VARIABILITY IN THE PHYSICAL AND TRANSPORT PROPERTIES REGARDING DRYING BEHAVIOUR FOR REGROWTH AND PLANTATION BLACKBUTT TIMBER IN NEW SOUTH WALES

A thesis submitted in fulfillment
of the requirements for the degree of
Doctor of Philosophy

by

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MARCH 2007

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ACKNOWLEDGEMENTS

The completion of this thesis was achieved with the help, support and guidance from a lot of people. Firstly, I would like to thank my supervisor, Associate Professor Tim Langrish for choosing me and giving me a chance to be the candidate for this PhD thesis. His continuous guidance, help and training allowed me to develop my critical thinking, problem solving and writing skills to a level which has been highly commended by others. Secondly, thanks to Forests NSW, specifically to both my industrial supervisors, Dr. Ross Dickson and Mr. Bill Joe, for providing the timber, and allowing and teaching me to understand how the aims of this thesis fit into the timber drying industry. You have opened my eyes to see this thesis from a different perspective.

I am also grateful to Mr. Dennis Trevaskis and Mr. Lindsay Nicks for cutting all those timber samples (even if the request was only short notice) which are the foundation of this thesis. No timber to dry, no thesis! I've enjoyed both your friendly chats during the completion of this thesis and might I say, made the whole experience extremely worthwhile and fun. Thank you for your friendship, it will surely be treasured forever.

Thank you also to Mr. Trevor Shearing, Dr. Nawshad Haque and Dr. Loren Pordage. Mr. Shearing for helping me with the mechanical properties' testing, Dr. Haque for helping me understand the concepts of timber drying and using his thesis as reference, and Dr. Pordage for making me use his optimization code and answering numerous questions up to the very end.

I would like to acknowledge the Australian Research Council, from whom I received a scholarship throughout my postgraduate life. The same goes to Forests NSW for their assistance, both physically and financially, for this thesis.

The ‘Drying Technology’ group of the School of Chemical and Biomolecular Engineering, The University of Sydney, whom I not only consider as postgraduate mates, but friends – we all started as “rookie’s” in our projects, but due to our support for each other, I wouldn’t have been able to complete this thesis without you guys and gals.

Thank you to Mrs. Ellen Spinner, Mrs. Annette Alexander and Ms. Katharyn Thomas – for all the help especially for all the ‘behind the scenes’ administration work associated with this PhD study.

Last, but not the least, my family – Rene, Nanette, OJ and KC. Through the happy times and the sad times, you encouraged me to value my efforts in this thesis, even during the times when it seemed it didn’t. Your emotional, physical and intellectual support kept me going, through thick and thin. I am indebted to all of you forever.

LIST OF PUBLICATIONS

The following refereed papers were published as a result of the work presented in this thesis.

From work described in Chapters 4 and 6:

1) S.J. Cabardo and T.A.G. Langrish (2006), 'Variability in Transport Properties for Blackbutt Timber in New South Wales: Within and Between-Tree Variability', *Developments in Chemical Engineering and Mineral Processing*, 14(1/2), 173-181.

2) S.J. Cabardo, T.A.G. Langrish, R. Dickson, and B. Joe (2006), 'Variability in Transport Properties Regarding Drying Behaviour for Blackbutt Timber in New South Wales', *Drying Technology*, 24, 211-224.

3) S.J. Cabardo and T.A.G. Langrish (2006), 'Within-Tree Variability in the Drying Properties for Blackbutt Timber in NSW', Special Issue of the journal *MADERAS: CIENCIA Y TECNOLOGIA (Wood: Science and Technology)*, 8(1), 15-24.

From work described in Chapters 5 and 6:

1) S.J. Cabardo, T.A.G. Langrish, R. Dickson, and B. Joe, 'Variability in Mechanical and Drying Properties for Blackbutt Timber in New South Wales', *Journal of the Institute of Wood Science*, In press.

The following conference presentations were conducted and conference proceedings were published as a result of the work presented in this thesis.

National and International Conference Presentation:

1) Presented a paper coauthored by Tim Langrish entitled ‘Variability in Transport Properties for Blackbutt Timber in New South Wales: Within and Between-Tree Variability’ at the 32nd Australasian Chemical Engineering Conference, CHEMECA, 26-29 September 2004, Sydney, Australia.

2) Presented a paper coauthored by Tim Langrish entitled ‘Within-Tree Variability in Transport Properties for Blackbutt Timber in New South Wales’ at the Ninth International IUFRO Wood Drying Conference, 21-26 August 2005, Nanjing, China.

National and International Conference Proceedings:

1) Cabardo, S.J., & Langrish, T.A.G. (2004). ‘Variability in Transport Properties for Blackbutt Timber in New South Wales: Within and Between-Tree Variability’. Proceedings 32nd Australasian Chemical Engineering Conference, 26 – 29 September 2004, Sydney, Australia.

2) Cabardo, S.J.; T.A.G. Langrish. ‘Within-Tree Variability in Transport Properties for Blackbutt Timber in New South Wales’, Proceedings Ninth International IUFRO Wood Drying Conference, Nanjing, China, Aug 21-26, 2005; International Union of Forest Research Organizations; 334-339.

EXECUTIVE SUMMARY

The impact of the variability in timber properties has been a challenge for companies involved in drying timber, which have to handle these variations and at the same time meet the requirements stated in the Australian/New Zealand Standard for the assessment of dried timber quality (2001). The definition of quality considered in this study is to both minimize the dispersion of the final moisture contents in dried timber boards, and to reduce cracking/checking. Anecdotal evidence also suggests that the timber properties of plantation timber appear to be more variable compared with the properties of old growth or regrowth timber. Therefore, this thesis focuses on measuring the amount of variability of timber properties by conducting drying experiments using timber boards taken from different locations within a single tree and between trees, for regrowth and plantation blackbutt timber (*Eucalyptus pilularis* Sm.). The quantified variabilities were then used to develop optimized timber drying schedules that are intended to dry regrowth and plantation blackbutt boards as quickly as possible (highest productivity) without cracking (quality loss) in the presence of large biological variability. Blackbutt (*Eucalyptus pilularis* Sm.) was the chosen species for this thesis because of its abundance in New South Wales. It is considered to be one of the most important eucalypts for planting in NSW. It has superior growth and high survival rates compared with other eucalyptus species, and the timber is marketable. Lastly, conventional kiln drying was considered in this thesis compared with other drying methods such as air drying and solar kilns due to (arguably) better control of the drying conditions and faster throughput in conventional drying. The higher costs of conventional kiln drying are compensated, relative to open—air drying, by the reduction in stock level and faster turnaround of green to dried timber.

Firstly, an overview of previous work on the development and evaluation of different drying schedules was given. Previous work either developed optimized drying schedules to minimize the dispersion of the final moisture contents, or reduced cracking/checking. No schedule has been developed to satisfy both aspects of quality. In addition, only one report has taken into consideration biological variability in the development of an optimized drying schedule, but this approach has not been tested experimentally. In addition, the information on the variability of biological parameters was very limited, was assumed to be normally distributed, and the parameters were assumed to be uncorrelated with one another. There is little information about the variability in timber properties with respect to drying, including how strongly they are correlated. This thesis has particularly addressed this aspect of the problem.

Drying experiments using conventional kiln drying were conducted. The properties of two regrowth blackbutt logs (36 boards) and two plantation blackbutt logs (24 boards), have been measured and analysed for the within—tree variation of timber properties. In a separate set of experiments, two boards were taken from each log, from a total of 12 regrowth logs and 10 plantation logs, to study the between—tree variability of the timber properties of blackbutt timber. The timber properties measured consisted of the basic density, the initial moisture content, the diffusion coefficient, the failure strain, the failure stress, the modulus of elasticity and the shrinkage.

The amount of cracking or checking and the dispersion of final moisture contents were assessed. 90% of the regrowth timber and 90% of the plantation timber fell in the Class C quality for surface checking, regrowth timber fell in Class B for end checking, while the end checks in the plantation timber fell in Class C for quality. Regrowth timber therefore appeared here to have slightly better quality than plantation material when dried with the same drying schedule, as here, in agreement with anecdotal suggestions that plantation material is more difficult to dry well. 95% of both the regrowth and the plantation timber fell in Class E quality for internal checking. Overall, along with the assessment that both regrowth and plantation timber was Class C quality for the variation of final moisture contents, these regrowth timber boards and the plantation timber boards fell in the lower quality classes for the criteria of checking and target moisture content for appearance products. Quality Classes A and B are higher quality categories, for appearance—grade products.

The dispersion of the final moisture contents was greater with the plantation blackbutt timber (0.24 within; 0.36 between) than with the regrowth blackbutt timber (0.19 within; 0.15 between) for both within—tree and between—trees variability, respectively. In general, the diffusion coefficients for the timber in this thesis ranged between 1.14×10^{-10} and 6.77×10^{-10} m^2s^{-1}. There was a significant difference between the diffusion coefficients of the plantation and regrowth blackbutt timber for the within—tree test at a 0.05 significance level. The variation in the diffusion coefficients within a single plantation blackbutt log was higher than the variation in the diffusion coefficients within a regrowth blackbutt log. In addition, there was also a significant difference between the diffusion coefficients of regrowth and plantation blackbutt timber at a 0.05 significance level for between—trees variability.

The initial moisture contents, the diffusion coefficient, and shrinkage decreased from pith to bark and the basic density and the modulus of elasticity (MOE) increased in the same direction, within a tree, for both regrowth and plantation blackbutt. The results of the analysis of variance (ANOVA) showed that radial and circumferential effects were significant sources of the within—tree variations for the diffusion coefficient, the initial moisture content, the basic density, the failure strain, the failure stress, the modulus of elasticity and shrinkage. A similar result was found for the ANOVA between trees. The ANOVA results also indicated that the smaller—sized samples used for the analysis (i.e. sub—samples of eight boards for the within—tree test of regrowth blackbutt, sub—samples of four boards for the between—trees test of regrowth blackbutt, sub—samples of six boards for the within—tree test of plantation blackbutt, and sub—samples of six boards for the between—trees test of plantation timber) were sufficient to measure the key effects adequately for the variabilities of the physical, transport, and mechanical properties, provided that all combinations of sub—samples were considered. There was no significant difference between the ANOVA results for these smaller sized samples (less than 1% change), considering all combinations, and the ANOVA results for the ‘full’ board cases. Though the sample sizes were unusually small to represent population statistics by most standards, all combinations of the sub-sets were assessed and an averaged picture of the situation with smaller sample sizes was given.

Moreover, MOEs (both green and kiln—dried states) of plantation blackbutt were lower compared with the MOE of regrowth blackbutt. It is possible that the MOE was correlated with the basic density, and the basic density of regrowth blackbutt was higher than the basic density of plantation blackbutt. The shrinkage in the tangential direction was approximately twice the amount of radial shrinkage. The ranges of the measured radial shrinkage values were 0.024 – 0.094 mm mm^{-1} for regrowth blackbutt and 0.037 – 0.125 mm mm^{-1} for plantation blackbutt. The higher shrinkage values for plantation blackbutt timber show that plantation material is less stable dimensionally, and this situation is possibly due to the high juvenile wood content and low basic density. These differential (tangential:radial) shrinkage values ranged from 1.12 – 2.93 for regrowth blackbutt and 1.09 – 2.92 for plantation blackbutt.

Tests were conducted to determine the degree of statistical normality for the distribution of each property (physical, transport, and mechanical). The results of the normality tests showed that most timber properties for regrowth and plantation blackbutt timber were distributed normally on a linear scale based on the *W* test, both within and between—trees. On the other hand, some timber properties showed a better fit with the three—parameter lognormal distribution, such as the diffusion coefficient and the green failure strain for within—tree variability of regrowth timber.

The means and standard deviations of these distributions were further analysed by applying significance tests at a 0.05 level. For regrowth blackbutt, the data for the initial moisture content, the basic density, the diffusion coefficient, and shrinkage showed no significant differences, comparing the cases within and between—trees. The mechanical behaviour, however, was significantly different between each group and suggested that the two regrowth trees used for the within—tree test were stiffer than the 12 trees used for the between—trees test. It was possible that the mechanical properties were dependent on the geographic location where the tree was felled, and the heartwood content of each log. On the other hand, since all the plantation logs used for the within and between—trees tests were taken from one location, the mechanical properties were not significantly different within the plantation sample. The silviculture and the age of all the plantation trees were the same, which might have contributed to the small variation of the timber properties between the within—tree and between—trees cases for plantation material. Lastly, a significance test was conducted to compare the properties of regrowth and plantation blackbutt timber. Most timber properties (except for the initial moisture content) were significantly different between regrowth and plantation blackbutt. Plantation blackbutt timber had a lower basic density, higher diffusion coefficient and shrinkage, and the modulus of elasticity (both in its green and dried states) was lower compared with regrowth blackbutt timber. In addition to geographic location, heartwood/juvenile content, maturity (age), and differences in microfibril angle may have affected these timber properties in plantation blackbutt timber.

For all the experiments, the possibility that there is a correlation between high initial moisture contents, higher diffusion coefficients, low basic densities, and low green modulus of elasticity's (MOE) was assessed using principal components analysis (PCA). A principal components analysis was performed on the four parameters: the basic density, the initial moisture content, the diffusion coefficient, and the green MOE. The results of the PCA showed that the principal component for the within—tree and between—trees test accounted for 93% and 94% (for regrowth), and 92% and 90% (for plantation), respectively, of the total amount of variation within these parameters, giving some support for the mentioned correlation between the parameters.

The strong correlation between the diffusion coefficient and the basic density, ρ_D; the diffusion coefficient and the initial moisture content, X_i; and the diffusion coefficient, D, and the modulus of elasticity, E_G were represented by empirical equations. The F significance test was conducted to determine if the equations from the within—tree and between—trees tests, and the regrowth blackbutt and plantation blackbutt tests, were significantly different. The difference between the equations for the within—tree and between—trees variability of plantation blackbutt timber ($F_{actual} = 1.35 < F_{expected} = 2.13$) was the only result that showed no significant difference. A possible reason for this finding is that the boards from the within—tree and between—tree variability tests, hence the trees, were all felled from one location. On the other hand, the other tests compared boards that were taken from trees felled from different locations, including the regrowth blackbutt within trees, compared with between trees. The results of the significance tests imply that boards taken from one location, whether they are within—tree and between—tree samples, have probably come from the same overall population. Hence using any of the correlations (within—tree or between—trees for plantation blackbutt) would be suitable to estimate the diffusion coefficient of other plantation blackbutt samples at the same location. Overall, these empirical equations can be used to estimate important drying properties of other regrowth and plantation blackbutt samples, such as the diffusion coefficient, using easily measured properties, like the initial moisture content or the basic density, as long as the boards are taken from the same age group (i.e. regrowth or plantation) and the same location. Thereafter, the blackbutt timber boards may be segregated based on the range of diffusion coefficients as estimated from the densities or the initial moisture contents. Hence a suitable drying schedule should be chosen for each segregated group. Collapse was not significant for blackbutt samples studied in this thesis, and possibly this timber species in general, but it may be significant for other eucalyptus species such as collapse—prone *Eucalyptus regnans* F. Muell (mountain ash) This potential limitation means that care is needed in applying the relationships found in this thesis to collapse—prone species.

The same drying model was used to assess the effects of different drying schedules (i.e. increasing and decreasing the dry—bulb and wet—bulb temperatures of the original drying schedule by 5^{o}C and 10^{o}C) and of the potential correlations between the diffusion coefficient, the green MOE, the shrinkage coefficient (calculated from the tangential shrinkage), and the initial moisture content on the variability of final moisture contents, when the average moisture content within a stack of timber reached 15%. In addition, the maximum strain attained by the timber boards was also predicted. The results show that for regrowth blackbutt timber and accounting for within—tree variability, there was no relationship between the length of the drying schedule and the dispersion of final moisture contents. As the temperatures increased, the dispersion of the final moisture contents showed no consistent trend. The absence of a clear trend may be due to the different locations where the logs used for the within—tree test of regrowth variability were taken. On the other hand, the between—tree variability sensitivity tests for both regrowth and plantation blackbutt timber and the within—tree variability sensitivity test for plantation blackbutt timber show a relationship between the length of the drying schedule and the dispersion of final moisture contents. The dispersion of the final moisture contents decreased as temperatures increased. Generally, the '+10^{o}C' drying schedule gave the shortest time for the stack of timber to reach the target average moisture content, and its conditions produced the smallest dispersion of final moisture contents. It was also observed, however, for all sensitivity tests, that as the temperature of the drying schedule increased, the average predicted values decreased for the maximum strains reached. This is a very unusual result, because normally the strains and stresses would be expected to increase with increasing temperature. A possible reason for this is that within a piece of timber, as the temperatures increase, the diffusion coefficient will increase because the internal average temperature increases, so the internal resistance to mass transfer decreases, which leads to the moisture content gradient decreasing, even though the drying rate may slightly increase. This decreases both the drying time and the maximum strain reached as the temperature increases. There are limitations, however, associated when using high temperatures in kiln drying such as collapse and timber discolouration.

The optimization technique created by Pordage (2006) was improved by using a large number of measurements to quantify the variability in the properties of blackbutt timber. The first simulation accounted for the between—tree variability of the biological parameters in regrowth blackbutt, and the second simulation accounted for both the within and between—tree variability of the timber properties in plantation blackbutt. Since location was observed as a main source of variability, the timber properties used for each simulation were taken from the logs that were felled from the same location. The mean and the standard deviations of the initial moisture content, the reference diffusion coefficient, and the shrinkage coefficient of regrowth and plantation blackbutt timber boards measured in the actual drying experiments, along with the covariance between these properties represented by a covariance matrix, were used for each simulation. The total drying time of the optimized drying schedule of plantation blackbutt timber was longer (an additional 168 hours, i.e. 472 hours) compared with the total drying time of the optimized drying schedule of regrowth blackbutt timber (304 hours). Due to the greater variability present in plantation blackbutt, slower drying is required. Moreover, the total drying times from the ‘regrowth blackbutt’ optimization and the ‘plantation blackbutt’ optimization (which both accounted for variability) were shorter compared with the total drying time of the original drying schedule for 28 mm—thick mixed—sawn blackbutt boards, i.e. 504 hours. On the other hand, the total drying times of the optimized drying schedules of regrowth and plantation blackbutt timber were greater than the total drying time (152 hours) predicted by Pordage’s (2006) optimized drying schedule accounting for the variability of *Eucalyptus paniculata* (grey ironbark). He had limited information on the variability of the parameters of grey ironbark and thus used an estimate from another eucalyptus species, *Eucalyptus obliqua* (messmate), whereas in this thesis, the variabilities for regrowth and plantation blackbutt used for the optimization technique were measured and part of the scope for this study. Overall, this is a typical application of the data obtained in this thesis to the optimization of drying schedules.

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GLOSSARY

(a) Activation energy – Heat of evaporation for free water. Diffusion will occur when the water molecule gains a certain 'activation energy' in order to overcome the forces acting on it.

(b) Bound Water – moisture that is bound to cell walls within the timber.

(c) Conditioning – A treatment to equilibrate the timber's moisture content to a specific value.

(d) Convection – This moisture transport occurs when there is bulk movement of water (in timber), and the timber is permeable. Convection occurs under the influence of a pressure gradient.

(e) Copice – Regrowth trees that grow from dormant bunds located under the bark of tree stumps after the tree has been felled.

(f) Diffusion – molecular flow of water (in timber) from a region high concentration to that of low concentration. This is achieved under the influence of a concentration gradient.

(g) Distortion - A drying defect, otherwise known as warping, caused by the differential shrinkage along the three axes of a piece of wood. Distortion may either take the form of cup, bow, twist, spring or diamonding.

(h) Equilibrium moisture content (EMC) - the moisture content at which the timber neither gains nor loses moisture from the surrounding atmosphere.

(i) Fibre saturation point (FSP) – A theoretical point (usually 0.3 kg water/ kg dry material) where there is no free moisture within the cells, but only bound water remains in the cell walls. At this point, apparent shrinkage of the timber is expected to take place.

(j) Free water – moisture that is present within the cell cavities of timber.

(k) Heartwood – The section of the tree where the pits aspirate as the tree gets older. This used to be sapwood. Only diffusion is expected to occur in this region (when cells become blocked). This region also stored the tree's nutrients for winter, and increases the resistance of the tree towards insect attacks and decay.

(l) Initial centre moisture content – Moisture content at the centre of the timber before drying.

(m) Lignotuber growth - Swollen underground root structure (develop by most eucalypts). This root structure is capable of sprouting new shoots if the tree is damaged.

(n) Reference diffusion coefficient – Also known as the preactivation factor, the coefficient in front of the exponential factor expressing the temeperature dependence of the average diffusion coefficient.

(o) Sapwood - The region of cells that allows sap to flow between cells. Therefore, both convection and diffusion can occur in this part of the tree.

(p) Spiral grain – Fibres that take a spiral course about the timber trunk instead of the normal vertical course. The spiral may extend in a right handed or left-handed direction around the trunk.

(q) Strain coefficient – Parameter used to predict the strain during drying.