Simulating Solar Kiln Conditions using a Conventional Kiln

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This study assessed the possibility of using a conventional laboratory kiln to simulate solar kiln conditions and developed a mathematical model to predict the timber quality and moisture content profile during drying. The simulated temperature in the kiln was modelled on the actual temperature of a solar kiln based on the climatic conditions of Vientiane, Laos. The modelling for moisture content profile in boards was implemented in Matlab codes, which combined fundamental equations and validated the model with measured data. Timber quality assessment was performed based on quality standard AS/NZS 4787 (2001). The simulation results were similar with the measured solar kiln temperatures to within less than 2 °C in a day. The modelling correctly described the MC profile decrease during the drying process when compared with measured data. Further work is required regarding the method of measuring the MC data and anatomical properties. Assessed against the standard, timber quality at the end of drying was all graded as Class “A”, and timber distortion was within permissible limits.

Keywords: Simulation drying; Solar drying; Mathematical modelling; Timber quality

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INTRODUCTION

Simulations based on software models have been introduced and applied in many fields including flight simulation and medical education (Rolfe *et al.* 1970; Miller 1987; Hossain *et al.* 2005; Shenga *et al.* 2015). In timber drying research, numerical simulation and modelling have been used to predict the temperature and drying rates of boards inside solar kilns (Fortin *et al.* 2004; Hasan and Langrish 2014). However, using physical hardware to simulate the conditions of a solar kiln has not yet been attempted. It is possible to simulate the conditions of a solar kiln using such technology by manipulating the temperature and relative humidity. This strategy is supported by Roza (2005), who has argued that physical realization of a conceptual model can be achieved through hardware implementation of part or all of a conceptual model, *e.g.*, the layout of instrument panel in a mock-up or motion platform.

Solar drying methods usually involve cyclic or intermittent drying techniques where the temperature, humidity, and airflow within the kiln vary throughout the process (Kumar *et al.* 2013). Phonetip *et al.* (2017a) applied an intermittent drying schedule in solar drying and found that the oscillation of temperature inside a solar kiln did not respond to the intermittent schedule. For instance, the temperature gradient between the temperature oscillation in the conventional kiln and the solar kiln was 7 °C. Hence, mimicking the oscillation conditions of actual temperature inside a solar kiln by using a conventional kiln was suggested by Phonetip *et al.* (2017a). Changes in temperature and relative humidity (RH) can be manipulated in a conventional kiln over a 24-h cycle. This approach could provide a better understanding of solar drying characteristics rather than using intermittent drying schedules, which are based on heating and non-heating modes (Phonetip *et al.* 2017b). Oscillating conditions in a timber drying process have been the subject of numerous studies (Chua *et al.* 2003; Salin 2003; Sackey *et al.* 2004; Rémond *et al.* 2007; Milić *et al.* 2013). Salem *et al.* (2016) applied oscillating conditions of 15 °C and 45 °C and a relative humidity (RH) between 25% and 73% over a period of 24 h for 7.5 days. They used *TransPore* code to simulate drying of 27 mm thick *Fagus sylvatica* boards. The drying rate was 4.6%/day from an initial MC of 65% to 30%.

Understanding the changes in MC profile of a timber board during drying can be an indicator of timber stress development (Carlsson and Arfvidsson 2007). Many models have been developed to predict MC changes during drying (Pang 1996; Keey and Nijdam 2002; Fortin *et al.* 2004; Konopka *et al.* 2017). However, most are only applicable in continuous drying, whereas the technique of simulating a solar kiln drying process using a conventional kiln has not yet been applied. In recent studies, measurement of the MC profile in 40 mm thick *Eucalyptus delegatensis* boards has been conducted during intermittent drying (Yuniarti 2015; Phonetip *et al.* 2017b) and solar drying (Phonetip *et al.* 2017a). However, a mathematical model that could predict the change in MC profile during intermittent drying has not yet been developed. Such a model could be used to predict timber quality against the MC profile during drying.

Timber degradation, which occurs during drying, is evidence of poor drying conditions. Phonetip *et al.* (2017a) found that surface and internal checks formed in boards were similar, whether the identical drying schedule used intermittent drying in a conventional laboratory kiln or a solar kiln. For instance, the drying conditions used in an intermittent drying experiment were 45 °C and 60% of relative humidity (RH) for 9 h during the heating phase (daytime), and ambient temperature with RH of 80% for 15 h during the non-heating phase (night time). However, the temperature oscillations inside the solar kiln varied from the conventional laboratory kiln by more than 7 °C. The authors concluded that surface checks, found in the sample boards, might have formed when the temperature reached more than 45 °C in the solar kiln. Haque (2006) predicted that internal temperature of a solar kiln should be set at 43 °C, to avoid excessive stresses in boards dried at the latitude for Melbourne, Victoria.

Eucalyptus species have been grown in Laos for decades. Eucalyptus plantations accounted for approximately 13,129 hectares in 2014; *i.e.*, *Eucalyptus camaldulensis, Eucalyptus urophylla* and modified species (Oji Lao Plantation Company 2014). Traditionally, timber in Laos is partly air dried before being kiln dried. For instance, the average initial MC of timber ranged between 57% to 68% (Redman 2016). There is an increasing interest among timber companies to use solar kilns in Laos, but drying schedules based on Lao's climatic conditions and solar kilns have not yet been developed (Phonetip 2014). Solar kilns of the greenhouse type usually depend on solar radiation, which ultimately affects drying time (Phonetip *et al.* 2017d). The average temperature inside the solar kiln is also influenced by internal air velocity (Khater *et al.* 2004). Conducting a solar drying experiment requires knowledge of the right conditions (*e.g.*, duration of dry season, radiation). Therefore, exploring the capability of a conventional kiln in a laboratory as a simulator of climatic conditions in Laos and for similar geographical latitudes may be a useful method for conducting experiments in solar drying.

This study simulated temperature oscillation in a solar kiln using a conventional laboratory kiln, developed a mathematical model for predicting the moisture content profile in timber boards during drying, and assessed surface and internal check formation during drying, as well as timber quality at the end of drying.

EXPERIMENTAL

Nomenclature

Abbreviations used in this paper are defined in Table 1.

Table 1. Abbreviations

ΔT	Absolute different values (°C)
T_{si}	temperature at a specific step in the simulated reality (°C)
T_{ai}	temperature at a specific step in the actual measurement (°C)
M	The different value between the MC and EMC (%)
M_0	The different value between the initial MC of the boards and EMC (%)
D	The diffusion coefficient (m^2/s)
t	Time (days)
x	The spatial coordinate (m)
B_n	The amplitudes of the sinusoidal functions that for the MC profile (%)
β_n	The roots of $\beta_n \cdot tan(\beta_n) = \frac{h \cdot l}{D}$
h	Coefficient of convective moisture loss from the surface of the wood

Materials

Twenty-one samples of *Eucalyptus delegatensis* boards of 40 x 100 x 900 mm were used in this study. Before the experiments, the ends of each board were sealed with silicone and covered with aluminum foil to prevent moisture loss from the end grain. A drill press machine (Model BD-16, McMillan, Taiwan), was used to take core samples of boards for determining MC profile.

Methods

Simulation method

The experiment was conducted in Melbourne, Australia. The maximum solar radiation in Vientiane, Laos is 6 kWh/m^2/day, which is comparable to the radiation in Melbourne, Australia (SSE 2017). Therefore, the ambient temperature in Vientiane was considered to develop a drying schedule for this simulation study. The temperature gradient between the kiln temperature and ambient temperature was based on Phonetip *et al.* (2017d). The temperature gradient values were then added to mean ambient temperature; this mimics the temperature values from step 1 through to step 9 per day, as shown in Table . The oscillating temperature used in this experiment was based on the condition of Vientiane, Laos. These temperature values were used as the simulated temperature in the conventional kiln, with the oscillation in the average temperature being derived from March and April (summer period). The RH settings were derived from Phonetip, *et al.* (2017b), as maximum RH in Vientiane does not exceed 80% during night time (non-heating) and it is lower than 60% during heating (day time) (SSE 2017). Therefore, this current experiment, RH level inside the kiln was assigned at 60% during heating while non-heating was 80%. A fan speed of 800 rpm was applied to provide an air velocity of 1 m/s through the sample board stack.

Table 2. Drying Schedule for Mimicking a Solar Kiln Using a Conventional Laboratory Kiln

Simulation parameters	A repeated cycle of 24 h a day								
Steps	1	2	3	4	5	6	7	8	9
Average *T* in Vientiane (ºC) (SSE 2017)	25	28	33	34	30	28	26	25	25
T gradient (ºC) (Phonetip *et al.* 2017d)	4	10	10	5	0	0	0	0	0
Mimicking temperature (ºC)	29	38	43	39	30	28	26	25	25
Solar kiln RH (%) (Phonetip *et al.* 2017b)	60	60	60	60	80	80	80	80	80
Time interval (h) (Phonetip *et al.* 2017d)	3	3	1	3	3	3	3	2	3

A simulation fidelity assessment was used to determine the reliability of the proposed temperature selection for the experiments, based on the absolute difference in values (ΔT) between the actual measured temperature in solar kilns and the simulated temperature in laboratory kilns (Roza 2005) at specific moments during the daily cycle. The calculation is expressed as Eq 1,

$$\Delta T = \left|T_{si} - T_{ai}\right| \tag{1}$$

where T_{si} is the temperature (°C) at a specific step in the simulated reality. T_{ai} is the actual measurement of temperature inside a solar kiln.

Drying equipment

Boards were stacked as vertical layers of three boards each with a spacer of 25 x 25 mm in a conventional laboratory kiln (Model F311-2-25-CI-F, Shepherd Systems P/L, Rowville, Victoria, Australia). This kiln model is programmable to set the values for temperature and RH to nine steps. The time interval in hour unit for changing the level of temperature from one step to another has been shown in Table 2. The middle vertical boards (seven boards) were used to measure MC profiles and surface and internal check development. The remaining 14 boards were used to assess timber quality at the end of drying.

Mathematical modelling the development of moisture content profile during drying

A diffusion model was used to forecast the MC profile in the drying boards. The one-dimensional diffusion equation is defined as follows,

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \tag{2}$$

where M is $Mc - EMC$; EMC is the equilibrium moisture content; t is time; x is the spatial coordinate; and D is the diffusion coefficient (m^2/s) and also dependent on MC.

In the case of a board (where $-l \le x \le l$), with evaporation at the surfaces, the boundary MC conditions of the problem are shown below,

$$\left.\frac{\partial M}{\partial x}\right|_{x=0} = 0 \tag{3}$$

$$D\left.\frac{\partial M}{\partial x}\right|_{x=l} = -hM|_{x=l} \tag{4}$$

$$M|_{t=0} = M_o \tag{5}$$

where M_o is $Mi - EMC$; and M_i is the initial moisture content of the boards.

Using separation of variables, the diffusion equation will have a solution of the form shown in Eq. 6.

$$\frac{Mc-EMC}{Mi-EMC} = \sum_{n=1}^{\infty} \frac{2}{\beta_n} sin(\beta_n) \cdot cos\left(\frac{\beta_n x}{l}\right) \cdot e^{-\frac{{\beta_n}^2 D\, t}{l^2}} \tag{6}$$

The method of measuring the MC profile of 40 mm thick board during drying, using the coring method, was derived from Phonetip *et al.* (2017b). Core samples were taken at the 9th, 16th, 22nd, 36th, 46th, and 82nd day after the start of drying.

The surface and internal checks were measured using ImageJ analysis software (1.49v, USA). The method for counting and measuring the area of internal checks, and the depth of the surface checks on the cross cut of the transverse sections of boards, was developed by Phonetip *et al.* (2017c). Drying quality assessment was based on the Australian and New Zealand standard AS/NZS 4787 (2001). The method of measuring the compressive and tensile strain was derived from McMillen (1958).

RESULTS AND DISCUSSION

Fig.Figure 1 shows the oscillation of the temperature and RH in the simulation kiln. The temperature oscillated from 20 °C to 43 °C, and the RH was 60% to 85%. The temperature reached the set value of 43 °C. RH was 60% during the daytime, but RH exceeded the set point by 5% during the night.

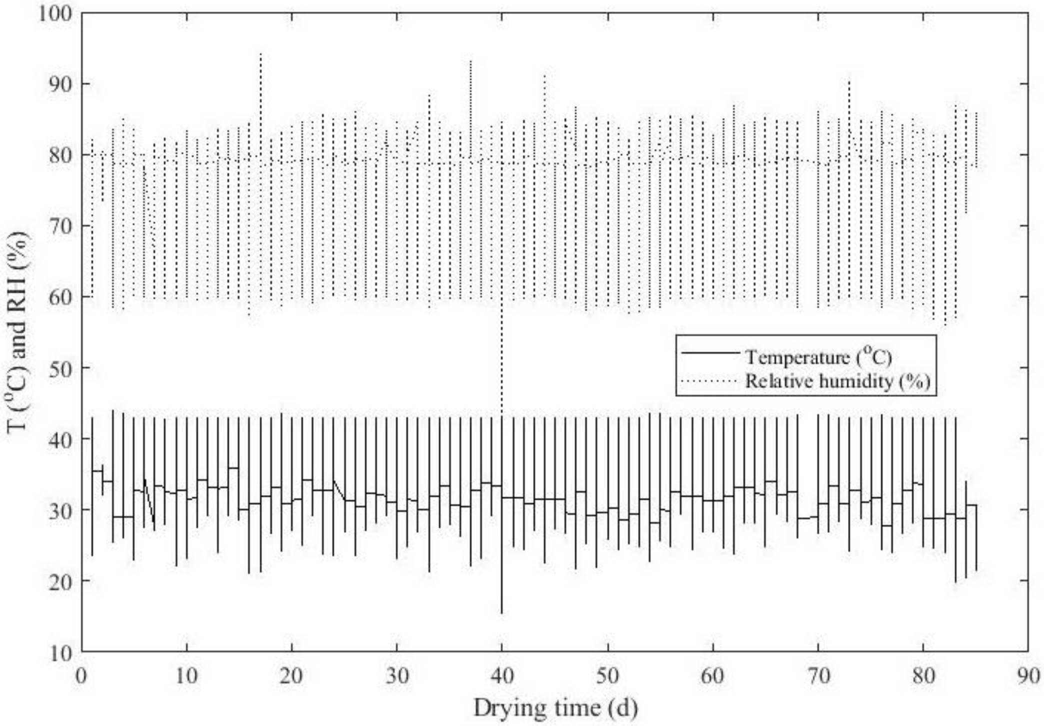

Fig. 1. Temperature and relative humidity conditions in a simulation kiln

Figure 2a shows the average kiln temperature and ambient temperature. During the night time, the temperature was higher than the ambient temperature, by up to 8 °C. This increase in the temperature inside the kiln was dependent on the internal fan speed; *i.e.* at 600 rpm (21 Hz), the temperature inside the kiln was higher than ambient by 4.7 ± 1.2 °C, at 800 rpm/28 Hz by 8.0 ± 1.7 °C, and at 1000 rpm/35Hz r by 12.1 ± 0.6 °C (Phonetip 2016). This was also found by Khater *et al.* (2004). Thus, initial setting values for the temperature should consider the applied fan speed, which could affect the temperature gradient.

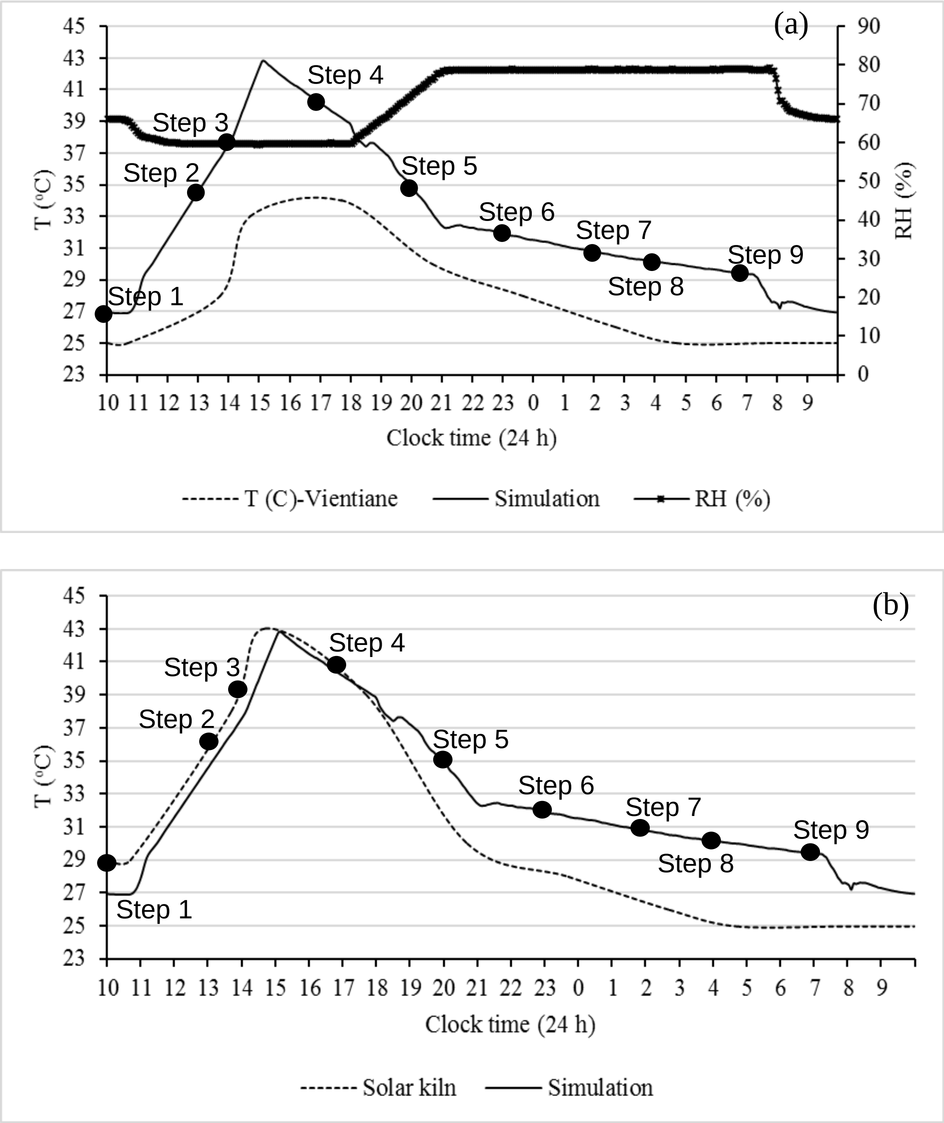

Fig. 2. Simulation of temperature and relative humidity inside kiln and ambient temperature (a) and the actual temperature inside the solar kiln and the simulated temperature (b).

The simulated temperature, at steps 1, 2, 3, and 4 (from 10 AM to 5 PM), were the same as the actual temperature of the solar kiln, with an error of less than 2 °C (Fig. 2b). The absolute differences in temperature were 2 °C, 1 °C, 2 °C, and 0 °C, respectively, for step 1 through step 4. However, the kiln temperature during night time varied considerably; *i.e.*, the absolute difference was 3 °C at Step 5; 4 °C at Step 6 and Step 7; 5 °C at Step 8, and 3 °C at Step 9. Comparing this result with the previous study by Phonetip *et al.* (2017a), using an intermittent drying method, the variation of absolute temperature was from 2 °C to 7 °C during day time, which was 5 °C higher than in the current simulation study. This implies that the simulation produced results that were consistent with solar drying rather than the simple intermittent method. However, it would be better to have a cooling/venting system installed in the conventional kiln when conducting simulation drying, to allow the kiln temperature to reach ambient temperature during the night time. As discussed above, it was not possible for the kiln temperature to reach the ambient temperature levels, due to the effect of the fan speed on temperature. Thus, switching off the fan could reduce the temperature and provide savings in energy consumption.

The MC of the boards decreased from the initial MC of 80% to fibre saturation point (*fsp*) 25% during 28 days (Fig. 4). The drying rate was 2 times slower than the rate established in Salem*, et al.* (2016) for 27 mm thick boards. The average rate of drying from *fsp* to 13% was 0.2% per day, which was similar to the drying rate in the intermittent drying (Phonetip *et al.* 2017b) and the solar drying (Phonetip *et al.* 2017a). It took 82 days to reach a MC of 13% at the end of drying. The error bars in Fig. 3 indicate the variation of MC in the sample boards, at each assessment time during the experiment.

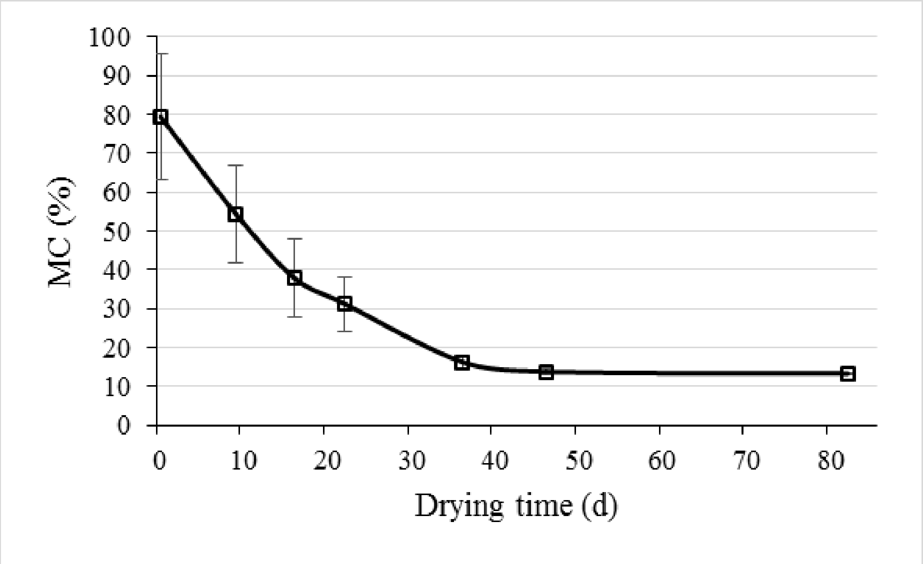

Fig. 3. Decrease of average moisture content of timber boards

Figure 4 shows the drying profiles of the boards as a function of time and distance from the centre of the board, based on the measured data and the results of the simulation using Eq. 6. The measured change in the moisture content was 5% faster than predicted by the model; (*i.e;* at 9, 16, and 22 days at the middle board than). After drying for 36 days and 46 days the drying rates were faster than predicted (*i.e.*, 13% and 10%). These variations in MC may be caused by the coring method used in taking the core samples (Phonetip *et al.* 2017b). In the earlier study, the authors stated that the process of taking core samples caused variation in the profile to occur because the process generated steam. Therefore, the drying rate in the middle of the board dried faster than the model predicted, because the effect of taking the core could have contributed to some acceleration in the core drying.

After drying for 9 days, the average MC at the case of the boards had reached *fsp.* This was similar to previous findings (Phonetip *et al.* 2017a, b). When the MC in case boards was 45% to 75%, the drying rate was estimated to be about 3.9 ± 1.2% /day. When case boards dropped below 30% MC, the drying rate was less than 0.2 ± 0.1%/day (Fig. 5).

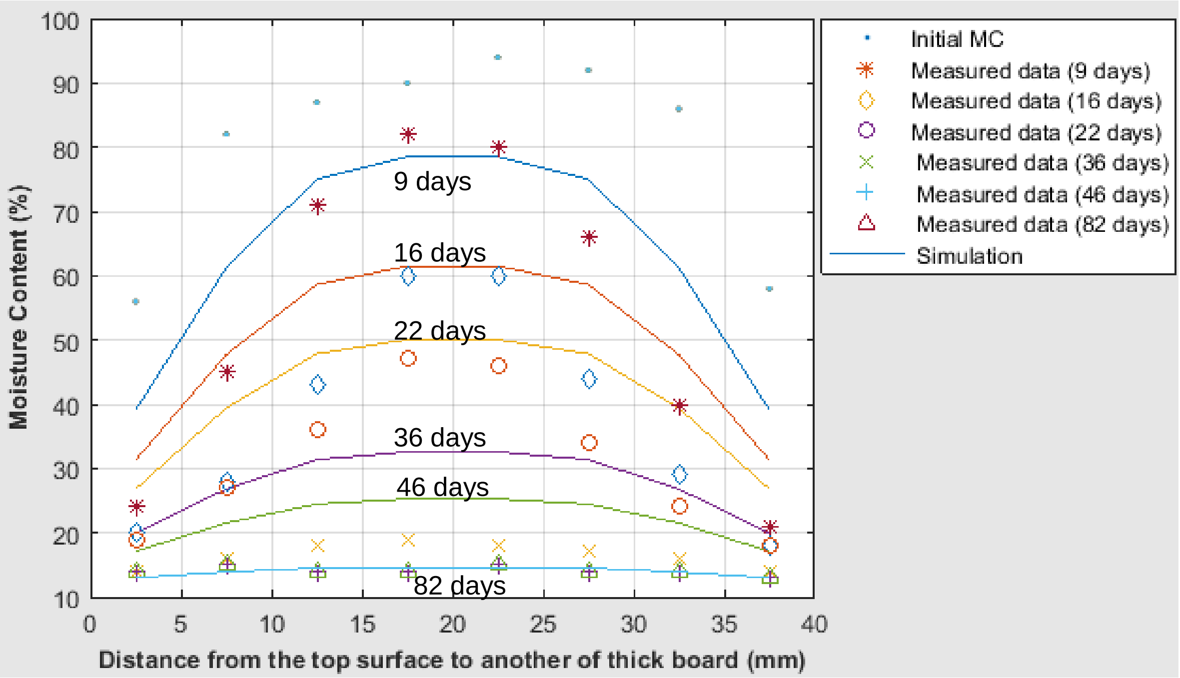

Fig. 4. Drying profile as a function of time and distance from the centre of the board based on the measured data and the results of the simulation using Eq. 6

The drying rate at the case boards, based on measured data, was 50% faster than the drying rate predicted using the mathematical modelling (Fig. 4). Considering the anatomical structure of *E. delegatensis*, the ray cells (8 to 14/mm^2) are long and thin on tangential longitudinal section (Illic 1997). Thus, free water could easily move and evaporate from board surfaces faster than expected using Eq. 6. Therefore, optimization of the mathematical modeling would require further work by considering the anatomical structure of the *E. delegatensis* species.

There was no surface check formation when the first assessment was made on the 9th day (Table 2). Six sample boards out of the total of seven showed no surface checking when the assessment was made on the 16th, 22nd, 36th, and 46th days and at the end of drying. Only one sample board had surface checks with a maximum depth of 13 mm when the board had a MC gradient of 44 ± 20% at the 16th day of drying. The surface checks developed up to 17 mm deep at an MC gradient of 26 ± 14%, based on the assessment on the 22nd day. The surface checking appeared more slowly than in both the intermittent drying and solar drying processes by 6 days (Phonetip *et al.* 2017a, b). A transverse section of the sample board with surface checking was carefully examined and it was found that the sample was a back-sawn board. High shrinkage in a tangential direction (*i.e.*, 8.5%) of *Eucalyptus delegatensis* (Bootle 2005) could contribute to the surface checking.

The high shrinkage of many hardwoods and some softwoods make them extremely difficult to dry without degrading the quality, especially with back-sawn boards (Roza and Mills 1997; FPL 2010). This implies that applying a temperature up to the maximum of 43 °C could help minimize surface checking for quarter-sawn boards but may not be suitable for back-sawn boards. Thus, sawn-board pattern should be tested by numerical simulation, which was introduced by Hasan and Langrish (2014) for further validation.

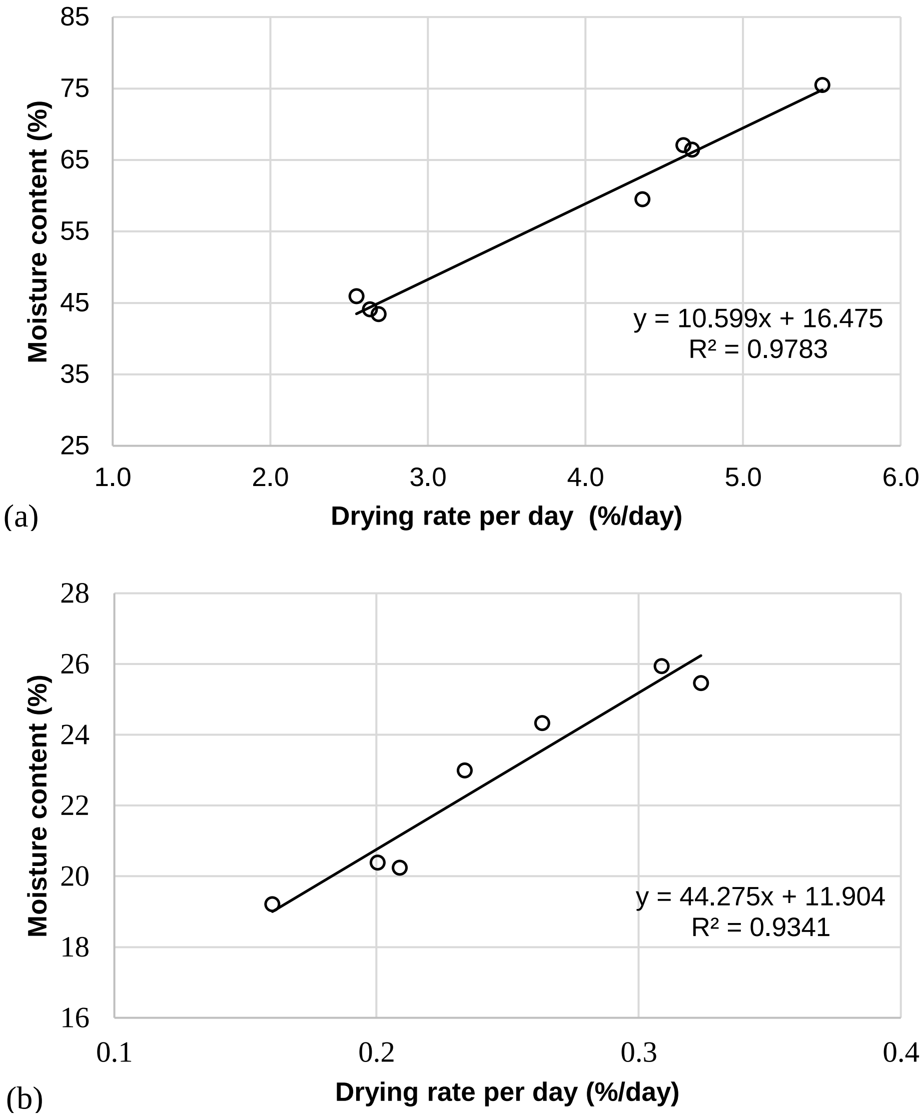

Fig. 5. Drying rate at the case boards above fiber saturation point-fsp (a) and below fsp (b)

Internal checking was found when boards were assessed on the 16th, 22nd, 36th, and 46th day. The number of checks and the percentage loss of the total cross section area analyzed (40 cm^2) at the assessment days were: 8 (0.04%), 6 (0.02%), 25 (0.03%), and 9 (0.03%), respectively, as presented in Table 3. Based on AS/NZS 4787:2001 (AS/NZS 2001), the loss area due to the internal checking on cross section was graded "A/B" (Table 3) which was consistent with previous findings (Phonetip *et al.* 2017a; Phonetip *et al.* 2017b).

Table 3. Assessment of Surface and Internal Checking during Drying of 7 Boards

Defects	Drying Time (day)					
	Initial stage	9	16	22	36	46
Depth of surface checking (mm)/sample	0	0	13/1	5/1	17/1	3/1
Number of internal checking/sample	0	0	8/1	6/3	25/1	9/2
Mean percentage loss of cross section caused by internal checks (%)	0	0	0.04	0.02	0.03	0.03

At the end of drying, timber quality was assessed based on AS/NZS 4787 (2001) (Table 4). Loss of area due to internal checks on the transverse section, stress residual and collapse were graded as Class “A/B”. Bow was under the permissible level of 10 mm. Spring, twist, end checking and cupping were under the permissible level of 5 mm. The average compressive and tensile strain was equalized at 0.2 mm/mm.

Table 4. Timber Quality Assessment of 12 Boards after Drying Based on AS/NZS 4787 (2001)

Quality parameters	Quality classes
Loss of area of internal checks (%)	0.0/ Class “A/B”
Stress residual (mm)	0.9±0.1/ Class “B”
Collapse (mm)	0.0/ Class “A/B”
Bow (mm)	1.3±0.7/UP[a*]
Spring (mm)	1.1±0.3/UP[b]
Twist (mm)	2.2±0.3/UP[b]
End checking (mm)	0.0/UP[b]
Cupping (mm)	1.4±0.4/UP[b]
Average compressive strain (mm/mm)	0.2
Average tensile strain (mm/mm)	0.2

[*] Note: Under the permissible (UP[a]) level for the bow of 10 mm, and UP[b] level for the spring, twist, end checking, cupping of 5 mm.

CONCLUSIONS

1. Drying of *Eucalyptus delegatensis* board using the simulation of a solar kiln in Vientiane, Laos took 82 days from the initial moisture content (MC) of 80% to 13% under oscillated drying conditions. Simulating solar kiln conditions using a conventional kiln was possible with less than 2 °C of error during daytime and 5 °C at night time. During night time, the kiln temperature was affected by ambient conditions and the speed of internal fans. To get a similar temperature to the actual temperature in solar kilns, the internal fans should be switched off or an air cooling system should be installed to allow the kiln temperature to reach ambient level during the night time.
2. The predicted model described the MC profile during drying. Due to variation in the MC profile predicted by the model, when compared with the measured data, the anatomical structure of timbers should be considered as another parameter for improving the model.
3. The surface checks formed at the 9th day of assessment but appeared on only one back-sawn board out of the total of seven sampled boards. Internal checks were very small

in shape. Timber quality after drying to 13% was determined based on the assessment of drying quality AS/NZS 4787 (2001). The internal check, stress residual, and collapse were graded as class "A". Bow, spring, twist and end check were under permissible levels. The tensile and compressive strain was equalised at the average of 0.2 (mm/mm).

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Article submitted: January 16, 2018; Peer review completed: March 17, 2018; Revised version received and accepted: March 28, 2018; Published: April 2, 2018.
DOI: 10.15376/biores.13.2.3740-3752