Haque, Dr. M. Nawshadul[1]
Langrish, Associate Prof., T.A.G.[2]

[1]Wood Products & Processing Unit
Forest Research, Private Bag 3020
Rotorua, New Zealand
Tel: +64-7-343 5370
Fax: +64-7- 343 5507
Email: Nawshad.Haque@forestresearch.co.nz

[2]Department of Chemical Engineering
University of Sydney, NSW 2006, Australia
Tel: +61-2-9351 4568
Fax: +61-2-9351 2854
Email: timl@chem.eng.usyd.edu.au

Performance of an Industrial Solar Kiln for Drying Timber

Intended category: Sustainable Energies/Technology

ABSTRACT

The Australasian timber industry is showing an increasing interest in the use of solar kilns to accelerate the pre-drying stages for hardwoods. Research studies around the world have claimed that the advantages of solar kilns are shorter drying times, better product quality and low operating costs compared with open-air drying and lower energy cost compared with conventional kiln drying. This study assessed the actual performance of an instrumented industrial solar kiln. Solar energy, ambient temperature and humidity, kiln temperature and humidity and wood moisture contents were recorded on site (at Boral Timber's solar kiln at Heron's Creek, NSW, Australia) using sensors and an electronic data acquisition and logging system. The average increases in air temperatures in the kiln (compared with ambient conditions) were 17.3°C (May-June), 13.8°C (July-August), 10°C (September-October), 8.2°C (November-March) and 7.5°C (March-May) for five runs monitored, respectively. Drying times were three to four months from an initial (43 to 62% dry-basis) to a final moisture content (12 to 22% dry-basis). Overall the solar kiln has been considered as an acceptable alternative to air-drying method for pre-drying of hardwoods.

Keywords: sustainable; renewable energy; wood seasoning; timber processing; hardwood; pre-drying.

INTRODUCTION

Over the last few decades, much research and development has been conducted into the use of solar kilns for timber drying. This has led to the commercial use and availability of solar kilns in the timber industry over recent years (Desch and Dinwoodie, 1996). Solar kilns have been in operation in many countries around the world since the 1960s.

Research into and development of solar kilns for timber drying started at the Forest Research Institute at Dehra Dun, North India (Rehman and Chawla, 1961) and at Madison, Wisconsin, USA (Johnson, 1961). Later, a greenhouse type solar dryer was developed in the US Forest Products Laboratory, Madison and tested for drying oak boards (Peck, 1962). It was also tested at Rio Piedras, Puerto Rico for drying mahogany lumber (Maldonado and Peck, 1962).

More than forty designs of research kiln using solar energy have been built over the last forty years and, in addition, a considerable variety of commercially run kilns are also operating (Plumptre and Jayanetti, 1996). These kilns can be divided into two broad categories; greenhouse type solar kilns (some common designs are shown in Figure 1); and solar kilns with external collectors. Further division of greenhouse solar kilns may be made on the basis of kiln capacity and the geographical location of the kiln. The common features of various solar kiln designs for drying timber in Australia are presented in Table 1.

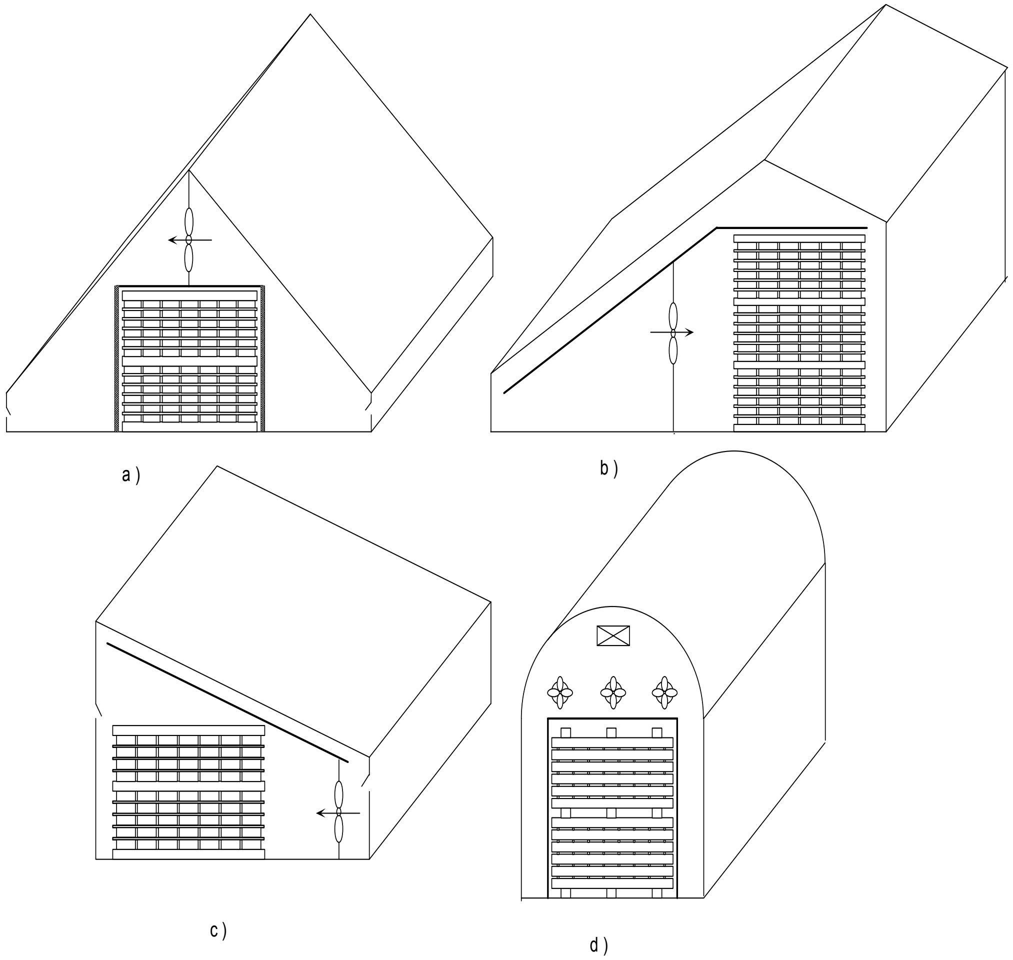

Figure 1: Greenhouse solar kiln designs. a) Prototype Guyana design by Themelin (1984), a tent-like structure; b) Oxford design by Plumptre (1979), double-sided inclined absorbers; c) Queensland Department of Primary Industries (DPI) design by Gough (1977), box like structure; and d) Western Australia Conservation and Land Management (CALM) design by McDonald (1991), tunnel like structure.

Table 1: Solar kiln designs in Australia (industry visits and FORTECH, 1994).

Types of solar kiln	Salient features
The Wood-Mizer Kiln	Fork-lift loading. 8 m^3 (for 25 mm board), drying time 7 days from air-dried to 12% moisture content. 374 m^3 per annum capacity. Financial analysis was done in 1994. Fixed cost: Capital cost \$20,000. Variable cost: wood \$450, labour one person per year \$25000, repair & maintenance \$2000 per year, electricity for fans \$1500 per year. Return: flooring timber \$1000 per m^3, decking timber \$850 per m^3.
The Queensland Department of Primary Industries (DPI) Kiln	Capital & establishment cost \$15000 (estimated), \$25000 (real). 10 m^3 of wood to dry in 10 days from air-dried to 12% moisture content. Variable costs are the same as above.
The Western Australia CALM (Conservation and Land Management) Kiln	For drying green timber, as air-drying is difficult in WA due to the harshness of the climate. 30 m^3 capacity. 6 weeks for 25 mm and 12 weeks for 50 mm board from green to 12% moisture content. Common installations are twin 85 m^3 chambers with auxiliary LPG heating. Provision of water sprays and supplementary heating with separate controlling room. 1360 m^3 per year capacity based on full time operation.
Advanced Solar Assisted kiln (similar to CALM kiln).	30-160 m^3 capacity, better control system than previous CALM kiln, auxiliary heating by gas or steam. Kiln structure is a square section aluminium frame "greenhouse" structure. The structure is rated to withstand 150 km per hour wind. Approximate size is length 8-10 m, width 4-8 m and height 4.5 m for 30-100 m^3. Covering is an inflated double skin ultraviolet resistant plastic cover, resistant sun damage for 2 years. Humidity, temperature and air flow direction are automatically regulated via electronically controlled sensors, vents, heater, reversible fans and water sprays to keep constant (regulated) temperatures and humidities, loaded using fork-lift. Cost: \$70000 (old design) to \$120000 (new design) 1999.
Solar Dryers Australia Kiln, Bellingen, NSW	Insulated shipping container, large solar collector on the roof, plastic cover on roof, S2 Model 12 m^3, S3 70-100 m^3 and GS 30-50 m^3 capacity, fork-lift or steel track and trolley loading, with gas-fired additional heating system, microprocessor controlled fans and vents, currently in combination with solar water heater.
Solar Assisted Slip Kiln, Australian Choice Timber, Bayswater, Victoria	40-150 m^3 capacity, similar to CALM kiln but with different arrangement for forklift or crane access; the kiln slips off-the-charge when loading or unloading after removing four bolts and unclipping one end-wall plastic cover. Cost is \$ 17500 for the smallest unit.

It has been claimed from numerous studies around the world that some advantages of solar kilns are as follows: a) drying time is significantly shorter than air drying; b) drying quality is substantially better than air drying; c) drying to a low equilibrium moisture content (e.g. 8-10%) is possible for most locations, compared with air drying; d) the system has low operating costs (solar energy, less fuel required for additional heating), and e) less skill is required to operate than for conventional kiln drying. The major disadvantages are: a) solar kilns depend on weather conditions (affected by rain, cloudy days), resulting in less controllability by the operator, and b) less predictable outcomes than from drying in conventional kilns. There is also little understanding of optimum designs for different climatic conditions and geographical locations and no common standards for comparison between various designs. A study on mathematical modelling and validation of a solar kiln model has been published (Haque and Langrish, 2003). The aim of this paper is to assess and describe the actual performance of an industrial greenhouse solar kiln for drying Australian eucalypt timber and to comment on its suitability in New Zealand.

MATERIALS AND METHODS

The solar kiln used by Boral Timber at Herons Creek site near Wauchope, NSW, Australia is shown in Figure 2. This kiln was manufactured in Western Australia by Advanced Environmental Structures Pty Ltd. and was supplied by Australian Design Hardwoods Pty Ltd., located at Gloucester, NSW. The kiln is essentially a rectangular chamber of corrugated iron sheets painted matt black within a tunnel like greenhouse structure with a plastic cover. This double skin plastic cover rests on a large curved aluminium structure and is always kept inflated by a small fan. The size of the kiln is 11.2 m long, 11.2 m wide and 6.5 m high. The main chamber size for loading timber stack is 7 m long, 6.5 wide and 4.5 high. The timber is loaded in the kiln through large front doors at the western end. The board size (green) was 6 m long, 270 mm wide and 43 mm thick. Five circulating fans are mounted at the rear of the kiln structure (eastern end) for forcing air through the timber stack. A fan with a vent opening is located on the front wall on top of the large door and is used to expel the damp humid air out of the kiln. Another vent opening is located on the rear wall to allow fresh dry ambient air into the kiln. This vent opens due to the suction force of air caused by the vent fan. Five atomisers for water spraying are also used for increasing the humidity when required. All these elements including the temperature and the relative humidity sensors and the drying schedules are controlled via a wall-mounted PLC unit with a display monitor located in an adjacent control room. The kiln floor is constructed from concrete. The walls and roof consist of double glazed polythene and are supported by a large number of hollow square section aluminium bar.

The internal air temperature and relative humidity during the process of timber drying in this solar kiln were measured at two minute intervals using two stand-alone data loggers (Tinytag Plus TGP-1500, manufactured by Gemini Data Loggers, UK). The ambient air temperature and relative humidity were similarly measured continuously. The solar radiation flux was measured using a secondary standard pyranometer (EP09 Pyranometer, Middleton Solar Instruments, manufactured by Carter-Scott Design, Victoria, Australia) with an electronic data logging system to record these data.

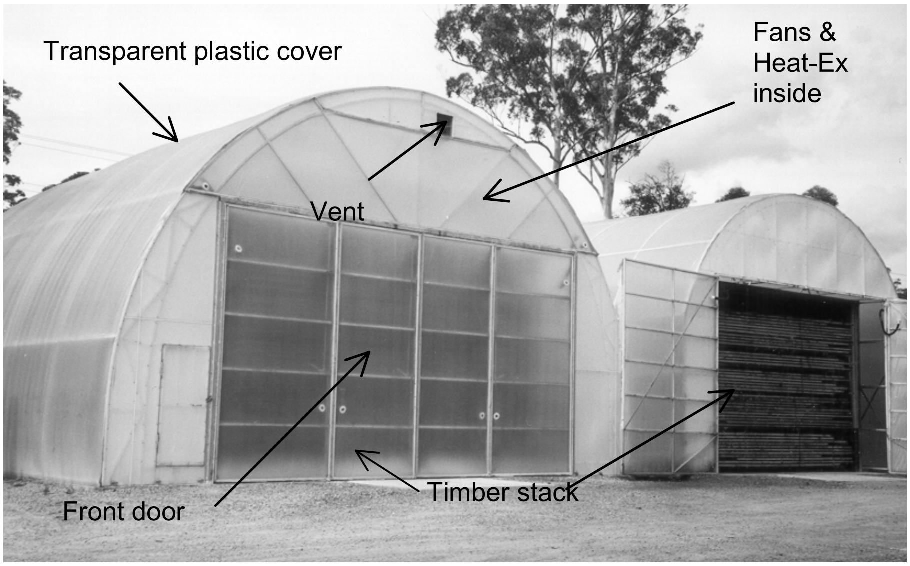

Figure 2: Solar kilns at Boral Timber's Herons Creek site, NSW, Australia.

Procedure for Measuring Moisture content

Blackbutt (*Eucalyptus pilularis*) timber, a hardwood species, was selected for this study because this species represents 90% of timber processed by Boral Timber. The moisture content of the charge was determined using small biscuit samples (20 mm long) from two ends of a kiln sample (300 mm long), taken from a representative board of the timber stack. Sixteen such samples were collected from eight boards taken from the whole batch of timber. These biscuit samples were weighed on a top pan balance and then dried in an oven set at $105 \pm 2^{o}C$ for 24 hours. The moisture content was calculated based on the dry weight and the initial green weight of these biscuit samples. The kiln samples were also weighed on a top pan balance. The dry weights of the kiln samples were estimated based on the oven-dry moisture contents of the biscuit samples assuming that these represent the kiln samples, so the initial moisture contents of the kiln samples were assumed to be the same as those of the biscuit samples. Eight kiln samples were placed at strategic locations in the solar kiln (three samples at both the front and rear ends, and two samples in the middle of the kiln; about two metres above the kiln floor). Each kiln sample was regularly weighed during the drying test. The moisture contents were calculated based on the estimated dry weights of the kiln samples. These locations of kiln samples are the standard industrial practice in many hardwood timber companies. The moisture content reported here is the average of eight samples, which are taken to represent the whole batch of timber.

RESULTS AND DISCUSSION

A typical drying schedule adapted and used for this study for drying timber in the solar kilns is shown in Table 2. This stepped drying schedule applies to conditions of very low temperature (25°C) and very high humidity (85 to 90%) in the beginning of drying to avoid surface checks and distortions. Gradually the temperature is increased and relative humidity is decreased based on the stack average moisture content.

Table 2: Typical moisture-content based schedule for drying 43 mm thick blackbutt boards (Haque, 2002).

Initial moisture content (%)	Dry-bulb temperature (^oC)	Wet-bulb temperature (^oC)	Relative humidity (%)	Equilibrium moisture content (%)
70	25	24	85	18.0
60	25	23	80	16.0
45	30	27	75	14
35	35	30	70	12.5
30	35	29	65	11.3
25	35	28	55	9.5
20	40	29	45	7.8
15	45	29	30	5.7
14	45	26	22	4.0
13	55	26	15	2.0
10	55	25	12	1.5
Recondition	45	40	75	12.8

A summary of the actual performance is shown in Table 3 in terms of drying times, initial and final moisture contents for five batches during different seasons. The first batch of timber was dried in the solar kiln from 5 May 2000 to 29 June 2000 (Figure 3). The initial average moisture content was about 55%. The final average moisture content of this batch of timber after 55 days of drying was about 16%. The actual temperatures and relative humidities cycled up or down due to day-night variations in weather conditions. The heat exchanger was used to provide additional heat input when there was no solar energy available. However, during nights, weekends and holidays, the boiler was shut down, and no additional heating was available. The drying curve suggested the drying rate was reasonably fast (40% reduction in moisture content in 55 days), compared with open-air drying (20% reduction in moisture content, from an initial moisture content of 60% to 40% in 55 days collected from one run for the matched samples) at the same time (season).

Table 3: Drying times for all batches.

Batch number	Dates (from the beginning of drying to the end)	Average initial MC (%)	Average Final MC (%)	Drying time (days)
1	May 05 to June 29, 2000	55	16	55
2	July 05 to August 29, 2000	62	22	55
3	September 01 to October 20, 2000	50	20	42
4	November 09, 2000 to March 07, 2001	43	12	119
5	March 14 to May 25, 2001	53	19	74

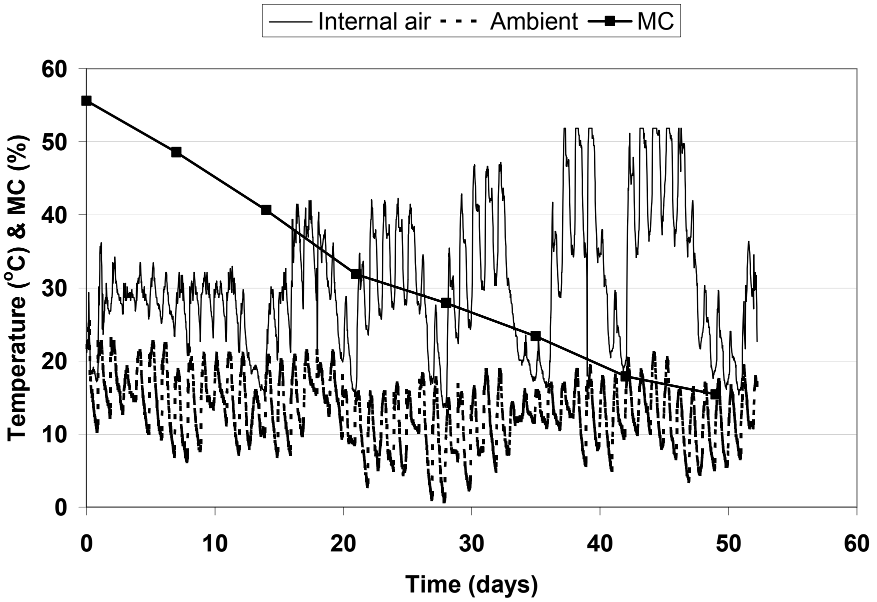

Figure 3: Measured internal and ambient temperatures and moisture contents of timber for the first run.

The second batch of timber was dried from 5 July 2000 to 29 August 2000 (Figure 4). The drying time was 55 days from the initial moisture content of 62% reducing to the final moisture content of 22%. The third batch of timber was dried from 1 September 2000 to 20 October 2000 (Figure 5). The drying time was shorter, i.e. after 42 days, the moisture content reduced from 50% to 20%, compared with the first and the second batches, which took 55 days for a similar reduction rate in moisture content. The relatively shorter drying time for the third batch was due to the lower initial moisture content and the difference in climatic conditions, specifically that, in NSW, the warmer months are generally between September to March and the cooler months are between May to August of the year. The highest ambient temperature was recorded as 45^{o}C on October 20, 2000 at 12:22 pm during the drying of the third batch. At this time, the highest solar energy flux was recorded (1217 W/m^2) for this run. This highest temperature is comparable with the reported annual maximum of 44^{o}C for Wauchope State Forest's weather station in NSW (18 km away from the test site) during the month of November (BOM, 2002). The fourth batch of timber was dried during the yearly close down in months of December to January (Figure 6). No steam heating was available at those times. For about eight weeks (the time from the fourth to the twelfth week), the timber was just left in the kiln at a setting of 35^{o}C temperature and 80% relative humidity, so the drying time was longer than the first three batches (119 days). There was no heat from the heat exchanger available during this time. Although the moisture content measurement was unavailable during this time, it might have taken 50 days to reach 20% moisture content.

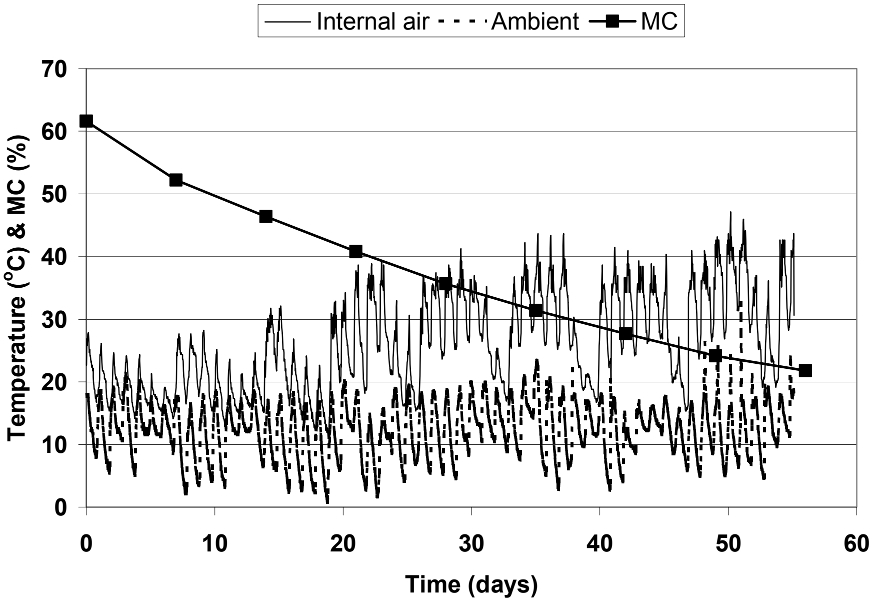

Figure 4: Measured internal and ambient temperatures and moisture contents of timber for the second run.

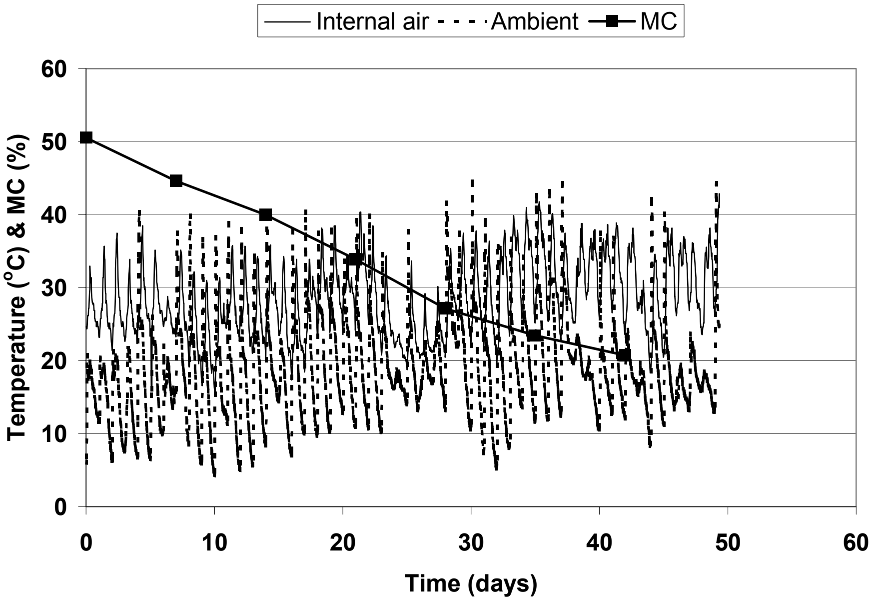

Figure 5: Measured internal and ambient temperatures and moisture contents of timber for the third run.

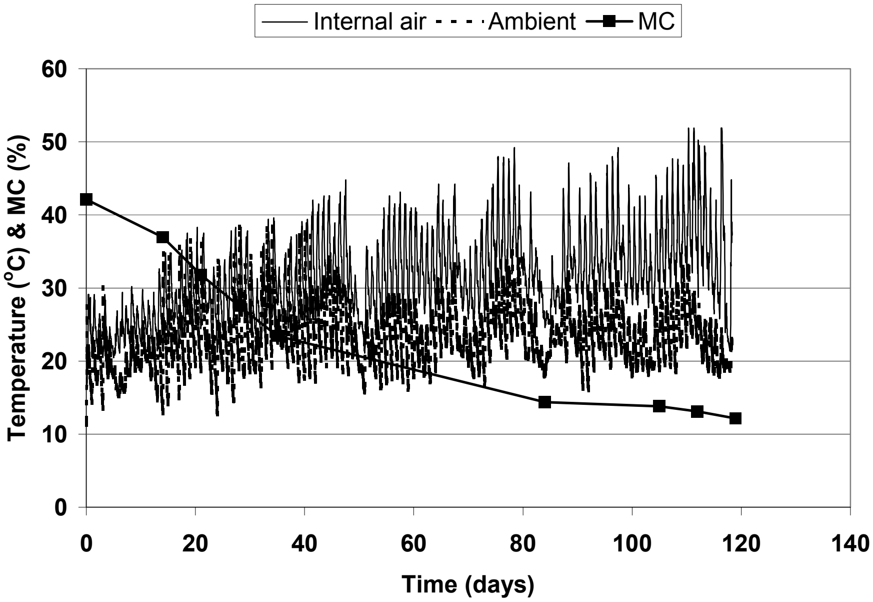

Figure 6: Measured internal and ambient temperatures and moisture contents of timber for the fourth run.

For all these above runs, the heat exchanger was manually turned "off" for the first three weeks, because the setpoint temperature 25°C could easily be achieved with solar energy only. At night, the boiler was shut down so there was no additional energy available. During the third run ambient temperature was higher than the internal temperature of the solar kiln because of the hot summer days. However, the automatic vents released excess heat to maintain the temperature near the set-point dry-bulb (maximum 45°C) in the kiln. The average increases (averaged with respect to time) in the air temperatures for the kiln (compared with ambient conditions) were 17.3°C, 13.8°C, 10°C, and 8.2°C (for runs 1 to 4), respectively, while the average decreases for relative humidities (kiln - ambient) were 21.8%, 15%, 21.9%, and 23.9% for runs 1 to 4, respectively.

The actual ambient and internal air temperatures for the fifth run are shown in Figure 7. This drying test was monitored from March 14 to May 25, 2001. The recorded solar radiation for the first 60 days during this run is shown in Figure 8. There are variations in solar energy flux due to the cloudy days. There is a decreasing trend of solar energy flux towards the end because of the relatively cooler weather of the late April to the early May. The average increase in air temperatures for the kiln (compared with ambient conditions) was 7.4°C, while the average decrease in relative humidities (kiln - ambient) was 22% for this run. It is necessary to distinguish between the initial period, when no heating was used (until 28 days) and the final period for run 5, when the heat exchanger was used heavily (Figure 9). The use of the heat exchanger increases the kiln temperature and decreases the relative humidity in the kiln air compared with the ambient air. The average differences in the temperature and relative humidity were 5°C (increase) and 19% (decrease), respectively, for the initial period until 39 days when there was only little additional heat input. In comparison, these averages were 9°C and 24% for the later period when the heat exchanger was used heavily. The initial moisture content of 53% reduced to the final moisture content of 20% in 74 days.

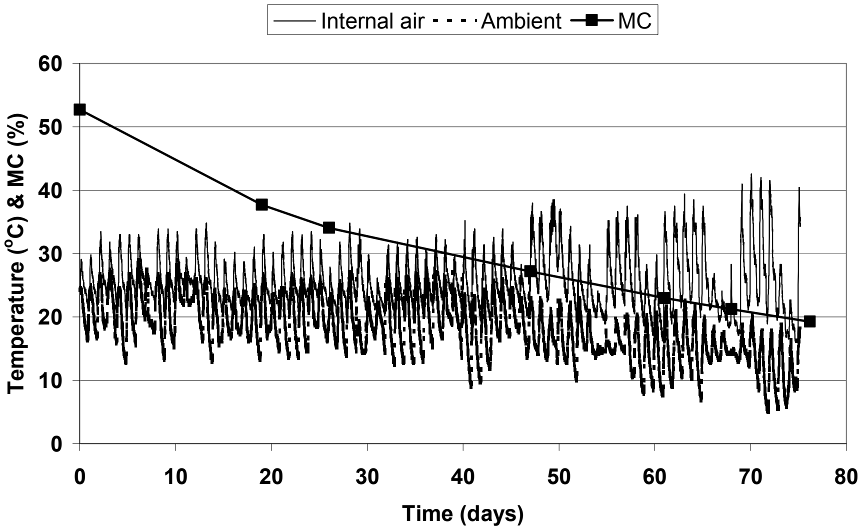

Figure 7: Measured internal and ambient temperatures and moisture contents of timber for the fifth run.

The significance of the temperature differences in terms of drying times can be assessed approximately in the following way. Since the board dimensions in length and width are much greater than the thickness, this three-dimensional transport problem can be reduced to one dimension along the thickness with little loss of accuracy. With this assumption, it has been shown (Doe *et al.*, 1994) that moisture transport within Australian hardwoods such as blackbutt may be adequately described by a simple Fickian diffusion model:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial X}{\partial z} \right) \qquad (1)$$

Here X is the moisture content and z is the position within the timber board thickness. D represents a temperature-dependent diffusion coefficient,

$$D = D_r \exp^{-D_E/T} \qquad (2)$$

Here D_r is a reference diffusion coefficient, D_E is the activation energy, and T is the temperature.

These figures show the overall enhancement in the severity of drying conditions inside solar kilns. Run 4 is particularly significant, since very little steam heating was used in this experiment, so the 8°C increase in the average air temperature cannot be attributed to the use of steam, but is due to solar input alone.

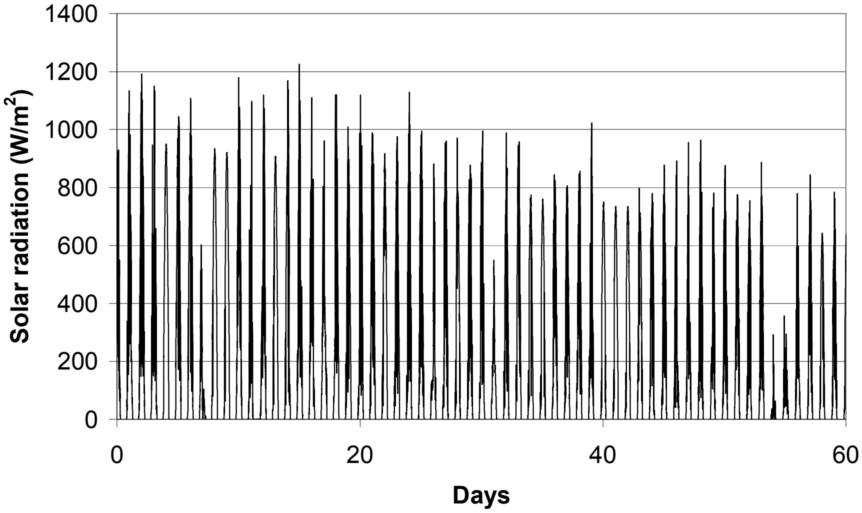

Figure 8: Measured solar radiation at Boral Timber's Herons Creek site, NSW, Australia for 60 days during 14 March to 15 May.

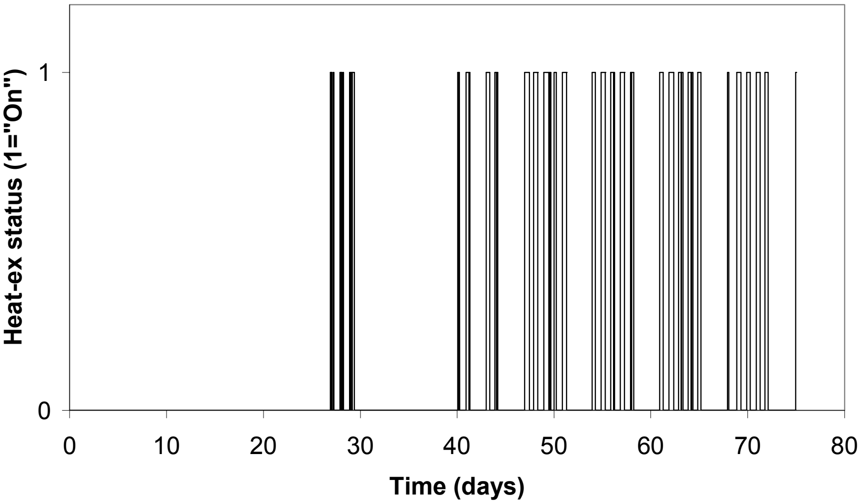

Figure 9: Status of heat exchanger for the fifth run during 14 March to 25 May.

The validation of this drying model by comparison with experimental results is reported in detail (Haque and Langrish, 2003). The diffusion model using moisture content gradient as a driving force was applied successfully (Doe *et al.*, 1994; Wu, 1989; Langrish *et al.*, 1997). It was also noted that diffusion is the generally suggested mechanism for the drying of impermeable hardwoods such as eucalypts (Keey *et al.*, 2000). The fitted activation energy and reference diffusion coefficient in the drying model with experimental data were found to be 3730 K and 1.15×10^{-5} m/s^2 (Haque, 2002). The activation energy parameter quantifies the temperature dependency of the diffusion coefficient. For example, the diffusion coefficient at 30^{o}C is likely to be 5.1×10^{-11} m/s^2, about 1.5 times greater than that at 20^{o}C (3.3×10^{-11} m/s^2) according to the diffusion equation shown above. This difference in the diffusion coefficient is then likely to be reflected in a corresponding reduction in drying time at 30^{o}C compared with 20^{o}C, since the constant-coefficient solution of the diffusion equation (McCabe and Smith, 1976) indicates that the drying time is inversely proportional to the diffusion coefficient. Hence the (kiln - ambient) temperature differences of around 10^{o}C are likely to enhance drying throughputs by approximately 50%, because of the 50% increase in diffusion coefficient. The reduction of predrying time from about six to eight months by air drying to two months by solar kiln drying for 25 mm thick boards is also consistent with this explanation, since this increase in productivity is over 50%.

Generally the solar kiln reduced the drying time from six months to two to three months for predrying compared with open-air drying (as practiced conventionally for hardwoods). This result is consistent with earlier studies (Read *et al*., 1974; Sharma *et al*., 1974 and Gough, 1977) that compared solar drying with air drying. These studies found that solar drying was generally 50% faster than air drying for the majority of hardwood wood species. Alpine ash (*Eucalyptus delegatensis*) timber was dried in an external collector type solar kiln at Griffith, NSW, Australia (Read *et al*., 1974). An extensive comparison was made for various types of hardwood timber (Sharma *et al*., 1974). The drying time was 50% shorter in a greenhouse solar kiln than for air drying of timber at Dehra Dun, India. The drying quality was judged to be better in terms of significantly less surface checks than open-air drying during this assessment because of the protection from direct sun and rain, similarly found as in above previous studies. The estimated recovery was about 2% higher, which is equivalent to 320 m^{3} per year of dry timber assuming that the board mill capacity is 16000 m^{3} per year (typical of industrial operations in New South Wales), since the exposed top layer in open-air drying is generally damaged due to direct sun and rain. This recovery is equivalent to an annual monetary value (not selling value) of AUS \$480,000 for the processing of 960 m^{3} of green logs (which produce 320 m^{3} of dry timber), assuming that the log purchase and conversion costs are about \$500 per m^{3}.

Comments on the Suitability of Solar Kilns for New Zealand and Economic Aspects

Solar kilns may be suitable in New Zealand for small-scale operations (particularly for drying native impermeable hardwoods such as beech and other low value wood for heating). Generally the calorific value of dry wood is about two and half times higher than green wood in a domestic wood burner. The daily mean solar radiation in Northern NSW in Australia is around 20 MJ/m^{2}, which is comparable with 13-23 MJ/m^{2} for most regions in NZ. The average sunshine hours in NZ are around 2100 per year, slightly less compared with Australia. Significant additional heating would be necessary for the months from April to September when the radiation level decreases to 3 to 11 MJ/m^{2}/day in NZ. Average daily solar radiation for Rotorua, NZ is shown in Figure 10. This technology may be ideal for the wood-workers and small-scale sawmills for drying their small amount of specialised timber with good quality and minimum cost. An experimental glasshouse type solar dryer (without any humidity control) was operated for drying 50 mm thick radiata pine green off-saw boards at Forest Research Institute, Rotorua, New Zealand (Williams, 1982). During the winter months, the drying rate was very slow and equilibrium moisture contents were unacceptably high (up to 19.3%) for most uses (10-12% required). According to this study, surface checking occurred on a significant number of boards at any time of year. He suggested that some control of humidity was needed to avoid surface checking, and that an auxiliary heat source was required for a regular supply of dried timber. Humidity control was present in the kiln studied by Haque & Langrish (2003), and solar kilns with better controls are becoming available recently for commercial operation, which may overcome this problem. His second report (Williams, 1983) compared solar drying with air drying and concluded that surface checking was worse in air drying and the drying rate was clearly superior in the solar dryer. However, significant sapstain infection occurred in the solar dryer, but sapstain was almost non-existent in the air drying charges. For NZ situation, solar module can be an additional feature on the conventional drying kiln, so when there is solar energy available, the kiln will use solar energy, otherwise energy from the conventional source will be used. Solar kilns are also currently in use by furniture manufacturers in the UK where the weather is much cooler than weather in NZ (Guest, 2003).

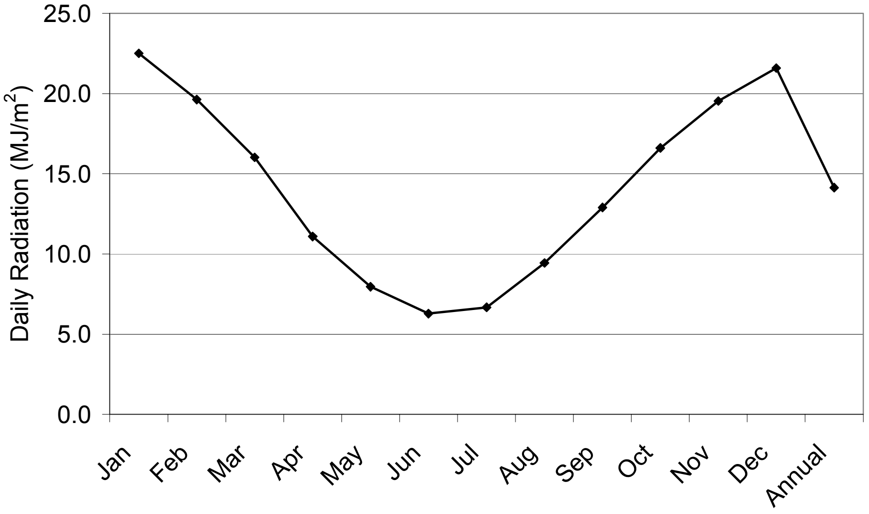

Figure 10: Average daily solar radiation for Rotorua, NZ, historical data for Rotorua 1971-2000 (NIWA, 2002).

Imre (1986) has discussed various aspects of solar drying including the economic analysis of various dryer designs. His economic assessment includes cost savings by avoiding environmental pollution. He considered that rentability, i.e. an acceptable payback time, and technological applicability were the main prerequisites for solar drying. The payback time was defined as the time at which the sum of the investment and the annual expenses with compounded interest was equal to the total savings with compounded interest gained by the use of solar energy instead of fuel. The yearly savings consisted of two main parts, one was the cost for annually-displaced energy and the other was the saving by the use of solar energy. The first part was calculated from the difference between the incident energy on the collector surfaces and the losses in a solar dryer multiplied by the unit price of the substituted energy. The second part was calculated from the yearly savings gained by avoiding environmental pollution, (i.e. the costs which should be spent on neutralising the pollutants of driers using fuels to avoid greater damage to the environment) plus the yearly savings from the transportation cost of other energy carriers, saving through product quality improvement or by the use of solar energy in a place without any other source of energy. This technology was recommended for material usually dried at mild, low temperatures, and where continuous drying operations were not required. The possible economic efficiency was dependent on the geographical position, because the global irradiance is the function of geographical position. The economic efficiency could be increased by ensuring the utilisation of the dryer for a long period of the year for multiple products at different times of the year. Economic assessment from this study showed that the shortest payback time (0.5 to 3 years) could be reached with a simple structure and cheap solar dryers (by reducing the investment, maintenance and energy cost). The approximate price for a unit varies from AUS$ 10000 to 70000 depending on the volume, sophistication of operation and the control system. It is estimated from the actual assessment that 20 to 30% energy savings may be possible with this additional capital cost.

CONCLUSIONS

The actual performance of an industrial solar kiln (120 m^3 wood stack capacity) showed that the average increases in air temperatures in the kiln (compared with ambient conditions) were 17.3°C (May-June), 13.8°C (July-August), 10°C (September-October), 8.2°C (November-March) and 7.5°C (March-May) for five runs monitored, respectively. Drying times were two to three months from an initial (the range was 43 to 62% dry-basis) to a final moisture content (the range was 12 to 22% dry-basis). Overall the solar kiln has been considered as an acceptable alternative to the air-drying method for the pre-drying of hardwoods. In the winter season external heat was added to increase the air temperature in the kiln while in the summer months such additional heat was unnecessary for this low temperature drying.

ACKNOWLEDGEMENTS

The authors would like to thank Boral Timber and the Department of Chemical Engineering within the Faculty of Engineering, University of Sydney for their financial support.

REFERENCES

BOM. (2002). Bureau of Meteorology Climate extremes data for New South Wales. Retrieved from http://www.bom.gov.au/climate/averages/tables/cw_060034.shtml, accessed in February 2002.

Desch, H.E., & Dinwoodie, J.M. (1996). *Timber: Structure, Properties, Conversion and Use*. London: Macmillan Press Ltd.

Doe, P.E., Oliver, A.R., & Booker, J.D. (1994). A Non-Linear Strain and Moisture Content Model of Variable Hardwood Drying Schedules. In: *Proc. 4th IUFRO International Wood Drying Conference*, Aug 9-13, 1994; Rotorua, New Zealand: Forest Research Institute.

FORTECH. (1994). *The Feasibility of Establishing Kiln Drying Facilities for Small to Medium Scale Sawmills on the New South Wales Coast*. Sydney: NSW Forest Products Association Limited.

Gough, D.K. (1977). *The Design and Operation of a Solar Timber Kiln, Fiji Timbers and Their Uses No. 67*. Suva: Department of Forestry.

Guest, J. (2003). An introduction to drying wood using a solar assisted kiln. Retrieved from http://www.jonathan-guest.co.uk/solar-kiln.htm, accessed on 15 March 2004.

Haque, M. N. (2002). Modelling of Solar Kilns and the Development of An Optimised Schedule for Drying Hardwood Timber. University of Sydney, Australia: Ph.D. Thesis.

Haque, M.N., & Langrish, T.A.G. (2003). Mathematical modelling of solar kilns for drying timber: Model development and validation. *Drying Technology*, *21*(3), 457-477.

Imre, L. (1986). Technical and economical evaluation of solar drying. *Drying Technology*, 1986, *4*(4), 503-512.

Johnson, C.L. (1961). Wind-powered solar-heated lumber dryer. *Southern Lumberman*, *203*(2532), 41-44.

Keey, R.B., Langrish, T.A.G., & Walker, J.C.F. (2000). *Kiln-Drying of Lumber*. Berlin: Springer.

Langrish, T.A.G., Brooke, A.S., Davis, C.L., Musch, H.E., & Barton, G.W. (1997). An improved drying schedule for Austrailan ironbark timber: optimisation and experimental validation. *Drying Technology –An International Journal*, *15*(1), 47-70.

Maldonado, E.D., & Peck, E.C. (1962). Drying by solar radiation in Puerto Rico. *Forest Products Journal*, *12*(10), 487-488.

McCabe, W.L., & Smith, J.C. (1976). *Unit Operations of Chemical Engineering*. Kogakusha: McGraw-Hill.

McDonald, T.J.G. (1991). CALM Drying System - Low cost, solar assisted timber drying. Western Australia: Conservation and Land Management.

NIWA. (2002). National Institute of Water and Atmospheric Research data. Retrieved from http://www.niwa.co.nz/edu/resources/climate/radiation, accessed on 10 September, 2003.

Peck, E.C. (1962). Drying red oak by solar heat. *Forest Products Journal*, *12*(3), 103-107.

Plumptre, R.A. (1979). Simple solar heated timber dryers: design, performance and commercial viability. *Commonwealth Forestry Review*, *58*(4), 243-251.

Plumptre, R.A., & Jayanetti, D.L. (1996). *Solar Heated Timber Drying Kilns: A manual on their design and operation*. Bucks: TRADA Technology Ltd.

Read, W.R., Choda, A., & Copper, P.I. (1974). A solar timber kiln. *Solar Energy*, *15*, 309-316.

Rehman, M.A., & Chawla, O.P. (1961). *Seasoning of Timber Using Solar Energy, Indian Forest Bulletin No. 229*. Faridabad: Government of India Press.

Sharma, S.N., Nath, P., & Bali, B.I. (1974). A solar timber seasoning kiln. *Journal of the Timber Development Association India*, *18*(2), 10-26.

Themelin, A. (1984). *Development of a Prototype Solar Drying Kiln for French Guyianan Timber*. France: CEEMAT.

Williams, D.H. (1982). *The Use of Solar Energy for Timber Drying: Progress Report after One Year's Operation of the Rotorua Experimental Unit*, Forest Products Division, Project Record 184. Rotorua: NZ Forest Research Institute.

Williams, D.H. (1983). *The Use of Solar Energy for Timber Drying: Progress Report on Year 2 of the Rotorua Experimental Unit*, Forest Products Division, Project Record 261, Rotorua: NZ Forest Research Institute.

Wu, Q. (1989). An Investigation of Some Problems in Drying of Tasmanian Eucalypt Timbers. University of Tasmania: M.Eng.Sc. Thesis.