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Quality assessment of the drying process for *Eucalyptus delegatensis* timber using greenhouse solar drying technology

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Abstract

The aim of this study was to investigate the process of drying *Eucalyptus delegatensis* in a greenhouse solar kiln. Specific objectives were to assess stress formation, moisture gradients and timber distortion, the moisture content distribution within various sections of the timber stack, and internal checking and collapse development within the boards. The maximal temperature and relative humidity (RH) during day time were set at 43^{0}C/72% RH. In the night time the temperature was at ambient condition with 90% RH. The strain measurements were undertaken before and after the samples were sliced. The timber quality at the end of drying was assessed based on Australian and New Zealand standard (AS/NZS 4787:2001). The moisture content values in the three different sections (front, middle and end) of 2400 mm long boards were compared by Analysis of Variance. The results showed that the mean compressive strain was -2 x 10^{-4} mm/mm in the core layers and the tensile strain was 14 x 10^{-4} mm/mm in the outer layers. All sample boards were within the acceptable limits for cupping, spring and bow, even though the relative humidity level did not reach the set value. However, the amount of twist in three out of twelve sample boards was above the acceptable limit. Mean moisture gradient was 0.6%. There was a significant difference in moisture content at end section compared to the front and middle sections. Internal checking, collapse and residual stress were graded as Class "C" (class A is the highest grade and D is the lowest).

Keywords:
Solar kiln drying method, Timber quality assessment, Timber stress, Eucalyptus delegatensis, moisture content.

Introduction

Wood drying is a vital stage in producing high quality wood products. Solar drying methods usually involve cyclic or intermittent drying techniques where the temperature, humidity and airflow within the kiln vary throughout the process (Chua et al. 2003; Kumar et al. 2014; Langrish 2013). As reported by VijayaVenkataRaman et al. (2012) solar dryers have been developed by many researchers for different purposes, such as for mixed mode natural convection, to test a glasshouse-type solar timber dryer. Since there are many types of solar dryers for specific uses; for example, for drying timber, and for drying food. The design structure of solar kilns may require further improvements to fit their uses (Pirasteh et al. 2014; Singh et al. 2018). A series of modifications have been done to optimize their thermal and drying efficacy (Luna et al. 2009). For example, a mixed–mode solar kiln with black pebble bed as absorber and storage has been designed and evaluated (Ugwu et al. 2015).

Solar kiln drying offers benefits of improved timber quality, lower cost and is considered an environmentally friendly process. At night time is the period of no heating; this is known as a cooling period when drying stresses can be released (Herritsch et al. 2010). The use of diurnal energy through the solar kiln drying method reduces the drying cost. A comparison of the drying economics of solar kilns and steam kilns for 2.5 cm thick planks of *Tectona grandis, Artocarpus chaplasha, Michelia champaca, Albizia procera* revealed that total drying expenditure per annum for a solar dryer was approximately 60% of the steam kiln drying cost (Satta 1994). Solar kilns have been introduced as a suitable drying method in tropical countries; for example, in Sri Lanka where the solar radiation and temperature are high (Simpson and Tschernitz 1984).

Several drying schedules for solar kilns have been investigated so far (Brodie 2008; Haque 2006; Harris 2012; Hasan and Langrish 2014). However, a specific drying schedule is required for a particular species based on the intermittent method because solar dryer capacity is dependent on local diurnal conditions (Hasan and Langrish 2014). Chadwick and Langrish (1996) revealed that collapse and internal checks of *Eucalyptus pellita* dried in cyclic drying conditions were lower than in the continuous drying technique. Drying *Eucalyptus regnans* boards in an intermittent regime has also resulted in a lower number of internal checks than in the continuous drying method (Chafe 1995). Different schedules with different intensities of heat and relative humidity need to be investigated for their ability to improve the quality of timber using solar kilns.

The Alpine Ash (*Eucalyptus delegatensis)* , basic density is 536 kg/m^3. This species is widely distributed in the Southeast of New South Wales, Eastern Victoria and in Tasmania, Australia (llic et al. 2000). This timber species is used for many types of wood products in Australia such as furniture, flooring, architectural applications and timber framing. However, *Eucalyptus delegatensis* was grouped in a best-known collapsing species (Kauman 1960).

The objective of this study was to investigate the drying process of *Eucalyptus delegatensis* in a greenhouse solar kiln. Specific objectives were: to assess stress formation, moisture gradients and timber distortion; to evaluate the moisture content distribution within various sections of the timber stack; and to assess internal checking and collapse development within the boards.

Materials and methods

Solar kiln and control settings

The greenhouse type solar kiln (Solarkilns Pty Ltd, Kilsyth, VIC, Australia) with two layers of plastic cover was used in this study. The kiln was located in Melbourne, Australia, at 37º49'46.2"S 145º01'25.7"E. The black and white sheets were placed on the inner side for insulation and to collect heat from the sun's radiation, while the outer layer was transparent, which allowed radiation to propagate unhindered to the black sheet (Fig. 1). The insulation was 200 µm thick and made from polyethylene film. A control unit allowed the setting of temperature (±0.5ºC) and relative humidity (RH, ±2% between 0–90% and ±4% between 90–100%). A humidity/temperature transmitter (Testo 6621 duct version, Germany) was used to determine the relative humidity and temperature inside the kiln.

The parameters were set at a maximum temperature of 43ºC and 72% RH with air velocity of 1–2 m/s during day time (07:30–17:30), and at ambient temperature (AmbT) with 90% RH and air velocity of 0.5–1m/s at night time (17:30 – 07:30).

Fig. 1 Schematic view of solar kiln and timber stacking (Front view)

Timber preparation and test methods

Eucalyptus delegatensis timber from regrowth forest, 75 years old, was used in the study. Forty–eight back sawn boards (40 x100 x 2400 mm) were loaded into the kiln. The boards were stacked in 12 layers, with 4 boards on each layer and a 25 mm distance between the layers. Initial mean moisture content (MC) was 75%. Twelve sample boards (SB) were selected for the assessment of compressive and tensile stresses, MC gradient, and timber distortion, from Row 2, 6 and 10 of the stack (Figure 1). These boards were cut into 3 specimens 800 mm long (Fig. 2) and used to assess MC gradient, compressive and tensile stresses. Timber distortion was calculated and graded as per Australian standard of timber stress grading rule (AS 2007) at the end of drying run.

Fig. 2 Specimen positions of final moisture content (MC), moisture content gradients (Core MC) and compressive and tensile strains (ST)

The technique for assessing compressive and tensile stresses was derived and modified from McMillen (1955). The stress specimens were sliced to 8 layers with a thickness of 5mm each using a 14-inch bandsaw (LEDACRAFT BS350) (Fig. 3a). Layers 1 and 8 represent the surfaces or case areas while layers 4 and 5 represent the inner layers or core areas. Layers 2, 3, 6 and 7 are the areas in between the core and the case. The layers were measured using a digital calliper before slicing and then re-measured after slicing.

The MC gradient measurement technique was based on AS/NZS 4787:2001 (AS/NZS 2001) and the method of measuring moisture content gradient during drying was modified from Blakemore and Langrish (2008), among others. In total, 35 specimens were used for measuring core moisture gradients. All specimens were split with a guillotine into 8 layers with a thickness of 5 mm and a diameter of 20 mm for each layer (Fig. 3b).

Fig. 3 Slices for (a) compressive and tensile strain measurements and (b) determining MC profile of 8 layers

Sample cross sections, exposed by docking individual sections at 200 mm intervals along the 35SB, were observed, measured and graded for internal checking, timber collapse and residual drying stress based on AS/NZS 4787:2001 (AS/NZS 2001). The moisture content in three different sections of 2400 mm long boards, at the front (MC_F), middle (MC_M) and end (MC_E) (Fig. 4), were compared by Analysis of Variance (ANOVA) using MATLAB (V. R2015a).

Fig. 4 Sample boards designed for internal checking (IC) and moisture content (MC) measurements.
Note: the numbers from 1–10 indicate that checks were measured and collapse assessed at each cross-cut section

Results and discussion

Kiln and ambient conditions

The solar kiln was operating from 26th Nov 2014 until 3rd Feb 2015. The mean minimum temperature inside the solar kiln during the relaxation time was 16 ± 3ºC and the mean highest temperature during the day time was 36 ± 8ºC between 12:00pm – 2:00pm (Fig. 5a). The minimum and maximum night time temperature ranged from 12ºC to 23ºC while the minimum and maximum day time temperature was between 20º and 50ºC (Fig. 5b). The maximum temperature inside the kiln exceeded the set value (43ºC), which could result from insufficient thickness of the insulation layer, with the heat potentially conducting from the black side to the white side too quickly and the material not being heat resistant. Therefore, the design of the kiln insulation needs to be improved to ensure the temperature is well maintained, as suggested in numerous studies (Luna et al. 2009; Pirasteh et al. 2014; Singh et al. 2018).

The mean temperature of the solar kiln was 10ºC higher than the ambient day time temperature but the kiln and ambient temperatures were equalized at night. The mean RH inside the solar kiln (Figure 5a) ranged between 49% and 90%. The night time RH was kept at 90 ± 4%, but it decreased from sunrise to reach its lowest value of 49 ± 17% between 12:00pm–2:00pm. The range of night time RH was 54% –90% and the day time range was 49% – 70%RH.

Fig. 5 Internal temperature and relative humidity conditions of solar kiln during 24 hour cycles (a) and the mean minimum and maximum temperature inside the solar kiln (b)

The RH value during the day time was only able to reach 49%RH at 2pm, which was almost equal to the day time ambient condition. In contrast, at night time the RH reached 90%. During the drying experiment, a technical fault in the spray nozzle occurred in the kiln, which could be the reason why the set value for RH could not be reached.

As the kiln's temperature was based on ambient conditions, the rate of increment of temperature inside the solar kiln was varied. This could also affect the timber quality as on some days a high temperature was achieved with a very low relative humidity. There were 12 days during the drying period of 70 days when the temperature in the solar kiln reached more than 43ºC between 11:00am-12:00pm (Fig. 6).

Fig. 6 Number of days when the temperature inside the solar kiln was higher than 43ºC during day time

Drying rates and moisture content gradient

The mean moisture content of timber boards in the solar kiln decreased from green (75%) to below 12% after 70 days (Fig. 7). It can also be seen that it took 25 days to reach the fibre saturation point *(fsp)* of 25% MC. The final moisture content of the boards ranged from 11.8-12.1%.

Fig. 7 Development of mean moisture content over time of *E. delegatensis* in the solar kiln

The mean MC decreased by 0.3% per day from *fsp* to 12.0% MC after 45 days for *E. delegatensis*. This value is approximately 0.2% lower than the value that was predicted for Tasmanian eucalyptus (*E. obliqua*), 28mm thick boards under air velocity of 0.5 m/s (day time) and 0.05 m/s (relaxation) by Hasan and Langrish (2014). The difference could be due to the lower thickness of timber and lower air velocity used in the model compared to the current experiment. For example, Khater et al. (2004) revealed that the rate of moisture content loss in timber is faster at higher air velocity than at lower velocity. The mean moisture gradient at the end of the kiln run of all samples was 0.6% MC between outer and inner layers.

Compressive and tensile stresses

Compressive and tensile strains of all samples are shown in Table 1. The tensile stress was found at the outer layers (layer 1 & 8). The compressive stress was created in layers 2–7. The mean compressive strain was found at -2 x 10^{-4}mm/mm in inner layers 4 and 5, and the mean tensile strain at the end of the kiln run was a 14 x 10^{-4} mm/mm in surface layers 1 and 8. The maximum tension and compression was 44 x 10^{-4} mm/mm (in layer 1 & 8) and -46 x 10^{-4} mm/mm (in layer 3 & 6), respectively. The maximum strain level was lower than 80 x 10^{-4} mm/mm, which was predicted by the model developed by Hasan and Langrish (2014).

Timber distortion

Bow, spring, cupping, twist and the stress residual (Table 1) were measured according to AS 2082-2007 (AS 2007). Bow and spring were within the acceptable limit of 10 mm. The maximum measured values of bow, cupping and spring reached up to 3 mm for all boards. However, the measured twist of three samples boards out of twelve was above the acceptable limit of 5mm, reaching up to 9 mm. There were no end splits found in the boards.

Table 1. Statistical results of the timber qualities

Internal checking and collapse

Based on the results of the assessment of internal checking, timber collapse and the samples were graded as class "C", as shown in Table 2.

Table 2. Internal checks and collapse grading as per AS/NZS 4787:2001(AS/NZS 2001)

Measuring internal checks in the wood using a digital calliper may be inaccurate due to the very small shape of internal checks which are difficult to see with the naked eye.

Comparison of moisture content distribution along boards

The mean final moisture content of all boards was 12.0%, while the MC of boards at the front, middle and end (F, M, E) sections of the timber stack inside the solar kiln after drying were 12.1%, 12.1% and 11.8%, respectively. There is a significant difference for the E section compared to the F and M sections, as shown in Table 3. Section

E of the timber stack may have been affected by higher temperature than the remainder of the stack as it was closest to the wall of the solar kiln, which could cause the timber to dry quicker than other parts of the stack. Considering the difference of MC distribution among those sections, the mean MC difference between 12.1% and 11.8% was very small, less than 1%. The final moisture content of dried timber with such a small difference means the three groups would be accepted in commercial operations.

Table 3. Comparison of the moisture content distribution in three sections of the boards

Conclusion

The analysis of stress formation in *E. delegatensis* under the solar kiln conditions showed that the mean compressive strain was -2 x 10^{-4} mm/mm in the core layers and the tensile strain was 14 x 10^{-4} mm/mm in the outer layers. Mean MC gradient was 0.6 % between outer and inner layers. All sample boards were under the acceptable limit of 10mm for bow and spring, but twist exceeded the limit of 5 mm in three out of twelve boards. For internal checking, collapse and stress residual the boards were graded as class "C".

There was a significant difference in moisture content at the end section compared to the front and middle of the timber stack. Fluctuation of temperature inside the solar kiln is critical for reducing the timber drying degrades. It is suggested that controlling EMC in the kiln by keeping a high level of RH during times of higher temperature could reduce the rapid change of MC in wood that results in severe checking.

The method of achieving uniform temperate distribution in the solar kiln should be investigated. In particular, preventing the exposure of end sections of boards to high temperatures should be considered in future use of this greenhouse solar kiln.

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Table 1. Statistical results of the timber qualities

Parameters	Average (mm)	Minimum (mm)	Maximum (mm)
Strain: layer 1&8	14×10^{-4}	-41×10^{-4}	44×10^{-4}
Strain: layer 2&7	-6×10^{-4}	-41×10^{-4}	35×10^{-4}
Strain: layer 3&6	-14×10^{-4}	-46×10^{-4}	6×10^{-4}
Strain: layer 4&5	-2×10^{-4}	-41×10^{-4}	1×10^{-4}
Bow	1.1	0.2	3.0 [a]
Spring	1.2	0.4	2.8 [a]
Cupping	1.5	0.4	2.9
Twist *	3.0	1.1	9.0

[a] Under the permissible level of 5 mm as per AS 2082-2007 (AS, 2007)

*Note: * three samples out of twelve exceeded the permissible level.*

Table 2. Internal checks and collapse grading as per AS/NZS 4787:2001(AS/NZS, 2001)

Parameters	Average	Maximum	Overall Grading	Total number of samples
Internal checks (% loss of check/cross cut area)	0.2	8.3	C	350
Collapse (mm)	0.4	2.5	C	350

Table 3. Comparison of the moisture content distribution in three sections of the boards

Parts of Section	Average (%)	SE
F	12.1[a]	443×10^{-4}
M	12.1[a]	443×10^{-4}
E	11.8[b]	443×10^{-4}
LSD (0.05)		

[a] *The section of no significant difference among sections.*

[b] *The section of significant difference to other sections at the level of 0.05. SE is standard error.*

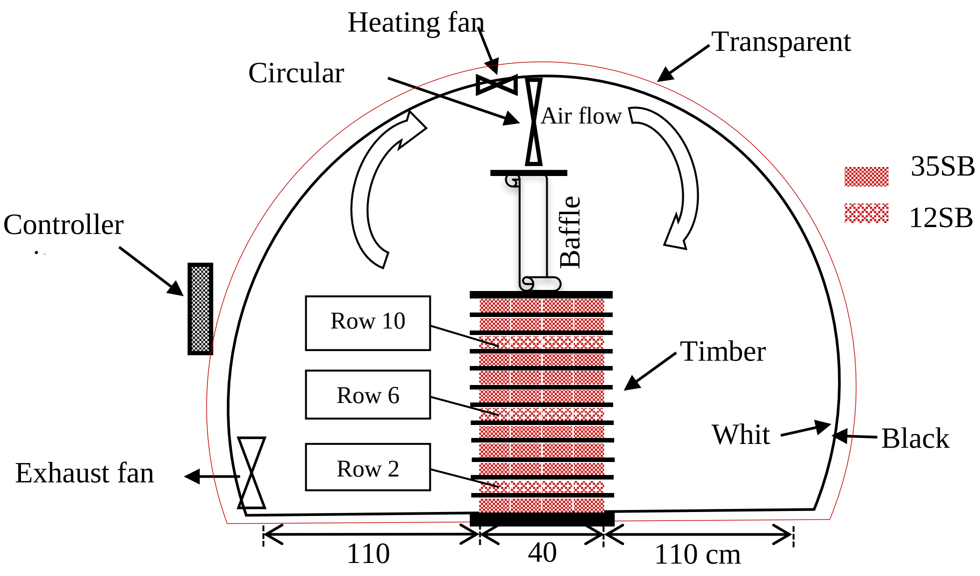


Fig. 1 Schematic view of solar kiln and timber stacking (Front view)

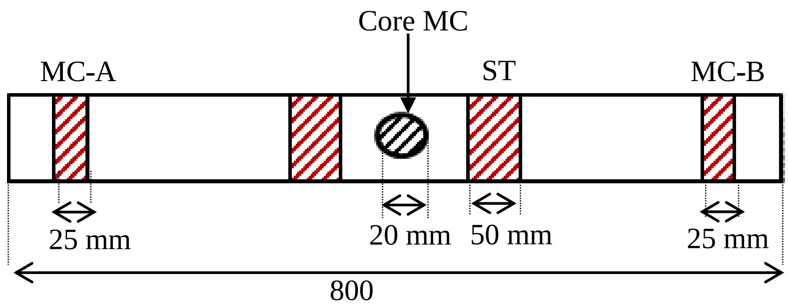


Fig. 2 Specimen positions of final moisture content (MC), moisture content gradients (Core MC) and compressive and tensile strains (ST)

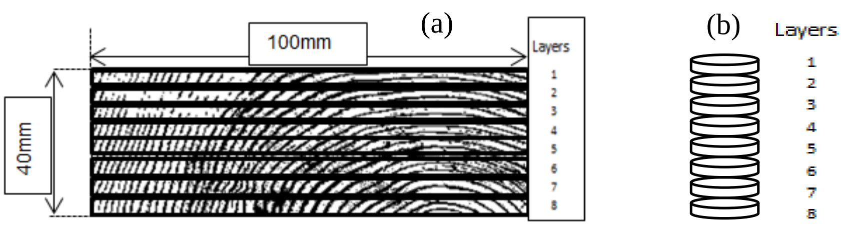


Fig. 3 Slices for (a) compressive and tensile strain measurements and (b) determining MC profile of 8 layers

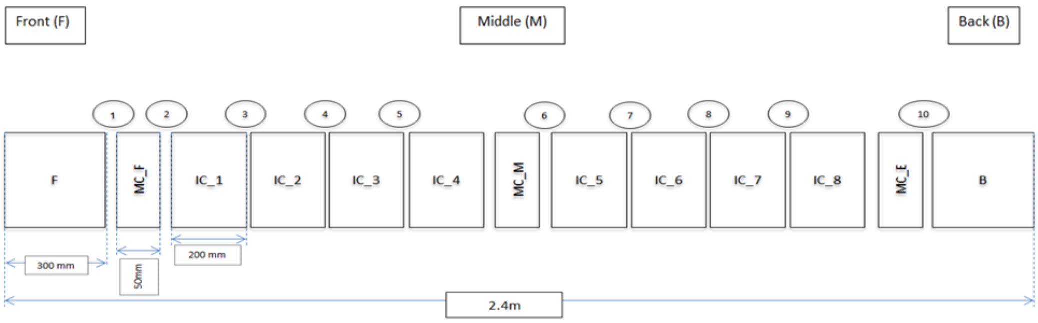
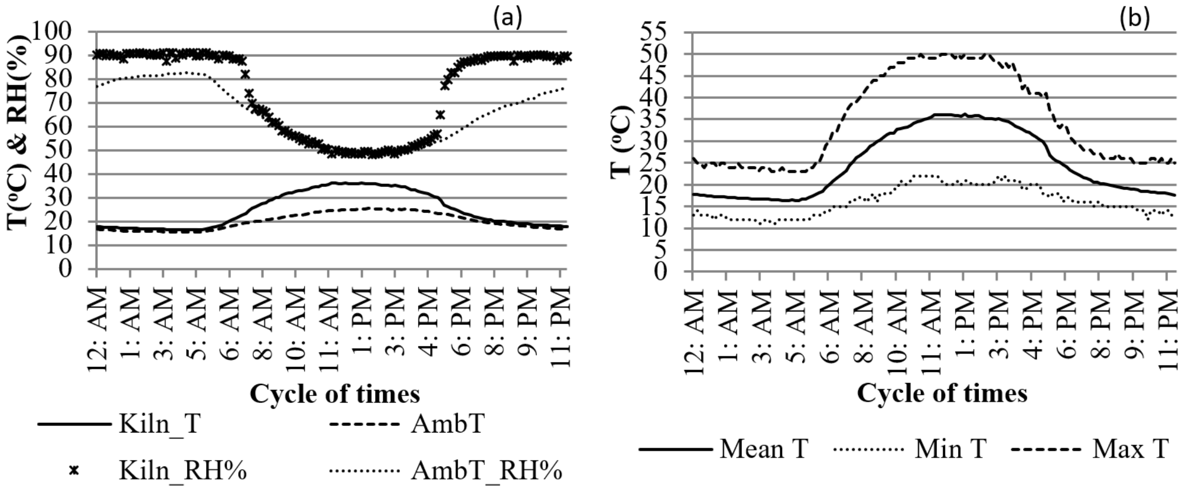


Fig. 4 Sample boards designed for internal checking (IC) and moisture content (MC) measurements.

Note: the numbers from 1–10 indicate that checks were measured and collapse assessed at each cross-cut section



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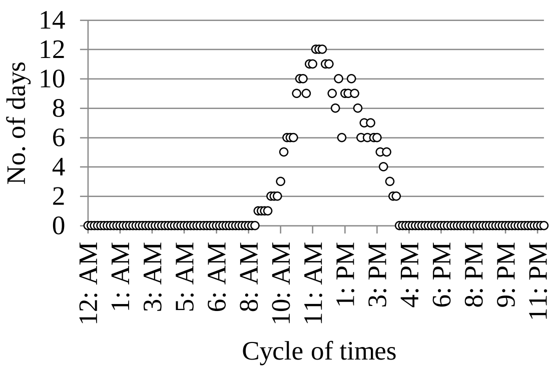

Fig. 6 Number of days when the temperature inside the solar kiln was higher than 43ºC during day time

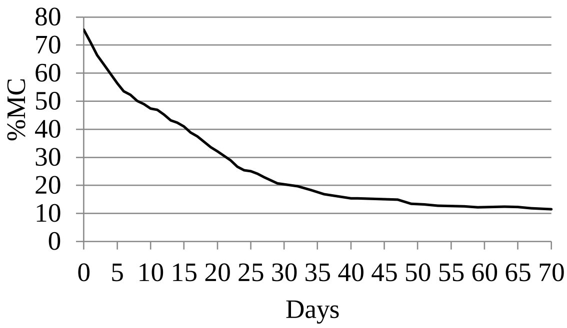

Fig. 7 Development of mean moisture content over time of *E. delegatensis* in the solar kiln