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EFFECT OF TEMPERATURE AND VACUUM ON THE DRYING RATE AND VARIOUS PARAMETERS OF WOOD SAMPLES, USING AN INDIGENOUSLY DESIGNED AND DEVELOPED VACUUM DRYING SYSTEM

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ABSTRACT

A vacuum drying system is being designed and developed at National Institute of Vacuum Science & Technology (NINVAST) to dry various materials under vacuum conditions. Its performance and capabilities are tested by carrying out different experiments on green (freshly cut) wood samples of Poplar and Eucalyptus with dimensions of 990.6 mm x 76.2 mm x 25.4 mm and 469.9 mm x 50.8 mm x 25.4 mm, respectively. These samples were dried from green moisture content (MC) 78% to 10% by this system at ultimate vacuum of about 1.6 x 103 pascal and at a temperature ranging from 35°C to 55°C for about 20 hrs. Drying quality tests included: prong test, warp measurement, surface checking and moisture content measurement, which were all performed. The resulting wood samples showed no dislocation and no excessive stress buildup. If compared to ordinary drying process, the vacuum drying is rapid and the drying rate increases with rise in temperature. The designed system is beneficial for commercial use.

Keywords: Moisture content; Quality tests; Vacuum system; Warp measurement

1. INTRODUCTION

In Pakistan wood is being used widely in construction processes of houses, buildings, furniture and in other industries as well. Poplar has a low density and favourable mechanical properties; hence it is being applied in light construction. It is also being used in variety of semi-manufactured and final products (packaging material, veneer-based products, board materials to pulp and paper). Eucalyptus (species of timber) when dried becomes progressively stronger and lightweight, which has advantage in furniture and construction (Boever et al., 2010). However, there is no proper method for drying wood prior to its use in Pakistan. Wood samples are either placed in the sunshine for air drying or left for months to dry or oven-dried within one month. Wood dried according to these methods (particularly air drying) may have excessive stress, dislocation, moisture accumulation, colour change and warps that make it inappropriate for application in sophisticated industrial and household building products or projects.

Moreover, the drying rate is slow to such an extent that it becomes an impediment in completion of such projects within a stipulated time period. In order to introduce a standard method for drying wood, an attempt is being made to dry certain wood species under vacuum and study their properties. Research work also aims at reducing the drying rate and improving

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quality of the finished products.

Vacuum drying is the process in which wood samples are placed in a leak tight vacuum chamber. When the vacuum pump is switched on, pressure on the samples is lowered. As the boiling point of water is substantially lowered when vacuum is achieved over the wood, it starts boiling and the moisture drawn out of the wood. Fresh wood contains a lot of moisture, which makes it inappropriate for its utilization in various products. The moisture must be removed before its usage in various industrial and house building projects (Rietz, 1957; Rietz and Page, 1971). The process of removing moisture from wood is known as wood seasoning. When seasoning is performed at a pressure less than atmospheric pressure, it is known as “vacuum seasoning”. Seasoning is one of the most important steps in converting raw wood into finished products. During the seasoning process, gross weight is reduced and handling cost is minimized. Besides, it also improves the paint-ability, glue-ability and water movement within the wood which reduces the severity of the moisture gradient.

Vacuum drying of wood began in 1920 in Sweden where it gained a patent in 1922. Then a lot of experiments were carried out in different laboratories around the world (Russel, 1994). The first industrial vacuum dryer was manufactured in 1962 using cyclic technology (Pagnozzi, 1983). In 1964 with the help of electric resistance plates, a small vacuum wood dryer was developed. The most significant development in the vacuum dryer took place in 1975 when a dryer with hot air heating was invented. The first radio frequency vacuum dryer was produced in 1970 (Koppleman, 1976). Maspell introduced vacuum kilns in 1966 with contact plate heating and now vacuum drying is playing an important role in the wood industry all over the world (Cividini, 1993)

During vacuum drying, the pressure outside the wood is lesser than when compared to the moisture pressure inside the wood. Due to this pressure difference, moisture is transferred and water vapors are removed from wood (Chen & Lamb, 1995a). According to Darcy’s Law, the amount of moisture transferred is directly proportional to the permeability. The permeability of wood in the longitudinal direction is about 10,000 times greater than the permeability in the transverse direction, so under pressure most moisture moves in the longitudinal direction (Chen & Lamb, 2001). Apart from boiling, there exists a boiling front inside the wood. When moisture moves from the boiling front to the surface of wood it is converted into steam, but when moisture moves from the front end to the centre of wood it is not converted into steam rather the moisture moves into a liquid phase. This movement occurs due to capillary action. The flow rate of the boiling front depends on the amount of heat supply and properties of wood (Chen & Lamb, 1995b).

Since 1970, vacuum drying of thick, refractory, high-value species has become more favorable. The most attractive advantage of vacuum drying is that the vacuum lowers the boiling point of water, e.g. at 150 mm Hg, water boils at about 54^{o}C, resulting in more rapid surface evaporation (Eckelman, C.A.,). At a lower drying temperature, wood is stronger and can withstand a greater internal stresses without defects occurring (Bousque, 2000).

A lot of work has been performed by various researchers in different laboratories of the world in the last few decades on vacuum drying of wood (Harris & Taras, 1984). During the vacuum drying of wood, the samples under testing conditions are placed in a leak tight vacuum drying chamber and a pump is switched on to reduce the pressure in the chamber, which results in the lowering of boiling temperature of water contents in the wood samples (Simpson, 1987). In general, vacuum drying is rapid and the quality of product produced is better (Wengert & Lamb, 1982). During the vacuum drying, the sample undergoing the test does not change in colour (Moldrup & Moldrup, 1992).

2. EXPERIMENTAL SETUP

In this study, a vacuum drying system was designed and developed at National Institute of Vacuum Science & Technology (NINVAST) and its drying quality was evaluated. The system was applied to dry, green wood at a low level of energy consumption and with short drying time. The experimental set up of the vacuum drying system is shown in Figure 1.

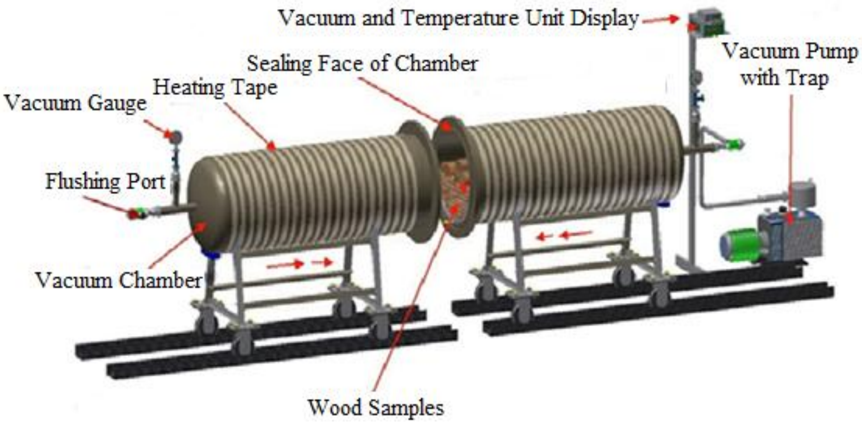

Figure 1 Experimental setup for vacuum seasoning of wood

It consists of two vacuum chambers fabricated with stainless steel, each having a length of 1640 mm and a diameter of 1210 mm. These chambers can be used separately as well as combined, depending upon the size and shape of the material to be dried. A separate arrangement with a door is provided to use these chambers individually. A mechanical rotary vacuum pump LH D-60 having a range from atmospheric to 10^{-1} pascal is attached with the vacuum chambers to slowly evacuate the system. The heating tapes are Heraus WITTMAN brand, 1000 watts and a temperature range up to 260^{o}C with thermocouple sensors, which are used to monitor the temperature along with a digital display unit and a temperature controller. A cold trap was used to condense and collect the water vapour from the wood.

3. METHODOLOGY

For testing of our vacuum drying system, samples were prepared from Poplar and Eucalyptus trees with dimensions of 990.6 mm x 76.2 mm x 25.4 mm and 469.9 mm x 50.8 mm x 25.4 mm. The samples were marked to distinguish them from each other. Most of the samples were knot free or contained only small pin knots. When these were about to be put in the chamber for drying, several centimeters from both ends of the boards were cut off and discarded. Then 2.54 cm moisture sections from both ends were cut to measure the initial MC of the sample.

Then these samples were placed in the special tray held inside the vacuum chamber as shown in Figure 1. The chamber was closed and made leak tight. The chamber with the wood samples inside was heated to the desired temperature. The vacuum pump connected to the chamber was then turned on to maintain a vacuum level of 1.6×10^{3} pascal. To measure the amount of moisture, a moisture sensor (Hydrometer HTR 300) was inserted into each sample at different locations after each run and data is recorded. When the MC of samples reached approximately 10%, heating was stopped and drying quality was tested, which included a warp test, prong test and surface checking.

4. RESULTS AND DISCUSSION

4.1. Dry Run without Wood Samples

To study the relationship between temperature and pressure inside the chamber, a number of experiments were performed. Table 1 illustrates that with the passage of time the temperature is increasing inside the vacuum chamber and the pressure is decreasing continuously which validate that the system is suitable for rapid vacuum drying of wood. The situation is shown graphically in Figures 2, 3 and 4.

Table 1 Time versus external, internal temperature and pressure of the chamber

Time (min)	External Surface Temperature (°C)	Internal Temperature (°C)	Pressure (pascal)	Log P
0	21	20	1×10^{5}	5.0
15	58.6	30.8	3.1×10^{3}	3.49
30	98.2	44.2	2.3×10^{1}	1.36
45	102	51.8	7.5	8.75×10^{-1}
60	119	59	4.7	6.72×10^{-1}
75	122	64.8	3.8	5.80×10^{-1}
90	124	67.2	3.5	5.44×10^{-1}
105	126	68.5	3.4	5.31×10^{-1}

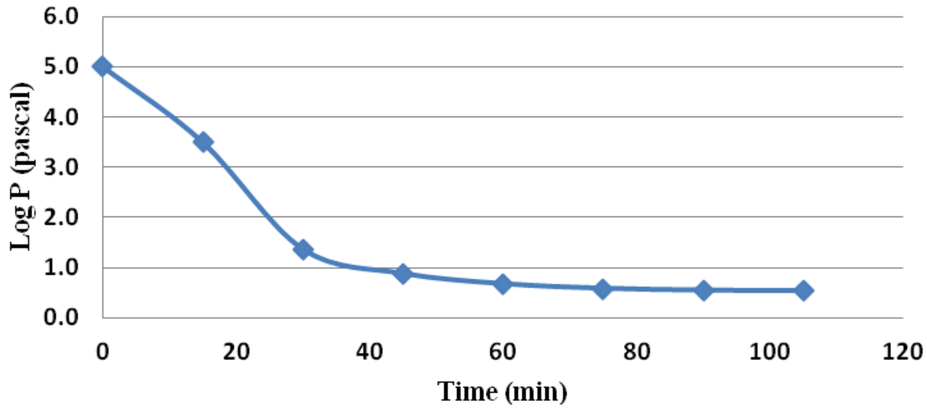

Figure 2 Rate of fall in pressure inside the chamber

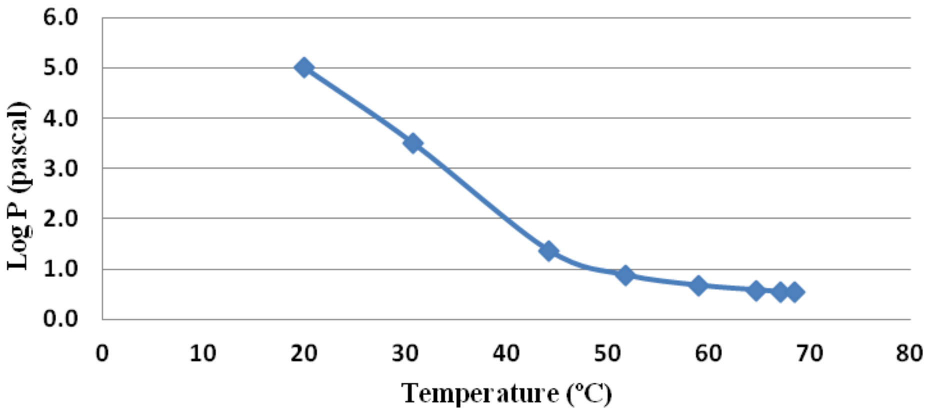

Figure 3 Temperature and pressure inside the chamber

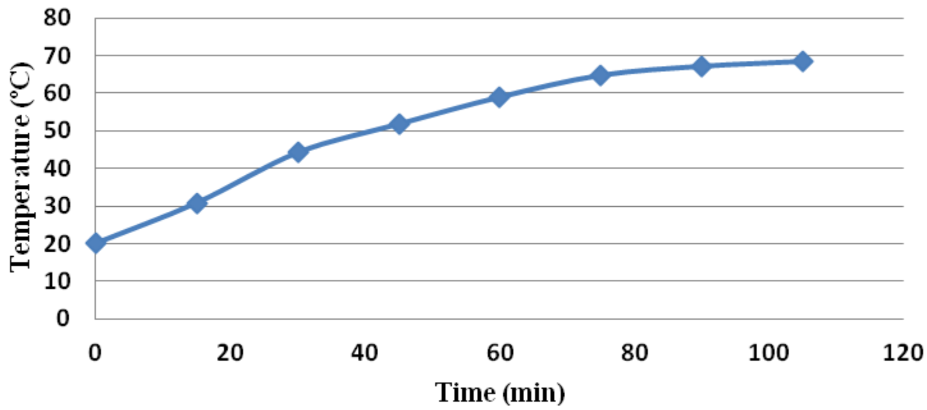

Figure 4 Variation of temperature with time (min) inside the chamber

After attaining ultimate vacuum and temperature in the chamber and recording the data, the valve on vacuum pump side was closed and the vacuum thermal chamber was allowed to cool down and the temperature inside the chamber was recorded. The observations made are shown graphically in Figure 5.

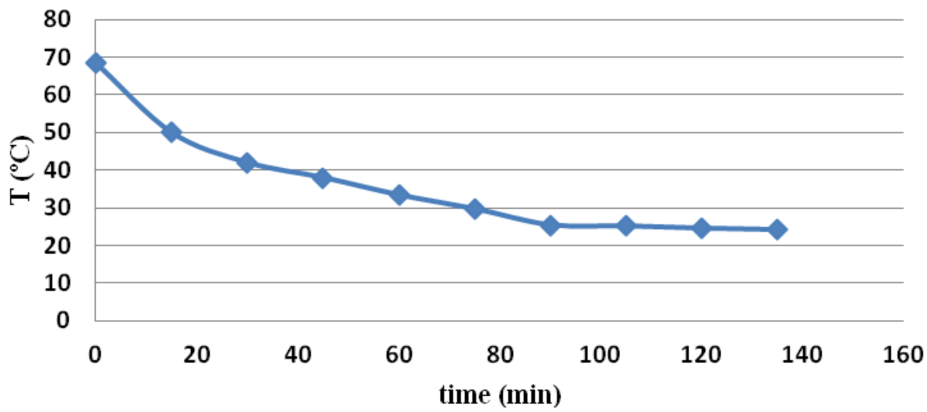

Figure 5 Fall in internal temperature when heating tapes are switched off

4.2. Wood Samples

A total number of seventeen samples of Eucalyptus and Poplar were used and these were marked with tags as 1E, 2E, 3E, 4E, 5E, 6E, 7E and 1P, 2P, 3P, 4P, 5P, 6P, 7P, 8P, 9P, 10P, respectively. Four Poplar boards and one Eucalyptus board with dimensions of 990.6 mm x 76.2 mm x 25.4 mm and six pieces of each Poplar and Eucalyptus with dimensions of 469.9 mm x 50.8 mm x 25.4 mm were sawn and made smooth. In order to avoid losing moisture, specimens were wrapped in plastic film and sealed in plastic bags and test results were taken outside the chamber after each run.

4.3. Dry Test with Wood Samples

The samples were placed on the tray, which was inserted within the chamber. The chamber was then heated to the desired temperature. The vacuum pump was switched on to achieve a desired vacuum level. In order to check temperature, pressure and moisture content after each run, a number of experiments were performed and the data of required parameters after regular time intervals were noted down. After a run of four hours the heating was stopped and pump was switched off. The above-mentioned procedure was repeated for four runs and recorded data is presented below in Table 2 and Table 3.

Table 2 Time versus external, internal temperature and pressure inside the chamber

Time (min)	External surface temperature (ºC)	Internal temperature (ºC)	Pressure (pascal)	Log P
1st Run				
0	18.4	16.4	1.0×10^5	5.0
30	62	19.5	1.8×10^3	3.255273
60	85	26.6	1.8×10^3	3.255273
90	90	31.6	1.7×10^3	3.230449
120	94	33.7	1.6×10^3	3.204120
150	96	35.1	1.4×10^3	3.146128
180	97.5	35.5	1.2×10^3	3.079181
2ndRun				
0	19	17.4	1.0×10^5	5.0
30	76	28.8	1.9×10^3	3.278754
60	101	33.8	1.8×10^3	3.255273
90	104.5	36.2	1.8×10^3	3.255273
120	107	38.7	1.7×10^3	3.230449
150	109	40.0	1.6×10^3	3.204120
180	111	40.7	1.6×10^3	3.204120
210	113	42.7	1.5×10^3	3.176091
240	114	43.1	1.4×10^3	3.146128
270	115	43.5	1.3×10^3	3.113943
300	117	45.0	1.2×10^3	3.079181

Table 3 Time versus external, internal temperature and pressure inside the chamber

Time (min)	External surface temperature (ºC)	Internal temperature (ºC)	Pressure (pascal)	Log P
3rd Run				
0	20	17.8	1.0×10^5	5.0
30	80	21.9	1.8×10^3	3.255273
60	102	28.0	1.7×10^3	3.230449
90	115	32.8	1.6×10^3	3.204120
120	119	35.3	1.5×10^3	3.176091
150	109	30.6	8.5×10^2	2.929419
180	111	30.8	7.7×10^2	2.886491
210	115	31.0	7.3×10^2	2.863323
240	120	33.2	6.3×10^2	2.799341
270	122.7	34.9	5.9×10^2	2.770852
300	123.5	36.2	5.8×10^2	2.763428
4th Run				
0	18.4	17.2	1.0×10^5	5.0
30	90.8	27.5	1.9×10^3	3.278754
60	118.7	36.8	1.8×10^3	3.255273
90	121.6	42.3	1.8×10^3	3.255273
120	124	46.5	1.7×10^3	3.230449
150	124.5	50.0	1.6×10^3	3.204120
180	126	52.8	1.5×10^3	3.176091
210	127	54.0	1.4×10^3	3.146128
240	128	55.0	1.2×10^3	3.079181

Table 2 and Table 3 show that with the passage of time, an increase in temperature is slow as when compared to its increase during a dry run without wood samples, i.e. in the absence of wood samples after 90 minutes, the external temperature was 124ºC, internal temperature was 67.2^{o}C and pressure was 3.5×10^{0} pascal. In the presence of wood samples after 90 minutes, external temperature was 121.6ºC, internal temperature was 42.3ºC and pressure was 1.8×10^{3} pascal. This is due to presence of moisture inside the chamber after placing the green wood samples. Similarly moisture coming out of the wood samples affect the fall in pressure, which is also found to be slow. Experiments were also performed with the combination of the roots and rotary pump. In one of these experiments the roots pump is switched on after two hours of rotary pump action and it was observed that not only had a fall in pressure occurred immediately, but also the temperature decreased quickly. The reason behind that event was the rapid extraction of moisture from the wood samples. This situation is presented graphically in Figures 6, 7, and 8.

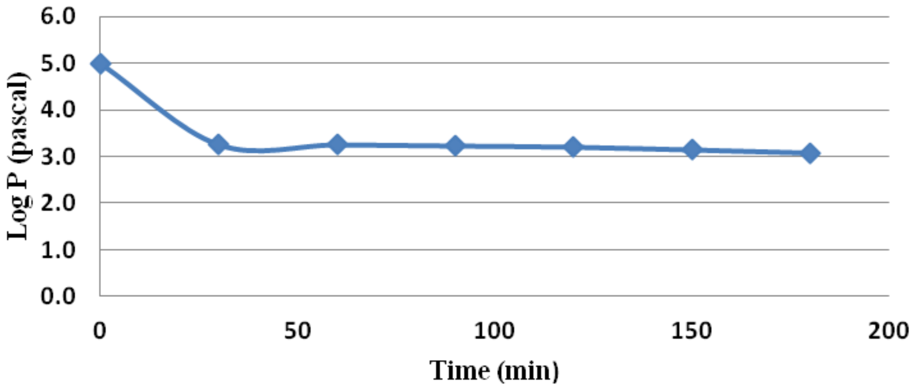

Figure 6a Rate of pressure fall inside the chamber in the presence of wood

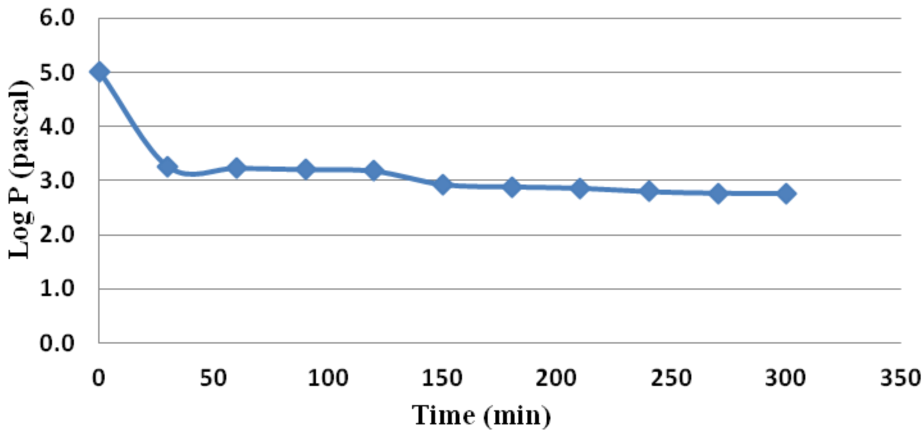

Figure 6b Rate of pressure fall inside the chamber with combination of the roots and rotary pump in the presence of wood samples

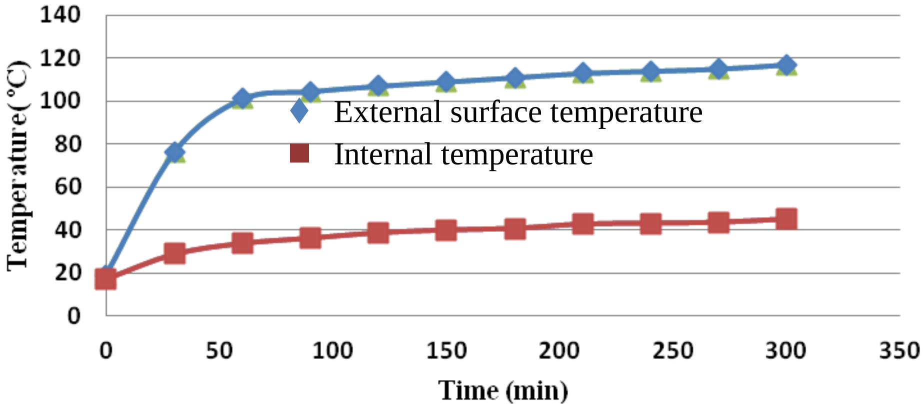

Figure 7 Rate of temperature increase inside and at the surface of the chamber in the presence of wood samples

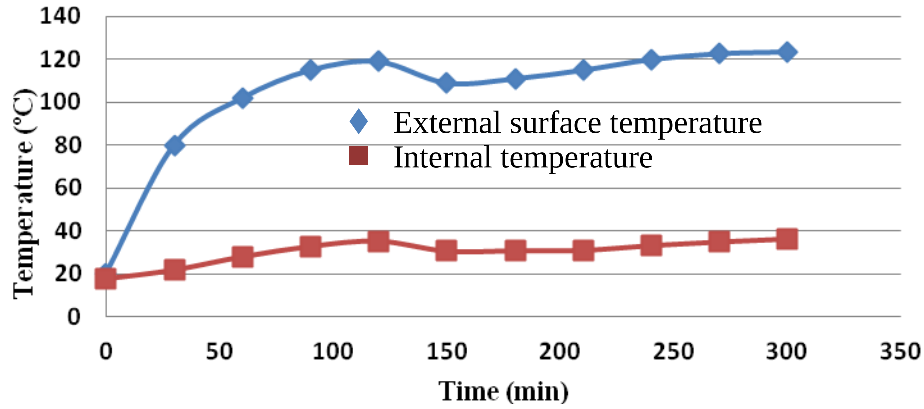

Figure 8 Rate of temperature increase inside and at the surface of the chamber in the presence of wood samples with the combination of the roots and rotary pump

Similarly, the increase in temperature became rapid with the decrease in the moisture content of the samples. That is why at the 1st run the maximum temperature attained was 35.5ºC inside the chamber, but in last run when the moisture content was low, the maximum achieved temperature was found to be 55ºC inside vacuum chamber. It is also obvious from Figure 8 that the fall in pressure had a prominent effect on the temperature which was lower when the roots pump was switched on. Figure 6a shows a fall in pressure when only the rotary vacuum pump is working, while in Figure 6b the deviation is due to the fact that when the roots pump is also switched on, then after two hours of run, the pressure fell immediately.

4.4. Drying Curve and Drying Rate

For each sample, experiments were performed to study different parameters, particularly the drying rate of the wood samples. Initially, finally, and at different runs, moisture contents were measured by inserting a moisture meter into five samples of each species i.e. Poplar/Eucalyptus, respectively under the same conditions of temperature, pressure and dimensions at different locations and then average moisture content of that species was calculated. Initial moisture content was measured immediately after cutting green wood from the trees. It was 78% for Eucalyptus and 72% for Poplar. After each run, the moisture content of each sample was measured. It was found that there was approximately a 15% to 25% fall in moisture content in each run. Figure 9 and Figure 10 illustrate the drying curves of the Poplar and Eucalyptus wood samples. The drying curves for all the samples showed a similar pattern. The samples taken at temperatures ranging from room temperature to 55ºC were dried, ranging from 78% to about 10% MC within 20 h. The recommended values for final moisture content ranged from 5.8 to 18.1% in different US locations (Simpson, 1999). In India, our neighbouring country, permissible moisture content for timber varies with respect to application and this ranges from 3% to 18% (Indian Standard 287, 1993). However, in Pakistan it is desirable to reduce moisture content below 20% of the initial moisture content in wood samples from an application point of view (Fatima et al., 2015).

The drying rate was calculated for each sample during vacuum drying. The average vacuum drying rate for one large and one small sample of Poplar and Eucalyptus is listed in Table 5. It was concluded that average drying rate of Eucalyptus was higher than that of Poplar.

Table 4 Percentage (%) Moisture Content (% MC) of Eucalyptus and Poplar samples

Time (hr)	Eucalyptus		Poplar	
	MC (%) (39″×3″×1″)	MC (%) (18.5″×2″×1″)	MC (%) (39″×3″×1″)	MC (%) (18.5″×2″×1″)
0	78.0	78.0	70.0	70.0
3	55.0	47.2	51.8	40.3
8	42.0	32.5	36.5	30.0
13	32.3	24.3	29.0	24.5
17	21.0	16.0	20.3	21.0
20	12.0	10.0	12.0	16.0

Note: 39″x3″x1″ = 990.6 mm x 76.2 mm x 25.4 mm and 18.5″x2″x1″) = 469.9 mm x 50.8 mm x 25.4 mm

Table 5 Average vacuum drying rate of Eucalyptus and Poplar

Sample	Initial MC (%)	Final MC (%)	Average Drying Rate (%/h)
6E(39″×3″×1″)	78	10	3.4
4E(18.5″×2″×1″)	78	12	3.3
9P(39″×3″×1″)	70	16	2.7
3P(18.5″×2″×1″)	70	12	2.9

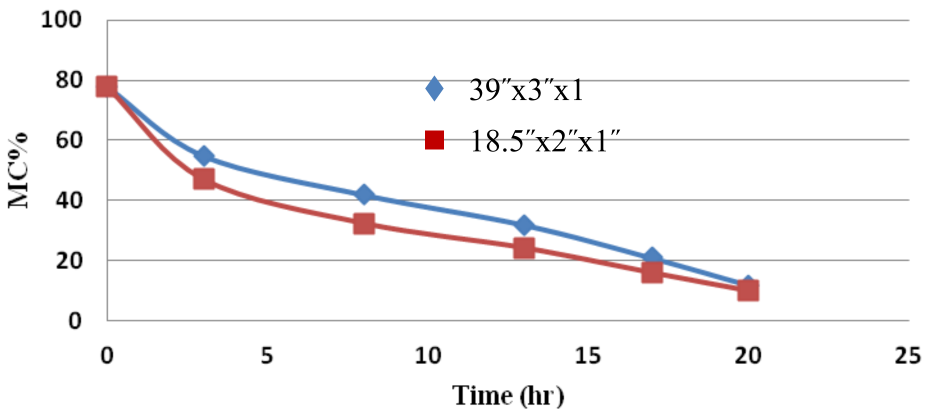

Figure 9 Drying curve for Eucalyptus samples

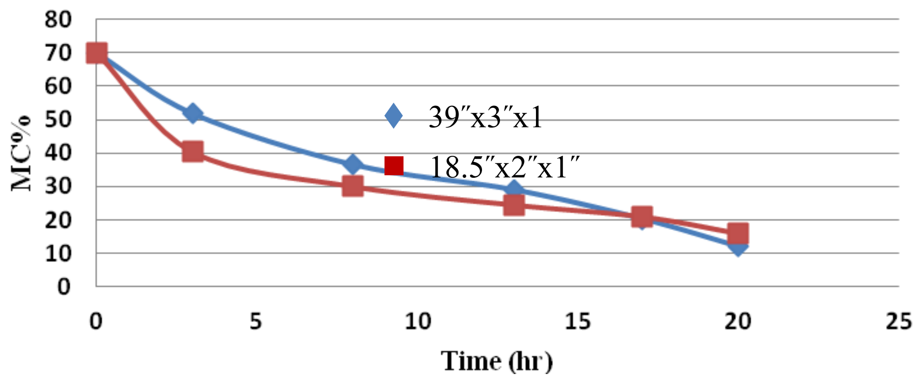

Figure 10 Drying curve for Poplar samples

4.5. Warp in Vacuum Drying

When one edge, face, or end of piece of wood shrinks more than the opposite edge, that face or end is called ‘warped’. Warp is caused by differential directional shrinkage as the wood dries from its green state (Wengert & Meyer, 1993). The four types of warps are cup, bow, crook and twist. An introduction to each type of warp is given below.

4.5.1. Cup

‘Cup’ is warp across the width of the face of piece of wood .When one face shrinks more in width than the opposite face, the end become cup-shaped.

4.5.2. Bow

When one face of the wood shrinks more in length then the other face, the warp produced is called ‘Bow’.

4.5.3. Crook

Warp that is produced along the length of the edge of the piece of wood is called a side bend or ‘Crook’. It is due to greater shrinkage at one end than the other that causes an edgewise curvature of the piece of wood.

4.5.4. Twist

‘Twist’ is the turning of the four corners of any face of a board so that they are no longer in the same plane. It occurs in wood containing spiral, wavy, diagonal, distorted, or interlocked grain.

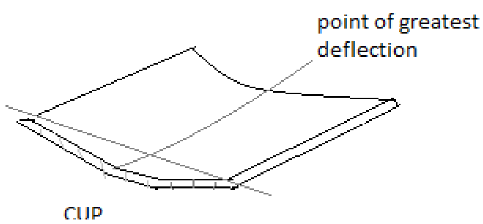

Figure 11 Warp across the width of the wood sample

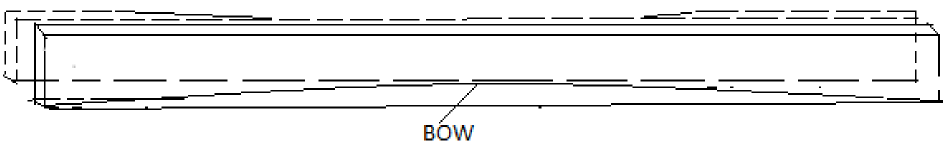

Figure 12 Shrinkage in the face of the wood sample

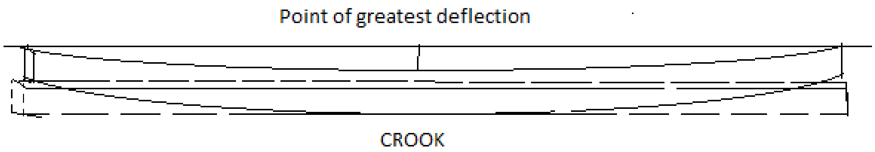

Figure 13 Side bent in the wood sample

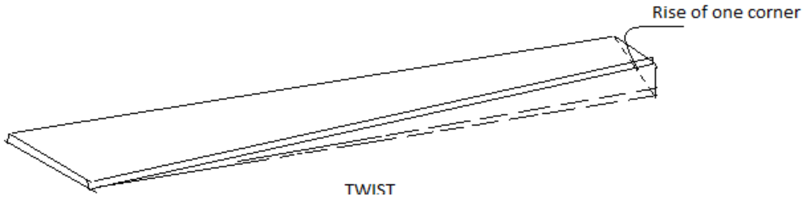

Figure 14 Turning of corners of the wood sample

4.6. Warp Measurements

General methodology could be applied to any of the crook, bow, twist, cup or combination of these qualities. According to this method, the original warp of the firstly cut green wood is measured at a particular temperature, pressure and moisture content, then second warp test of the same products under new conditions is measured and observations of the changes that take place in edge, face or end are noted (Magill, 2010). The crook, bow, cup and twist of each board are each measured initially and again at the end of each run. The crook and bow can be measured using a special warp jig in which displacement of the edge or face at every one-inch interval along the length of the board is measured. Twist can be measured by measuring the elevation at one corner above a plane on which the other three corners of the wood are held (Stanish, 1999). Samples of Poplar and Eucalyptus were sawn and made smooth, such that there was no warp initially. After vacuum drying, their warp measurements were taken and it was observed that there was more warp in the samples having greater length and width as compared to samples with smaller dimensions.

Table 6 Warp measurements of samples with dimension of 990.6 mm x 76.2 mm x 25.4 mm after vacuum drying

Sample (990.6 mm x 76.2 mm x 25.4 mm)	Cup (mm)	Bow (mm)	Crook (mm)	Twist (mm)
6E	1	2	2	4
7P	1	2	4	9
8P	0	1	3	6
9P	1	9	0	19
10P	0	8	5	15

The allowable values of Bow (1.30–1.90 cm-m^{-1}), Crook (0.6–0.90 cm-m^{-1}), and Twist (0.90–1.30 cm-m^{-1}) are shown for graded structural timber (Kretschmann et al., 1999; Faust, 1990; Simpson et al., 1998). As Eucalyptus is one of the timber species mentioned, these values are also being considered for these experiments.

These values are calculated by taking the average for a particular length from Table 7 and Table 8 and then converting the particular warp into the desired unit, e.g. for length = 39″ (0.99 m) (Table 6), the average value of Bow = 22 mm/5 (4.4 mm or 0.44 cm) = 0.44cm/0.99m = 0.44

cm-m^{-1}. It is clear from Table 8 that 'warp' produced in these samples are lower than the allowable values and the quality of the products is much better.

Table 7 Warp measurements of samples with dimension 469.9 mm x 50.8 mm x 25.4 mm after vacuum drying

Sample (469.9 mm x 50.8 mm x 25.4 mm)	Cup (mm)	Bow (mm)	Crook (mm)	Twist (mm)
1E	0	0	0	1
2E	0	0	0	1
3E	1	0	1	1
4E	0	0	1	0
5E	0	0	1	1
1P	0	0	1	0
2P	0	2	0	1
3P	0	3	1	9
4P	0	1	1	4
5P	2	0	0	0
6P	1	0	2	3

Table 8 Average values for different deformation parameters as well as total warp of Eucalyptus and Poplar samples of different lengths

Length of samples	Bow (cm-m^{-1})	Crook (cm-m^{-1})	Twist (cm-m^{-1})	Total Warp
39″= 0.99 m (Table 6)	0.44	0.28	1.06	1.78
18.5″= 0.469 m (Table 7)	0.11	0.155	0.40	0.665

4.7. Prong Test

The prong test is used to determine initial acceptability of the dried wood samples. In this method, a one-inch thick cross section of the wood is taken and cut into a U-shape. The wood is considered unacceptable if the ends of the U bend toward each other or away from each other. This is due to excessive stress build-up. It is obvious from the data listed in the Table 9 and Table 10 that there are more stresses in Poplar, when compared to Eucalyptus.

Table 9 Prong response of Eucalyptus samples after vacuum drying

Samples	Original distance (cm)	Prong distance after drying (cm)	Status prong test
1	2.4	2.2	passed
2	2.4	2.3	passed
3	2.5	2.5	passed
4	2.4	2.2	passed
5	2.4	2.4	passed
6	2.3	2.4	passed

Table 10 Prong response of Poplar samples after vacuum drying

Samples	Original Distance (cm)	Prong distance after drying (cm)	Status prong test
1	2.5	2.3	passed
2	2.4	2.6	passed
3	2.5	2.5	passed
4	2.5	1.9	failed
5	2.8	2.6	passed
6	2.6	2.2	failed

(a) (b)

Figure 15 Prong test showing: (a) acceptable piece of board; and (b) unacceptable piece of board with excessive stress build-up

5. CONCLUSION

The designed and developed vacuum drying system could be more useful for the small business community involved in commercial woodwork. Vacuum drying technology offers many opportunities to benefit wood quality from the perspective of productivity, quality and energy consumption. It is clear from the above results that the vacuum drying process is rapid and it is an alternative to conventional drying. Drying at 35°C, 45°C, and 55°C, respectively resulted in a drying time of less than 25 hours and there was a 3.35% drop in moisture content/hour of Eucalyptus and 2.8%/ per hour in Poplar samples. It was observed that rate of fall in pressure was less in the presence of wood samples during drying and was due to the presence of water content being extracted from the samples. The colour of the samples remained unchanged. Only a few samples failed the prong test (change in distance ≥ 3 mm), thus showing that less stress occurred in vacuum drying. All Eucalyptus samples passed the prong test and only 33.4% of Poplar samples failed the prong test. It was also concluded from the recorded data that less warp was produced in the samples, having smaller dimensions, when compared to the samples of larger dimensions (Table 8). In the initial MC, final MC and average drying rate depends on the species of wood being dried. With further optimization and testing for strengths and toughness, the drying time of wood can be reduced.

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