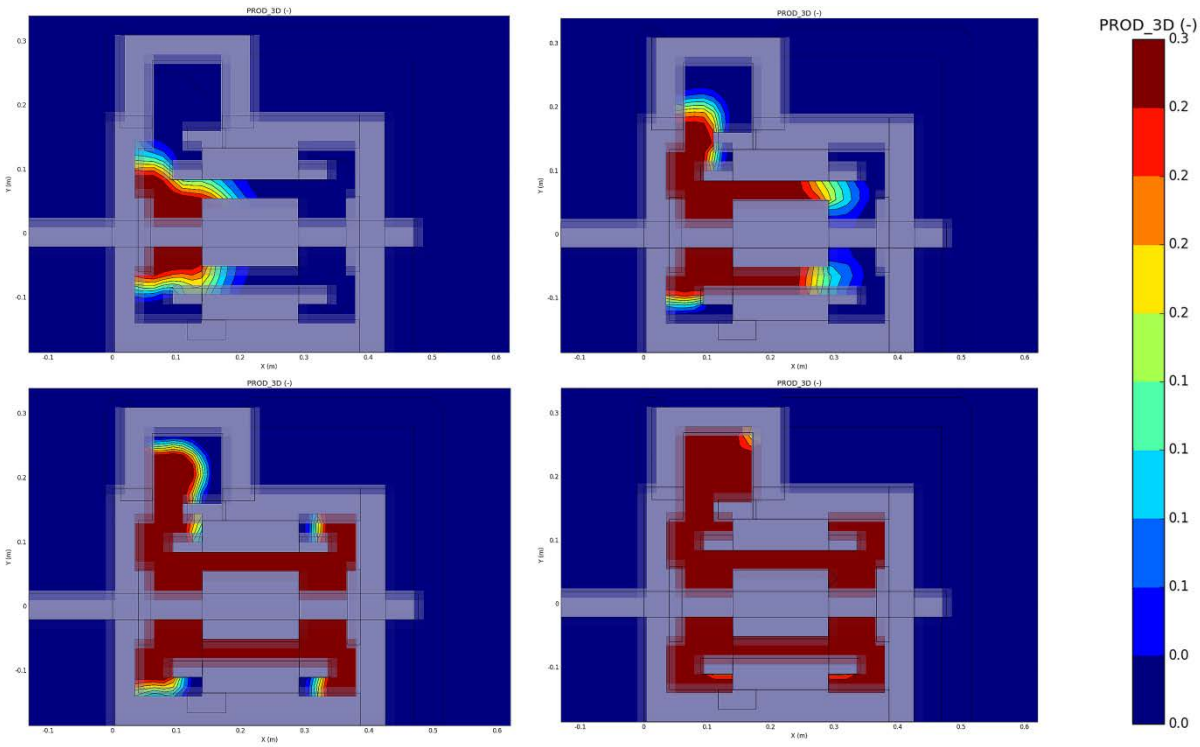


Figure 72 – Explosion development in 160 frame motor

Figure 72 above shows the development of the explosion through the motor, starting on the top left. The figure shows the consumption of the hydrogen/air mixture by means of the explosion.

TABLE 53 shows the explosion pressure results for this exercise.

TABLE 53 – RESULTS FROM 160 FRAME SIMULATION

Gas	% with air	Initial temp, °C	Pressure from FLACS		
			Ignition	Transducer	Max pressure, kPa
Hydrogen	31	20	NDE	TB	1,299
		-20	NDE	TB	1,498
		-40	NDE	TB	1,581
		-60	NDE	TB	1,632
Acetylene	14	20	TB	TB	1,292
		-20	TB	TB	1,493
		-40	TB	TB	1,608
		-60	TB	TB	1,720
Ethylene	8	20	TB	DE, NDE, TB	814
		-20	TB	DE, NDE, TB	873
		-40	TB	DE, NDE, TB	916
		-60	NDE	DE, NDE, TB	996
Hydrogen/ Methane (85/15)	24	20	TB	TB	908
		-20	TB	TB	961
		-40	TB	TB	976
		-60	TB	TB	1,035

The graphical examples of some of the results are shown in the following figures. Each of these incorporates an ignition scenario that resulted in at least one highest explosion pressure for the particular gas. In each case, the figures show the results at each of the four temperatures at which the tests were carried out. Figure 73 shows the results for the temperatures for hydrogen with the ignition at the non-drive end.

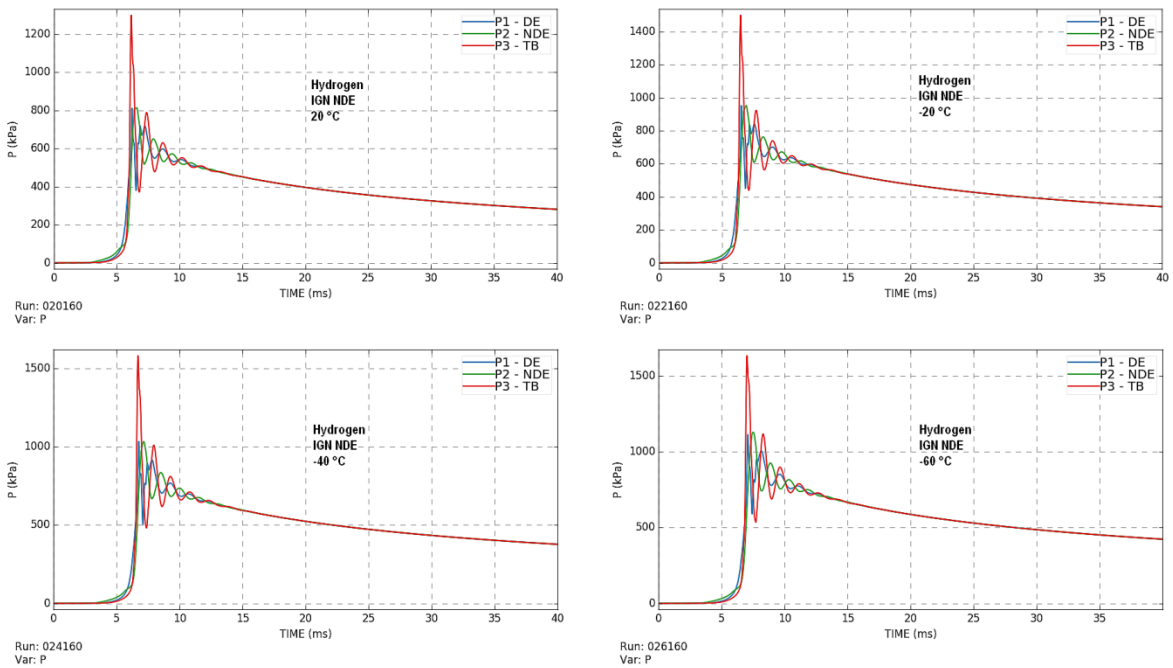


Figure 73 – 160 frame - Hydrogen - Ignition non-drive end

Figure 74 shows results for acetylene with the ignition under the terminal box.

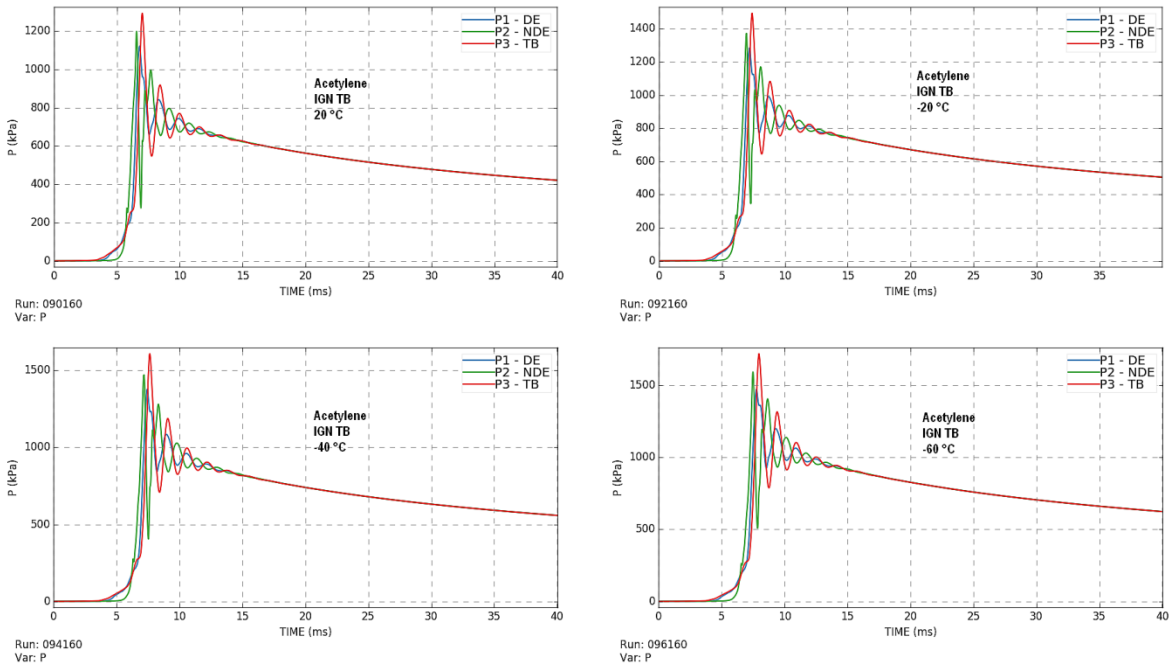


Figure 74 – 160 frame - Acetylene - Ignition terminal box

Figure 75 shows the results for ethylene with the ignition at the non-drive end.

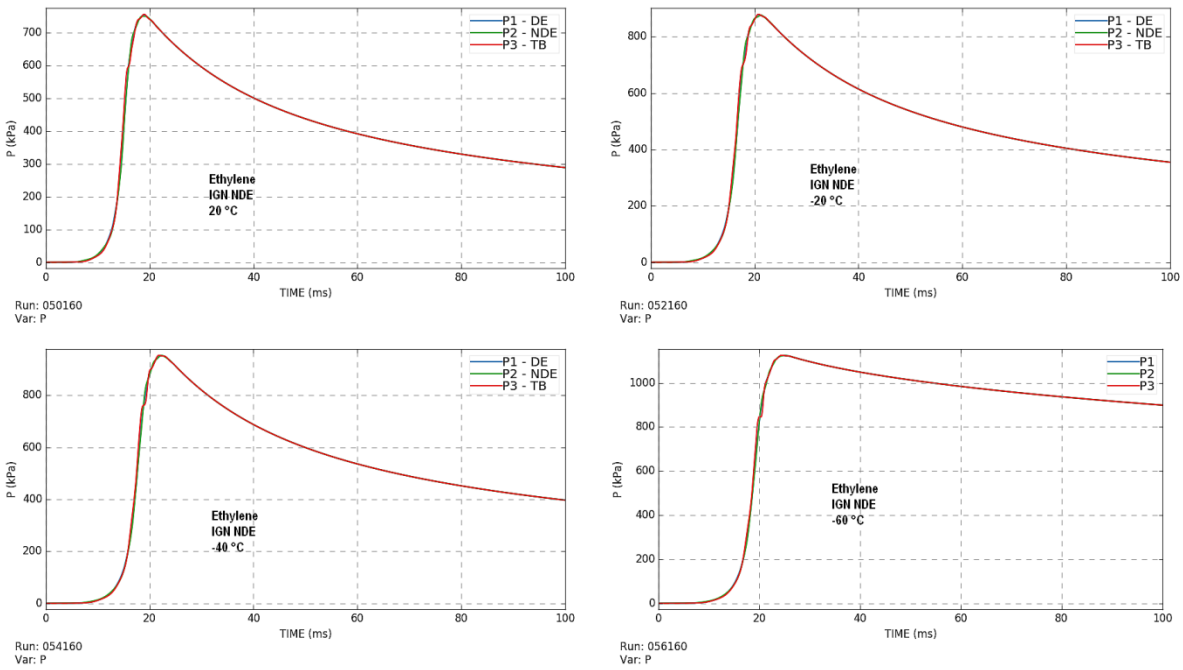


Figure 75 – 160 frame - Ethylene - Ignition non-drive end

Figure 76 shows the results for hydrogen/methane mixture with the ignition under the terminal box.

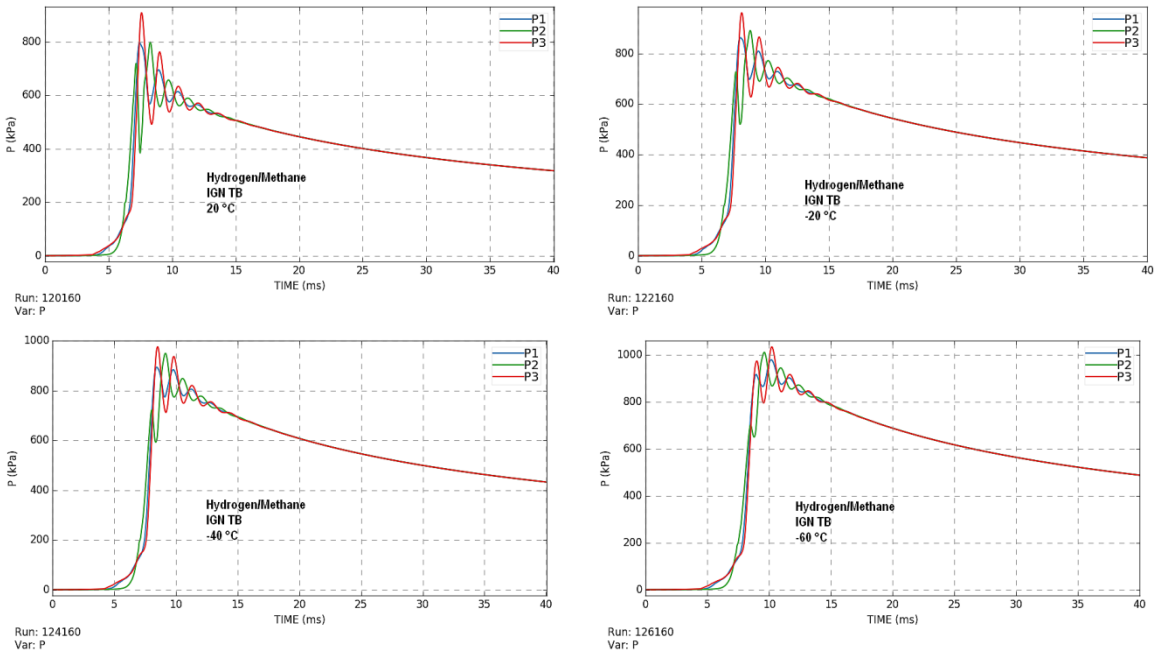


Figure 76 – 160 frame - Hydrogen/methane - Ignition non-drive end

Most of the above curves look like what might be expected. Comparison can be made with actual test results, and two examples are provided below for testing with hydrogen at +20 °C and -60 °C. The curves that look unusual are those for ethylene. All three traces show together and with the same maximum pressures. It is possible it relates to earlier discussions on the fact that at small grid sizes below 2 mm the flame speed increases and this may be somehow rather impacting on the results.

10.9.4 Comparison of 160 frame motor simulation results with testing

TABLE 54 shows the comparison between the simulation results and the test results for the 160 frame motor.

TABLE 54 – MAXIMUM PRESSURE 160 FRAME MOTOR SIMULATION COMPARED WITH TEST RESULTS

Gas	% with air	Initial temp, °C	Pressure from FLACS			Pressure from testing		
			Ignition	Transducer	Max pressure, kPa	Ignition	Transducer	Max pressure, kPa
Hydrogen	31	20	NDE	TB	1,299	DE	NDE	563
		-20	NDE	TB	1,498	TB	TB	762
		-40	NDE	TB	1,581	TB	DE	724
		-60	NDE	TB	1,632	DE	NDE	891
Acetylene	14	20	TB	TB	1,292	TB	NDE	655
		-20	TB	TB	1,493	DE	TB	928
		-40	TB	TB	1,608	DE	TB	963
		-60	TB	TB	1,720	TB	TB	1,098
Ethylene	8	20	TB	DE, NDE, TB	814	NDE	TB	844
		-20	TB	DE, NDE, TB	873	NDE	TB	873
		-40	TB	DE, NDE, TB	916	NDE	TB	1,102
		-60	NDE	DE, NDE, TB	996	NDE	TB	1,026
Hydrogen/ Methane (85/15)	24	20	TB	TB	908	NDE	TB	422
		-20	TB	TB	961	TB	NDE	501
		-40	TB	TB	976	TB	NDE	581
		-60	TB	TB	1,035	TB	NDE	256

Figure 77 and Figure 78 show the pressure curves for testing of the 160 frame motor with hydrogen, with the ignition at the drive end for the temperatures of 20 °C and -60 °C. Figure 79 shows the corresponding curves from the simulation.

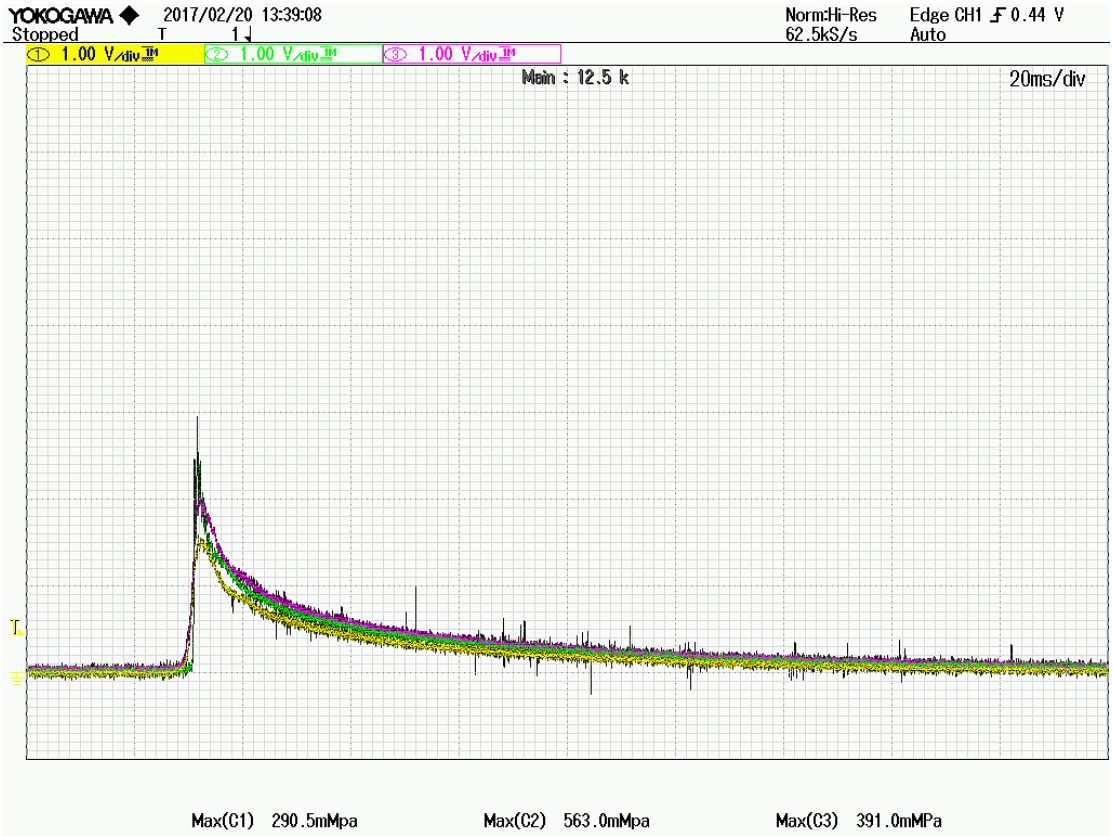


Figure 77 – Test of 160 frame motor with hydrogen at +20 °C

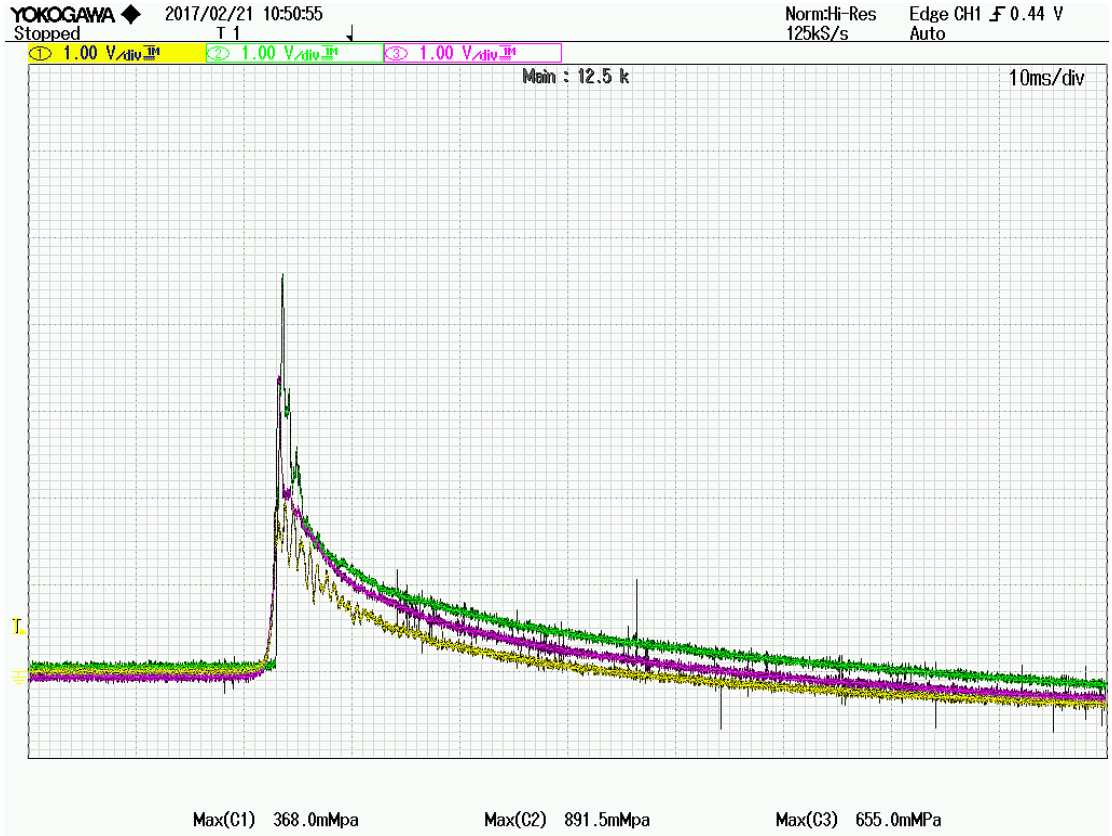


Figure 78 – Test of 160 frame motor with hydrogen at -60 °C

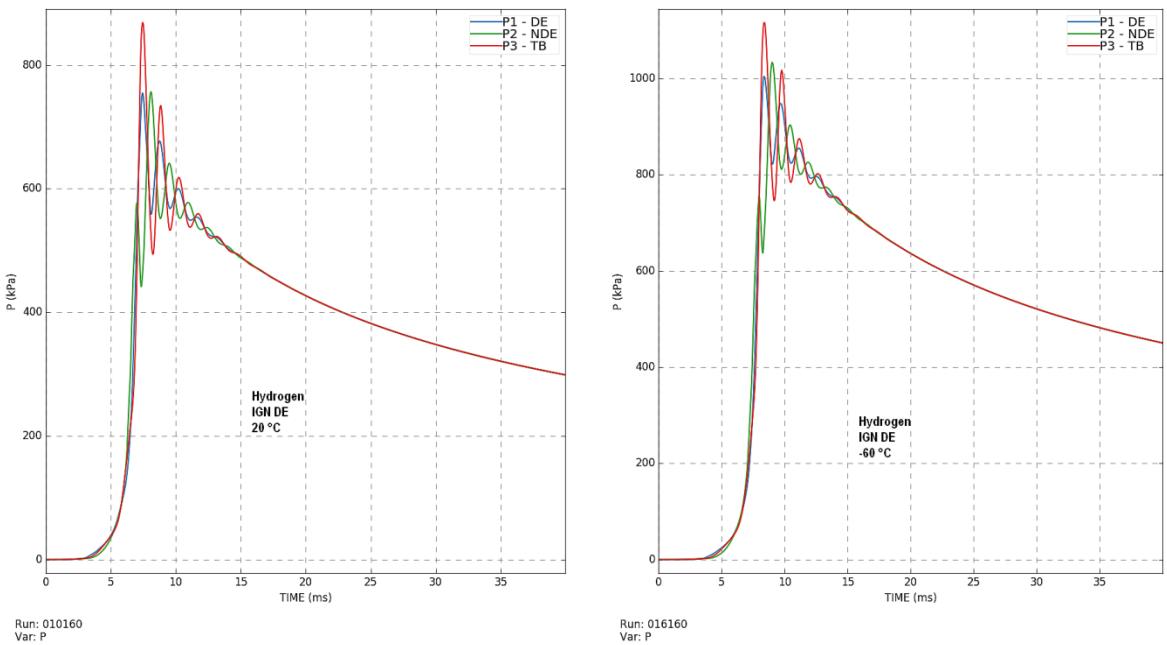


Figure 79 – Simulation of 160 frame motor with hydrogen at +20 and -60 °C

It is noticeable that the results for hydrogen, acetylene and hydrogen/methane are all significantly higher than the results of the testing. Strangely ethylene, even though the curves do not look correct, has results which are extremely close, and so in practice have achieved the aim of producing good correlation for maximum pressures. Regarding the other gases, it is likely that one of the contributing factors is the volume of the terminal box. The volume in this terminal box is more significant in relation to the motor than in the 355 frame motor looked at earlier. It is quite likely that such a large volume would have an impact on the results. In fact, in the case of acetylene and hydrogen/methane, the major scenario occurred completely within the terminal box of ignition and maximum pressure. This means that the geometry of the motor was not a significant factor in the results. In the case of testing the motor, the terminal box was partially filled with cables, and so the actual volume would have been less. It might be possible to simulate this scenario by introducing objects into the area to try to replicate the cables. But accurate modelling of the cables would be extremely difficult. This is an area that would require further investigation to see if there is a way of better modelling the scenario for cables entering the terminal box area. The alternative is to treat the empty terminal box area as a worst-case scenario to allow conservative figures to be produced on maximum pressures.

Further to the above, at the time the model was developed for the 160 frame motor for FLACS there was limited information available on the dimensions, and much was guessed, based on photographs. Just prior to the completing this thesis during a final visit to CQST for the thesis project I was able to carry out dimensional measurements on the motor. Some significant differences to the model were that the chamber terminal box is less high, making the actual volume smaller, the rotor/stator is closer to the non-drive end than the drive end, and the motor is shorter. Two of these should result in a smaller volume and hence may produce lower simulation explosion pressures. This is being highlighted as an area for future work, possibly with the new version of FLACS.

Since the modelling of the motor is still an approximation of the actual geometry, it is also useful to consider the results from the data mining exercise. For Group IIC the highest pressure obtained in those results was for acetylene with the pressure of 1,445 kPa on one motor and 1,271 kPa on another motor, both when tested with acetylene. Based on the scenarios, the results that were obtained for Group IIC with the simulation start to look quite promising. It should also be noted that only two tests were carried out at each temperature, whereas under normal pressure determination testing where pressure piling is present, five tests will be carried out at each pressure. So it is likely some higher pressures would occur with a larger number of tests. It is also likely that, if it had been feasible to test the motor running, higher pressures would have been obtained for some scenarios. Although this would also have necessitated introducing turbulence model into the simulation, it is possible that a

better correlation of maximum pressures may have been obtained between the motor tested and the simulation. So there may be value in looking at additional testing, involving more tests and rotation of this motor, or another motor suitable for operation at extremely low temperatures.

It is also appropriate to again mention the role of the air gap in the modelling. Similarly to the 355 frame motor, the air gap was significantly larger than in the actual motor. In the case of the 160 frame motor, the normal air gap is about 1 mm, and that used for simulation was 40.5 mm. This gap was achieved by reducing the diameter of the rotor. It would also be possible to achieve this by reducing some of the diameter of the stator as well as some of the diameter of the rotor. This is also likely to affect the simulation. But it is not possible to remove too much material from stator for simulation purposes because it would affect the geometry introduced by the winding overhangs. However, since the exercise here is to try to predict potential maximum expected pressures, there may be value in retaining the large air gap for simulation purposes.

Finally, the example pressure traces shown in the figures look quite good for hydrogen. In fact, all traces looked reasonable, with the exception of ethylene.

So when looking at the broader aim of the exercise to try to predict maximum potential explosion pressures, the results are actually quite good. However, the restriction on the ability to accurately develop geometries and to carry out simulations within the recognised limits of FLACS are certainly issues to be considered.

10.10 Conclusions on the potential to use FLACS for predicting explosion pressures

10.10.1 Some additional aspects regarding FLACS

There are some additional technical aspects of FLACS arising from the simulations that are worth discussing. First, in the explosion simulation scenarios, there are the options of "Gas explosion" and "Gas explosion (DDT)". Both were initially considered when simulating the 255 frame motor. However, on closer examination of the two options, it appears the only real advantage of the second option is when there is a possibility of deflagration to detonation transfer (DTT) occurring. While FLACS cannot measure the DTT situation, with the second option it can predict the possibility of DTT occurring. Since the likelihood of DDT on the motors in the range of motors considered for these simulations is extremely unlikely, the use of this option seems unnecessary. However, for very large flameproof motors where multiple tubes are used through the motor to improve cooling, the possibility of DDT becomes much bigger. If the capability of FLACS improves sufficiently to be able to accurately model the geometry of such motors, then there might be some value in applying this option.

Secondly, when carrying out pressure determination testing, a 5 kHz low pass filter is required by IEC 60079-1 to smooth the pressure results. Discussions were held with engineers from Gexcon to decide whether it would be necessary to simulate the use of such a filter on the pressure figures being obtained from the simulations. I was advised that the monitored "p" pressure data is typically smooth, and so it is possible to compare the FLACS data with the experimental data without modification of the FLACS data. There are some other more rigorous methods of applying filtering, but these are not specifically an option within FLACS. Given the significant variation in pressures associated with this testing, it appears simply using the "p" data from FLACS should be sufficient for these explosion pressure simulation exercises.

Thirdly, there is one common difference between the actual explosion curves and those shown in the simulations. The curves from the testing show the pressure decaying away to close to zero whereas the curves in the simulations shown a residual pressure. There two main factors that may contribute to this, probably in combination, as follows:

1) All the actual types of equipment tested were not perfectly sealed, and so the pressure could leak away. In contrast, it is assumed that FLACS treats the equipment as sealed, or nearly so, and the pressure may stay for longer periods.
2) The pressure transducers only measure dynamic pressure, and so if there were a residual static pressure, they would not show a reading. For FLACS the pressure measurement is a combination of static and dynamic pressure, and so any residual static pressure is likely to be still displayed.

To address 1) above it might be possible to introduce a small section of porosity in the models to allow pressure to fall away in similar fashion to equipment under test. This could be an area for future investigation.

10.10.2 Final discussion on FLACS

This chapter has provided a summary of the capabilities of FLACS, but more importantly, has reported on a number of different types of simulations, and the correlation of those with actual testing results. In addition to the preliminary simulations with a 255 frame motor, the following were the major simulation exercises carried out:

- A 355 frame motor without terminal box and with a terminal box, at normal ambient temperatures;
- The PTB proficiency testing artefact, at low temperatures; and
- A 160 frame motor at normal ambient temperature and down to extremely low temperatures.

Given the constraints of FLACS, which will be discussed in more detail below, the results obtained were better than anticipated. But they did highlight the need for more research and the desirability of improved capabilities within FLACS.

As has been discussed a number of times in relation to the various simulations, there are two major limitations of FLACS version v10.6 at this time. These are:

- The limitation on how small grid size should be for FLACS to produce accurate simulations and the difficulty this introduces into modelling geometries for flameproof equipment in general, and for flameproof motors in particular, because of their small air gaps
- The effective restriction to the use of only square or rectangular grids when modelling geometry with curves, leading to steps in the geometry and greater possibility of porosities not meeting requirements

However, it appears the above situation may change. I was advised during my last visit to Gexcon that the next version of FLACS will be able to handle smaller geometries, but they were not able to advise me what the minimum size is likely to be for that new version. They also advised me that there is a project underway in the USA to try to address the issue of stepped geometries that are introduced when using square grids on curved services, but it is unclear when that work might complete and how it might become available for public use. They also indicated that within Gexcon other research is being undertaken to investigate application to even smaller geometries for particular applications. It seems that if there were sufficient interest to provide some financial injection into the research, it might be possible to tailor FLACS to be able to apply more accurately model flameproof motors and hence the simulation of explosions inside them.

10.11 Summary of ANSYS FLUENT capabilities and approach

In the absence of personal hands-on experience using ANSYS FLUENT, I will report only briefly here on its capabilities as advertised by its suppliers and on the discussions I have had with my colleague, Pedro Maier, at WEG. The ANSYS suppliers claim that ANSYS provides a comprehensive suite of CFD software which can be applied to a wide range of phenomena, including combustion. They also indicate that ANSYS CFX forms part of the suite along with ANSYS FLUENT in carrying out CFD analysis. Pedro Maier (personal communication, 25 August 2017) has advised me on the differences between the two programs. He indicated that they differ regarding the kind of numerical solver that they use, with the main differences being:

- ANSYS CFX uses finite elements (cell vertex)
- ANSYS FLUENT uses finite volumes (cell centred)

He also indicated they were developed independently and have virtually the same options, but that FLUENT has a broader range of models from which to choose. He uses both for different kinds of problems. He has been using ANSYS FLUENT for the explosion simulations.

10.12 Simulations carried out at WEG on ANSYS FLUENT

It was clear from the beginning that one of the major challenges Pedro Maier faced was the large range of variables that needed to be specified to enable the program to produce the simulation of an explosion. The other significant challenge was the amount of processing time needed to produce a simulation using ANSYS FLUENT. One simulation was taking about a week to process on a desktop computer using a three-dimensional model. A compromise was made using a two-dimensional model, bringing down the processing time from days to hours. However, it is unclear whether such an approach will produce the necessary results to address complex configurations involving multiple pressure measuring points and varied ignition points. It could also prove impossible to apply this to complex motor geometries where the layout of the motor is not symmetrical.

Figure 80 shows an explosion simulation that was produced in ANSYS FLUENT using the 355 frame motor without a terminal box. This was also the same model discussed for FLACS earlier in this chapter. One potential benefit of using ANSYS FLUENT was its ability to model the geometry accurately using small grid sizes and the use of grids which were shaped to fit the circular nature of the geometry. So this may be a significant potential advantage over FLACS. Even if FLACS will be in a position to be used with smaller grid sizes, it may still be limited by its inability to accurately model curved shapes at this time.

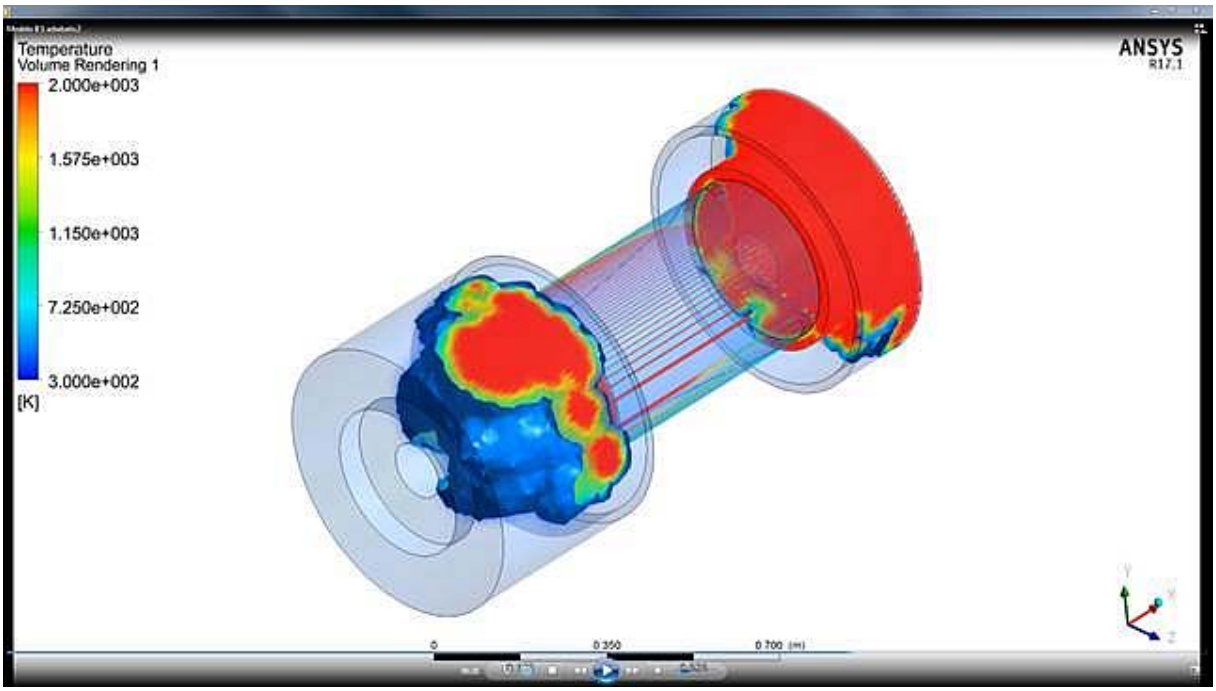


Figure 80 – FLUENT explosion simulation - 355 frame motor without terminal box

Research is continuing in WEG on the use of ANSYS FLUENT, and in particular to try to extend the modelling to the motor with the terminal box. At the time this thesis was being finalised, pressure of other work had delayed this exercise. However, it is planned that the joint paper mentioned earlier should be able to make clearer recommendations regarding the respective merits of ANSYS FLUENT and FLACS.

As part of his evaluation of ANSYS FLUENT, Pedro Maier also looked at applying it to a simplified two chamber two-dimensional model. In a report on this exercise (personal communication, 24 August 2017), he stated that:

> To accurately model the combustion process using computational fluid dynamics multiple fields of study must be considered, namely:
>
> - Chemical – define the reaction chemistry and mechanics, and its properties;
> - Fluid dynamics – define the turbulence behavior (sic) of the fluid;
> - Thermodynamics – consider or not the heat transfer;

- Numerical parameters – define correctly convergence criteria and time step to achieve consistent results.

He looked at each of these as part of the process of applying his model. Figure 81 below is a result of one of his simulations.

The most significant of his conclusions on this exercise was that despite the simplicity of the two-dimensional model tested, the simulations took one day each, with the expectation that a detailed three-dimensional model may take several days or weeks to finish.

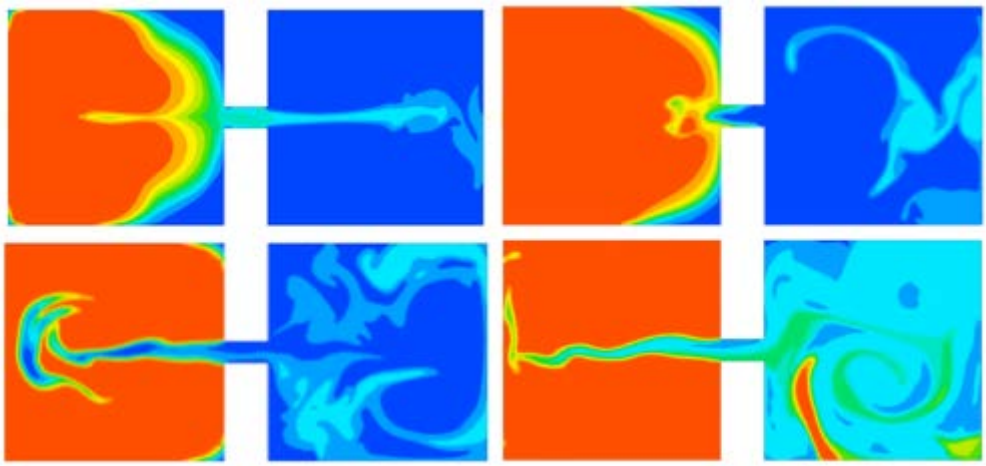


Figure 81 – FLUENT simulation with air gap of 10mm width

10.13 Conclusions on the potential use of ANSYS FLUENT for predicting explosion pressures

In summary, the following are the conclusions I have come to regarding ANSYS FLUENT, particularly in comparison with FLACS:

- It appears to require a greater in-depth knowledge of fluid dynamics than FLACS, and thus is more difficult to be used by someone like a design engineer
- It requires a significant amount of processing time, which could also become quite expensive if its capabilities are fully applied in the simulation process
- It does have the advantage over FLACS that it can apparently accurately model small geometries, including small air gaps which occur in motors

11 Thesis conclusions

I believe that the outcomes of this PhD project have been quite varied and in many cases quite significant. I hope that these outcomes will contribute to improvements in the next edition of IEC 60079-1, in particular for flameproof motors at "normal" and extremely low temperatures. The outcomes also apply to other flameproof equipment for normal and extremely low temperatures, especially where pressure piling is present.

In addition, I hope that the outcomes will provide better information for manufacturers when designing flameproof motors; noting that again that some of the findings, such as simulating explosions in flameproof equipment, could be more widely applied.

This chapter consolidates and, where necessary, amplifies many of the conclusions and recommendations that were included at the end of the preceding relevant chapters. They are broken down here into the five major elements of the project plan, as shown in 1.13, of:

1) Suitability of pressure safety factors
2) Extremely low temperature flame transmission
3) Validity of using increased pressures at low temperatures for pressure determination
4) Development of indicative pressures for flameproof motors
5) Investigations into the use of CFD to determine explosion pressures

One of the interesting aspects of this research was that information discovered in one of the elements sometimes provided explanations to results being obtained in other elements. An example of this is also discussed.

11.1 Suitability of pressure safety factors

Chapter 2 looked the suitability of explosion pressure safety factors. I concentrated on investigating the suitability of the current factors for pressure testing in IEC 60079-1 at normal and extremely low temperatures. It involved an in-depth analysis of the development of IEC 60079-1 and included an examination of the minutes of the first meetings held regarding the development of the first edition of that standard. The numbered recommendations here relate to proposed changes to the next edition of IEC 60079-1 which would be Edition 8.0. Recommendations regarding future work are contained in the next chapter.

11.1.1 Recommendation 1:

It is recommended that the specification for testing in the standard ambient range of -20 °C to +40 °C be more closely specified. There are some potential options that could be adopted, including restricting the allowable range. However, the best approach might be:

a) To allow testing in the current range;
b) Define a narrower band where no factors apply; and
c) Define factors to be applied for temperatures outside the narrow band but inside the current range.

It is likely the narrow band could embrace most of the ambient temperature conditions present in laboratories around the world.

11.1.2 Recommendation 2:

It is recommended that the current factors which are applied for overpressure testing be reviewed, possibly along the following lines:

a) Consider increasing the factor of 1.5 when pressure piling is not present, at least for Group II where ambient temperature ranges are likely to be larger;
b) Depending on how the above is applied, consider increasing factors used for extremely low temperatures to include provision for experimental error; and
c) Consider restoring the factor of three when pressure piling is present which was in the second edition of the standard prior to its first amendment.

11.1.3 Recommendation 3:

It is recommended that the requirement from earlier editions that five tests should be carried out in the case of pressure piling should be restored for Groups I and IIA.

11.1.4 Recommendation 4:

It is recommended that the need to retain or remove the hydrogen/methane mixture for pressure determination testing for Group IIB should be given careful consideration. On the basis of the evidence provided in this thesis, the recommendation here would be to delete it. However, if it is retained, the note regarding its use in IEC 60079-1 will require changing to make it clear that the hydrogen/methane mixture should be used in all cases where pressure piling may occur, not just in the situation where pressure piling has occurred with ethylene. The standard then will also need to take account of the use of the mixture at extremely low temperatures. Further, the standard places no tolerance on the ratio of hydrogen to methane and this should be rectified. A similar approach could be taken as for the flame transmission test for electrical equipment of Group I, ie "(12,5 ± 0,5) % methane-hydrogen [(58 ± 1) % methane and (42 ± 1) % hydrogen]" with the percentage suitably changed.

11.2 Extremely low temperature flame transmission

Chapter 3 found that there was a lack of published information that addresses how flame transmission might occur at low and extremely low temperatures, in particular where pressure piling may occur. Published information on MESG does not address low temperatures. There is limited information on the likely pressures that might be obtained at extremely low temperatures and no published information on the pressures that might be obtained when testing at gas percentages different to the stoichiometric mix.

Based on existing data for MESG and pressures obtained at extremely low temperatures down to -60 °C, the likely outcomes for testing with hydrogen and ethylene were examined and tested. The results for hydrogen indicated that there is a decreased probability of transmission at temperatures of -20 °C and lower temperatures, but that the presence of water resulting in ice and frost can be a factor in preventing transmission. The results for ethylene indicated a similar or slightly increased chance of flame transmission at lower temperatures when pressure piling is present, which is different to hydrogen. This confirms the trend from the analysis that could see some gases have increased probability of flame transmission at low temperatures.

11.3 Validity of using increased pressures at low temperatures for pressure determination

Tests were carried out using hydrogen and methane in relation to the formula as currently shown in IEC 60079-1 for pre-pressurisation for pressure determination for equipment intended for use in extremely low temperatures. In the case of pressure piling, the results provided consistently, and at times significantly lower explosion pressure figures, when using pre-pressurisation, in comparison to testing with the actual temperatures.

However, results in the chamber where pressure piling was not present, were not so conclusive as there are discrepancies in the results between those carried out under this project and those carried out by PTB when testing with hydrogen. Also, there was reasonable correlation of results for this chamber when testing with methane as part of this project.

The results did support the premise that the formula will need to be removed, need to be modified, or the option of its use restricted for the IEC 60079-1 standard. Chapter 7 explores a possible revision of the formula and the testing done to check the revised formula using hydrogen.

Should the formula be retained, it is recommended that the use of pre-pressurisation using the formula only be used as follows (derived from Edition 5.0):

For electrical equipment

- of Groups I, IIA, or IIB; or
- of Group IIC with internal free volume < 2 l,

other than rotating electrical machines (such as electric motors, generators and tachometers) that involve simple internal geometry such that pressure piling is not considered likely

Consideration should also be given to incorporating the modified formula as discussed in Chapter 6. But before that could occur, additional testing is recommended in 12.3 to assist in making the decision regarding the use of the formula in the standard.

11.4 Development of indicative pressures for flameproof motors

11.4.1 Data mining project

The main aim of the data mining project in Chapter 9 was to provide manufacturers with explosion pressure data that would assist them in the design of flameproof motors. The data that have been presented for Group IIB and Group IIC flameproof motors, together with the derived equations for calculating maximum pressure, should provide manufacturers with a good starting point in this regard. The data for Group I may provide some indication. These results are in relation to motors to be tested at ambient temperatures.

This data mining project has also delivered a significant amount of information about the various tests that need to be done when testing flameproof motors to determine the maximum explosion pressures and the most important scenarios that should be applied when carrying out those tests. Two of these scenarios are summarised below:

- The project confirmed the benefit of doing pressure determination testing on flameproof motors both when running and at rest, as either scenario has the potential to provide the highest explosion pressure
- The project indicated the need to take account of the scenario involving measuring pressure and providing an ignition source under the terminal box when there is a chamber under the terminal box open to the motor

It is reiterated here, that the proposed approach of estimating the likely maximum explosion pressures is only intended as a tool for manufacturers designing motors and not as a substitute for testing of motors. Experience has shown that occasionally very large unexpected explosion pressures can occur due to geometries that provide significant pressure piling or possibly even detonation. The pressures reported in the data presented in this thesis do not address this situation. But examples of these situations were found during the research. For example, in one case the cableway between the motor and the terminal box was responsible for a significant pressure piling situation. Due to the size of the pressure, it was necessary to use a filling compound in the chamber under the terminal box to reduce the pressure. Another situation involved a large motor with multiple internal cooling tubes that again led to very significant pressures occurring.

Notwithstanding that this exercise was aimed at providing information to manufacturers, it was noted from the data mining project that there were examples of pressures being obtained during testing that looked too low. Hence a recommendation is made to ensure motors in the range are not subjected to the overpressure test at an inappropriately low pressure. This could be done, for example, by deriving the best fit curve from the data.

11.4.2 Testing of the 160 frame motor

For the testing of the 160 frame motor it was found that for pressure determination in flameproof motors, the scenario that produces the highest explosion pressure at normal ambient temperatures may not be the same as the one that will produce the highest explosion pressures at lower temperatures. This further indicates that pre-pressurisation of equipment that may be subject to pressure piling is not a suitable method for determining maximum explosion pressures. This topic was discussed in Chapters 4, 5, 6 and 7.

A significant contributor to the likely scenarios that will produce maximum pressures at low temperatures is whether flame transmission will occur through the air gap. How this may occur is very dependent on the gas that is used for testing and may also be affected by the composition of the gas/air mixture if the stoichiometric mix is not close to the mixture that will be most likely to produce flame transmission. It is also dependent on the size of the air gap and length of the path through the air gap. For some motors, the air gap may be large enough for flame transmission to occur with any gas at any temperature.

An additional issue has been highlighted by this testing. For reference pressure testing, IEC 60079-1 has the option for electrical equipment intended for use at an ambient temperature below -20 °C, of determining the reference pressure at a temperature not higher than the minimum ambient temperature. However, the application of this clause means that the equipment need only be tested at that low temperature. It can be seen from the testing of the 160 frame motor that, if it were tested for use in -60 °C for group IIB, the reference pressure would be lower than if tested at -40 °C. It might even be feasible, looking at the explosion pressure for hydrogen/methane and the first round of testing for acetylene, for the explosion pressures at low temperatures to be lower than those at ambient temperatures. Therefore it may be necessary to test at other temperatures in addition to the minimum ambient temperature. For example, it might be necessary to test at normal ambient temperature and also at a point roughly midway between normal ambient temperature and the minimum ambient temperature.

For this research, only two tests were done at each temperature point for each gas. It would be useful to carry out additional testing to gather more data to provide better statistical confidence in the figures. It might then be possible to make estimations of the factors that could be applied at each temperature point for testing at low temperatures and to apply these factors to the ambient figures derived from the equations. It would then be possible to apply these factors to the ambient explosion pressure. Again, this is unlikely to be adequate for type testing of electric motors for the purposes of certification, but it would provide indicative figures for manufacturers. This would provide an alternative means to applying factors to that shown in TABLE 38.

So there may be value in looking at additional testing, involving more tests and rotation of this motor, or another motor suitable for operation at extremely low temperatures. This is further addressed in the next chapter.

11.5 Investigations into the use of CFD to determine explosion pressures

Chapter 10 has provided a summary of the capabilities of FLACS, but more importantly, has reported on a number of different types of simulations and the correlation of those with physical testing results. These simulations covered three different frame sizes of motor and the PTB proficiency testing artefact. These simulations produced results that were better than anticipated.

However, the research also highlighted the two major limitations of FLACS version v10.6 at this time. These are:

- The limitation on how small grid size should be for FLACS to produce accurate simulations and the difficulty this introduces into modelling geometries for flameproof equipment in general, and for flameproof motors, in particular, because of their small gaps
- The effective restriction to the use of only square or rectangular grids when modelling geometry with curves, leading to steps in the geometry and greater possibility of porosities not meeting requirements

However, it was noted that that the next version of FLACS will be able to handle smaller geometries. So it would be very informative to redo the simulations reported on with the new version. This is addressed in the next chapter.

It was also noted that there is a potential for targeted research to tailor FLACS to apply more accurately the modelling and simulation of explosions in flameproof motors.

Research is continuing in WEG on use of the ANSYS FLUENT program. However, based on progress to date, it is believed the following is the situation regarding ANSYS FLUENT, particularly in comparison with FLACS:

- It appears to require a greater in-depth knowledge of fluid dynamics than FLACS, and thus is more difficult for someone like a design engineer to use
- It requires a significant amount of processing time, which could also become quite expensive if its capabilities are fully applied in the simulation process
- It does have the advantage over FLACS that it can apparently accurately model small geometries, including small air gaps which occur in motors

11.6 Conclusions across more than one element of the project

Of interest in the above elements of the project was the correlation between two quite different tests. In Chapter 3 it was found that transmission became less likely with hydrogen as temperatures reduced. But for ethylene, it was found to be about the same or more likely. For testing in Chapter 9, this was partly borne out in the results of the testing of the 160 frame motor. There was flame transmission through the air gap with ethylene at all temperatures down to -60 °C. However, for hydrogen/methane and acetylene, flame transmission through the air gap became less likely at lower temperatures for certain scenarios.

12 Recommended future work

This chapter consolidates the recommendations for future work that were included in the preceding relevant chapters. They are broken down here into the five major elements of the project plan as discussed in the previous chapter, Chapter 11

12.1 Suitability of pressure safety factors

It is recommended that the impact of varying gas concentrations from the stoichiometric gas concentrations specified in the standard for pressure determination be investigated for situations where pressure piling may be present to see if higher pressures can be obtained in certain circumstances. For this, the concentrations included in the USA standards, for example in [54] and [55], for this testing could be used as a starting point.

It is recommended that consideration be given to carrying out tests to revalidate the experiments done by Lobay and PTB and with the temperature range extended down as far as -60 °C. This could include carrying out experiments with the hydrogen/methane mix if there is a likelihood that this will be retained in IEC 60079-1.

Although a significant number of simulations have been made with various scenarios in Chapter 10, it is recommended that consideration be given to doing research from first principles to correlate the results, based on the gas properties, such as thermal and mass diffusion.

12.2 Extremely low temperature flame transmission

It is recommended that additional research be carried out to clarify the situation regarding flame transmission at extremely low temperatures with other gases, such as acetylene, propane and methane. It is noted that some modification to the artefact used for testing for methane, and possibly also for propane, may be necessary to carry out this testing.

It was noted during the testing with ethylene, as discussed in 3.5.2, that the pressure figures at the low temperatures of -40 and -60 °C were lower than expected for the 18 mm diameter, 6 mm long nozzle. A closer analysis of the figures indicate that for the two cases where there was no transmission, the pressure figures were lower than any of the pressure figures obtained for -40 °C. So this provides a likely explanation for no transmission. At the time there were some problems with the gaskets being damaged by the pressures, and so this could be the cause of the low pressures. For the 2.0 mm diameter, 8 mm long nozzle, pressures at the very low temperatures were also lower than expected. So it is possible if the theoretical maximum pressures could be reached there may be transmission. Hence it is recommended these tests be repeated for the two ethylene nozzles at appropriate temperatures to see if the expected pressures can be achieved and if transmission then occurs.

The pressure developed within Chamber A2 when there is no flame transmission might have had an influence on flame transmission, particularly in the case of methane as discussed in 3.8.2. Hence investigation of this effect is recommended, including for the other gases. The timing of any pressure increase in Chamber A2 in relation to possible flame transmission is also relevant and will need to be considered.

The premise used in this topic was that increased internal pressure due to pressure piling can lead to the increased possibility of flame transmission. The tests done using ethylene appear to support this. The paper by INSEMEX [20] regarding the increased likelihood of transmission in flameproof motors discussed in 1.9 also supports this premise. Notwithstanding this, the influence of external pressure may also be a factor, and hence further research to clarify the relative and interrelational effects of internal and external increased pressure on flame transmission might be of value.

12.3 Validity of using increased pressures at low temperatures for pressure determination

It is recommended that, in regard to testing the validity of using increased pressures at low temperatures for pressure determination, additional testing be considered to assist in the decision process regarding the possible continued use of the formula, such as:

a) Testing with other gases, such as acetylene, ethylene and propane with the existing formula

b) Testing with other gases, such as methane, acetylene, ethylene and propane with the revised formula

c) Testing with a single chamber with various gases to better check the results when pressure piling is not present, to compare the two scenarios of pre-pressurisation using the formula and testing at the actual low temperatures

d) Carrying out more tests at each test temperature (possibly 10 instead of 5) to improve the statistical confidence in the results

e) Carrying out comparative tests to see if filling a sealed enclosure with gas/air mixture and then cooling it to the target temperature before exploding it, provides different explosion pressures to filling it with the gas/air mixture already at the same target temperature

12.4 Development of indicative pressures for flameproof motors

The amount of data arising from the data mining project was too small in the case of Group I motors to make estimations of likely maximum pressures for various frame sizes of Group I motors. Hence collection of additional data for Group I motors could be helpful in being able to make estimations of maximum pressures.

The data for Group IIB and Group IIC motors did not always involve consistent testing scenarios. So the collection of additional data for these two groups, preferably with similar testing scenarios, would lead to improved confidence in the estimations of likely maximum pressures.

For the testing of the 160 frame motor, only two tests were done at each temperature point for each gas. It would be useful to carry out additional testing to gather more data to provide better statistical confidence in the figures and the factors that might be derived from those figures. For such a test, it would also be desirable to test the motor both running and not running, provided a motor can be obtained that would operate at extremely low temperatures.

12.5 Investigations into the use of CFD to determine explosion pressures

If the next version of FLACS allows for smaller grid sizes and hence better addresses small geometries, it would be informative to apply it to the geometries addressed in this project for the 355 frame motor, 160 frame motor and the PTB artefact. For the 160 frame motor, the simulation could be applied to the later simulated model (see below).

As part of the above, it would also be useful to further investigate turbulence to address the situation when a motor is running, addressing the situations of motors both with and without an internal fan.

Some other matters that were identified for further investigation as part of the simulations include:

a) For the 355 frame motor the low pressures obtained with ethylene, including an apparent lack of pressure piling

b) Looking at different sizes for the artificially large air gap to see what results might be produced and how these compare with actual explosion pressures obtained when testing

c) Varying the mixture from the stoichiometric mix in FLACS to slow down the flame speed to see if improved results can be obtained when small grid sizes are involved, particularly in the case of methane with pressure piling

d) Investigating a way to model the scenario for cables entering the terminal box area

e) Introducing a small section of porosity in the models to allow pressure to fall away in similar fashion to equipment under test

f) Re-running the simulations for the 160 frame motor with the new version of FLACS, using the more accurate dimensions for the motor tested

Finally, it would be interesting to gauge the interest of motor manufacturers in the possibility of doing some applied research into the application of FLACS to more accurately simulate explosion pressures in flameproof motors.

13 List of Figures

14 List of Tables

15 References

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