EXPLORATORY STUDY OF THE EFFECT OF OSCILLATION DRYING
ON THICK HEMLOCK TIMBERS

by

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Abstract

This study was aimed at exploring the effect of oscillating the drying temperatures of a drying schedule on the drying characteristics of thick western hemlock timbers.

Pacific coast hemlock which is comprised of about 70% western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is one of the best quality and most abundant softwood species along the coast of British Columbia. The squares of 105 x 105mm of this species group is widely used for housing construction in Japan, and mostly imported from British Columbia. In recent years the overall demand has decreased and there is also a great market shift in demand from green to kiln-dried lumber. However, conventional kiln-drying of thick hemlock timbers has difficulties of long drying times, uneven final moisture content distribution within and between lumber, honeycombs, checking and splitting. Since most industries still use conventional dry kilns (also known as "heat-and-vent" kilns), it is imperative to explore alternative drying schedules to improve the quality of 105mm square dried Pacific coast hemlock.

In this study, thick industrial size square Pacific coast hemlock of dimensions 115 x 115 x 920 mm were dried in a laboratory conventional kiln, using a control schedule and four oscillating drying schedules with drying temperatures (wet bulb -T<sub>wb</sub>=53°C, dry bulb-<br>T<sub>db</sub>=60°C) oscillating at two amplitude and frequency combinations (3°C/4hours and 6°C/8 hours). The research results indicated that, the total effect of oscillating schedule on drying rate was more pronounced at the early stages of the drying process. Oscillating dry bulb temperatures at higher amplitudes increased drying rate by 12%, whereas the lower amplitude counterpart reduced kiln residence time by 14%. All schedules were also found to reduce moisture content variability between lumber. Core and shell moisture content variation slightly decreased when the wet bulb temperature was oscillated at low amplitudes. Climate oscillations also affect the drying stresses of thick hemlock lumber. Drying stresses in the lumber increased when oscillating the dry bulb temperature at lower amplitudes. Width shrinkage in the baby square hemlock lumber reduced in the low amplitude dry bulb oscillated schedule.
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Chapter 1

Introduction

Our society depends on wood and wood products for a variety of uses. The increase in world population automatically increases our dependency on this natural resource. Since the onset of the utilization of wood and wood products, mankind has consciously or unconsciously dried wood. Timber/lumber drying is an inevitable process in the forestry/wood chain, which almost all wood products have to undergo before its end use. It helps provide dimensional stability and reduce the weight of wood-in-use and in transportation. Drying wood below the moisture content of about 20% makes it more resistant to fungal and insect attack. Drying also prepares the wood for impregnation with liquid or gas preservatives. However, conventional batch kiln-drying, which is the most abundantly used kiln-drying technique brings with it certain difficulties like long drying times, uneven final moisture content distributions between and within lumber and drying defects, like surface checks, warp, casehardening and in some cases, discoloration. These difficulties are especially dominant with thick timbers and wood with wide green moisture content distributions and wet-pockets (also called sinker stock like western hemlock or sub-alpine fir).

The largest importer of British Columbian (BC) softwood lumber is Japan, and its imports grew from about 700 million board feet (1.65 million m$^3$) in 1970 to over 2.1 billion board feet (4.95 million m$^3$) in 1997. However, recently the lumber imports have declined significantly from their peak in 1997 to 1.6 billion board feet (3.8 million m$^3$) in 1998 which recovered slightly to 1.8 billion board feet (4.3 million m$^3$) in 1999 (see Figure 1.1). The Japanese market acceptance of traditional North American lumber has shifted to kiln-dried (Figure 1.1) products and 5-ply laminated posts from Scandinavia. Coastal BC producers have responded by initiating a program that is aimed at improving market acceptance, for coastal hemlock and especially research on drying strategies (COFI Fact Book 2000).
Japan imports Pacific Coast Hemlock (PCH), a mix of western hemlock and amabilis fir which are harvested and processed together, mostly for their traditional housing construction. The lumbers are mostly light coloured squares of 105mm (4 x 4in$^2$) in cross-section known as baby squares. They are used for the skeletal framework as vertical posts, horizontal girders, ridge beams and ground sills. According to Pesonen, (1993), baby squares accounts for about 23% of the total lumber used in these housing structures which is mostly imported from BC. Kaila (1991) indicated that 70% of all BC hemlock lumber exported to Japan, was baby squares. Due to their thickness, kiln drying of this timber product can easily lead to warping and internal checking (honey combing), as well as uneven kiln dried final moisture content.

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) constitute about 70% of the PCH group exported to Japan, whilst amabilis fir (*Abies amabilis* (Dougl.) Forbes) is about 30%. It is also traded as hemfir species in combination with five other species. The hemfir combination is one of the most important in the Western region of U.S.A, second only to the Douglas–fir and larch species group in terms of abundance, production

**Figure 1.1:** Annual Exports of BC Pacific Coast Hemlock to Japan (*after Taylor and van Leeuwan, 2000*) – Note: bf = board feet (100bf = 2.36m$^3$).
volumes, strength, and versatility in end use (WWPA 1997). It is the major sawn timber along the entire west coast of North America (Kozlik et al. 1972), and one of the best quality and most abundant softwood timbers in BC (Lin et al. 1973). According to COFI (2000), hemlock accounted for 17.7% of the total growing stock of BC in 1998, and about one-third of the 1998 BC log harvest came from coastal forests. Coastal BC harvested PCH accounted for the highest volume. With respect to lumber production, PCH was the highest amounting to 45.9% of the total BC lumber production in 1999.

As indicated earlier in Figure 1.1, in order to increase acceptance and hence export of PCH, the aspect of increased kiln drying proportion is very important. However, western hemlock has a wide range of green moisture content, ranging from 55% in heartwood to about 165% in sapwood (Mackay and Oliveira 1989). This poses an extreme difficulty in achieving the low kiln-dried final moisture content distribution required by Japanese customers. The wide variation in green moisture content within and between boards, and consequently wider kiln dried final moisture content variability has been attributed to the presence of wet wood (‘wet pockets’ or ‘sinker stock’) in western hemlock. These problems make it difficult to dry (Zhang et al. 1996), lead to costly drying defects (Knutson 1968, Mackay and Oliveira 1989), and reduces drying rate (Kozlik 1970).

In an effort to dry lumber with a minimum amount of drying defects, gentle drying schedules are employed that increase lumber kiln residence time. Reid (1961) suggested that drying times of exposed stacks in the open air could be up to one year for 25mm thick lumber. A four-stage complex kiln-drying schedule by Kininmonth (1974) could decrease the total drying-time for a 25mm thick lumber to seven months. In recent years, Langrish et al. (1992) observed that, by adopting intermittent drying with air temperature of 45°C and a wet-bulb depression of 10°C, the dried lumber were without honeycomb and with less casehardening than continuous drying, however, it took a longer time to yield the target moisture content.

Many researchers have approached the problem of pure western hemlock using different drying techniques. Applying a high temperature schedule to 105mm squares, Dubois
(1992) reported an average of about 92 hours drying time. High temperature drying however causes darkening of lumber surface and reduces strength properties (Kozlik 1976). Furthermore, it leads to higher amount of degrade like internal checking (honeycomb) (Salamon 1966, Sato and Hoshide 1969, Sumi and McMillen 1979, Oliveira and Mackay 1991). Presteaming was experimented by Avramidis and Oliveira (1993) using PCH baby squares and found to reduce the final moisture content variability, but improvements in drying rates were not observed. A recent study by Li et al. (1997) used vertical air gaps in the kiln stack to increase air velocity and fan revolutions. This increased drying rates of baby squares drying, but did not improve final moisture content variation.

According to Gerhards (1980), temperature has a significant influence on the tensile and compression strength of wood. Through oscillating humidity and temperature within the kiln, the phenomenon of "mechano-sorptive creep" (Ranta-Maunus 1990), which expresses stress relaxation, increases. Using extended bending test in the elastic region, Mohager and Torrati (1993) also proved the change in plasticity of cell walls associated with oscillating air humidity. Both temperature and humidity influence moisture movement and strength of wood, oscillating the climatic conditions in a dry kiln therefore can be used to dry wood in a gentler manner, without necessarily reducing drying rate. Fruewald et al. (2000) adopted the oscillating strategy to dry smaller dimensions (500 x 110 x 30mm³) of pine, spruce and beech. They reported an average reduction of 10% - 20% in drying times for all the species as compared to the normal conventional drying method. Terziev et al. (2002) however, working on 50mm thick tangential Scott pine planks (1000 x 130 x 50mm³) using oscillating schedule of amplitude ±1.2 to 2°C and ± 6 to 10°C at frequencies of 30min and 20-90min, respectively, did not record an improvement with regards to drying rate and wood quality.

These experiments however, investigated thin dimensions and different species and those which worked on PCH could not solve the three most difficult problems of final moisture content variability within and between timbers and slow drying rate in a single approach. Since most industries still use conventional dry kilns (also known as "heat-and-vent"
kilns), it is imperative to explore alternative drying schedules to improve the quality of 105mm square dried PCH.

The objective of this exploratory study is therefore to evaluate how oscillating drying schedule (ODS) affect the drying rate and therefore drying time, moisture content variation between and within timber and the extent of the drying defects.
Chapter 2

Background

2.1 Western hemlock characteristics and uses

Western hemlock also was named by botanist Stephen L. Endlicher in 1847 as “tsuga”. In Japanese, “tsu-ga” means “tree” and “mother” or “yew-leaved” referring to its short, flat needles. Amabilis fir is also known as lovely fir. “Amabilis” means lovely and due to the silvery nature of the under side of its needles, it’s also called silver fir (WWPA 1997). As described earlier PCH commercially belongs to the hemfir species combination. In BC, it grows along both the east and west sides of the coastal range, from sea level to mid elevations, as well as in the interior wet belt west of the Rocky Mountains where rainfall is high (shown deep green in Figure 2.1a).

Figure 2.1a: Occurrence of Western hemlock in British Columbia (source: BC Ministry of Forests, 1999).

Western hemlock, as shown in Figure (2.1b), is a relatively shade tolerant tree and as a mechanism for competition for sunlight the lower branches die and fall away thereby,
"pruning" itself as it grows. This helps to develop clear trunks up to three-quarters of its height, which is highly desirable in softwoods, as this leads to increased volumes of clear lumber in large logs. It is the most economically important timber compared to eastern hemlock and normally in a mixed stand with amabilis fir, Douglas-fir, sitka spruce and western red cedar (Bramhall and Wellwood 1976). The wood is superior to that of eastern hemlock for building purposes, and makes excellent pulp for paper production. Western hemlock trees grow to heights of 50m with diameters exceeding 1000mm (Mullins and McKnight 1981). Jozsa et al. (1998) in their work with 91 year old secondary growth trees reported an average height of 40.9m and 0.43m diameter including back at breast height.

Figure 2.2: Typical uses of hem-fir in wooden traditional housing in Japan (source: Coast Forest and Lumber Association, 1999).

The wood of western hemlock is a whitish to light yellowish brown wood with a little difference between sap- and heartwood. Therefore, it is considered as part of the whitewood exported to Japan. Western hemlock generally is straight and quite even-grained with a distinct annual ring, and has a specific gravity between 0.42 and 0.47 (Panshin and de Zeeuw 1970). It shrinks considerably during drying, but when dried close to the end-use moisture content it is dimensionally stable. It can also be easily
planed, machined, and has a high nail-holding capacity. With its modulus of elasticity of about 12000N/mm² and modulus of rupture of about 38N/mm², it is a very strong wood used for the same general purpose as that from Douglas-fir. Its applications can be found in residential and industrial construction, planning mill products, paneling products and crates, and competes with spruce in the plywood manufacture. The strength-to-weight ratio of PCH coupled with light color lends itself well for the construction of housing frames in post-and-beam traditional construction in Japan. Lumber of cross section between 90.5 x 90.5mm² and 105 x 105mm² (Kaila 1991, Li et al. 1997) are the major components in these housing frames. The baby squares are deployed as vertical columns (Hashira) and horizontal column supports (Dodai) as illustrated in Figure (2.2).

![Graph showing housing starts in Japan between 1972 and 2000](after Yamiguchi 2001 modified into graph)

**Figure 2.3:** Housing starts in Japan between 1972 and 2000 (after Yamiguchi 2001 modified into graph).

Japan with its population of about 125.7 million (1997 estimate) and a surface area of 377,835 km² has a high population density (332.7 persons/km²). Apart from North America, Japan is the only country that traditionally builds and lives in wooden homes
Cohen (1993) reported that about 42% of all housing starts in 1991 in Japan were wooden and in 1992, it was determined that 79% of lumber shipments went into housing construction (Gaston 1997). The earthquake in Kobe in 1995 also damaged almost 147,600 houses (Yamiguchi 2001), and caused a high volume of housing starts in 1996.

The housing starts in 1999 were 1.2 million. Japan's residential housing market has consistently been one of the largest and most dynamic in the world despite the economic doldrums (Figure 2.3). According to Yamiguchi (2001), out of a total of about 4.32 million m$^3$ of softwood imported from North America by Japan in 2000, about 3.84 million m$^3$ (89%) was from Canada (see Figure 2.4a for trend). The statistics also show that hemlock constituted the greater part of the softwood imports (Figure 2.4b). There are three main wooden house constructions in Japan, namely traditional post-and-beam (P&B), the 2” by 4” platform framed and prefabricated houses. The P&B accounts for almost 38.8% of all housing starts in 2000 and has the highest volume of all the wooden houses (see Table 2.1). From a survey of Japanese house builders, Roos and Eastin...
(2003) reported that 64% of them used traditional P&B in their construction, but predicted a drop in 2005. However, an increase in new P&B (often referred to as Rationalised Post-and-Beam System) methods of construction was also predicted for the same period. Of the P&B, the baby squares which are used for structural purposes as well as interior decoration accounts for the highest percentage.

Due to the fact that, the Japanese attach extra natural and aesthetic value to the wood; a whitish fine grain type PCH is preferable, especially for the "post" size of 105mm baby squares. As indicated in Figure 1.1, however, BC green hemlock exports to Japan have been decreasing as the kiln dried market increases. The survey from Roos and Eastin (2003) also indicated that the use of kiln-dried lumber by Japanese builders has increased by 59.2% over the past two years, whilst use of green lumber decreased by 61%. Evidently, this calls for increased drying of the PCH squares exported from BC. There is however difficulties experienced in drying thick western hemlock timbers, which includes baby squares. The next section discusses lumber drying, purpose and mechanisms underlying drying.

| Table 2.1: Breakdown of housing starts in 1999/2000 (after Yamiguchi, 2001) |
|-----------------|-----------------|-----------------|
|                 | 1999            | 2000            | 2000/1999        |
| Total           | 1,214,6011 (100%) | 1,229,843 (100%) | +1.3%           |
| Wood P&B        | 489,680 (40.3%)  | 476,700 (38.8%)  | -2.7%           |
| Wood 2x4        | 75,864 (6.2%)    | 79,114 (6.4%)    | +4.3%           |
| Pre-fab         | 185,724 (15.3%)  | 175,069 (14.2%)  | -5.7%           |
| Other Non-Wood  | 463,333 (38.2%)  | 498,960 (40.6%)  | +7.7%           |

2.2 Reasons for lumber drying (seasoning)

In order for wood to be converted to lumber, it requires the removal of some of the water to enhance its attributes and physical properties. This is termed as lumber drying or seasoning (Bachrich 1980, Bramhall and Wellwood 1976), the latter is mostly used to
refer to air-drying. Drying increases the value of the lumber that may allow the producer to obtain a higher dividend or provide market niche into otherwise inaccessible market segments. Increasing the value of lumber requires improving its usefulness, while minimizing quality losses and this leads us into the immediate and actual reasons for drying wood.

Lumber will always swell or shrink with changing environmental conditions. Drying lumber helps to provide dimensional stability in the material that can be turned or cut to precise dimensions. Therefore, drying lumber takes into consideration the end-use climate, which reflects the final moisture content and moisture gradient between the core and shell of the dried lumber. Stain and decay fungus, as well as many insects use wood as nutrients (food), so at a moisture content of more than 22%, wood is likely to be attacked by these biological organisms. Drying is therefore used to keep moisture content below this threshold to hinder any stain, mould or decay. Green lumber may contain adult insects, eggs or larvae and drying at elevated temperatures will sterilize or destroy any infestation. Keeping lumber at low moisture content is key to avoiding re-infestation. According to Bachrich (1980), lumber kept dry can last indefinitely. Kiln drying lumber may also assist in meeting any existing or future phytosanitary requirements of importing countries. Lumber drying is also used as pre-treatment before impregnating wood with preservatives especially in the pressure methods or with fire retardant chemicals.

Water has a strong molecular attraction to wood and can interfere with the cross-linking of glue and wood finishes. Drying wood therefore allows finishing like vanishing, painting and other surface treatments to be done properly and further improves its aesthetic value. Lumber requires moisture content of about 11% to allow gluing to form glued-laminated timbers and 3 to 4% for gluing softwood plywood (Bramhall and Wellwood 1976). Machining, planning, sanding, turning, shaping operations and assembly are easier to accomplish and enhanced when lumber is dried. There are many more wood end-uses which require specific moisture content and can only be achieved by controlled drying (see Table 2.2).
The cost of transportation of lumber by rail or truck is based on shipping weight. Drying wood to improve volume to weight ratio therefore, has a direct economic benefit. This was traditionally the primary purpose for drying softwood dimension construction lumber in areas serviced by rail (Bramhall and Wellwood 1976). Lumber is in its weakest state when the moisture content is above 30%. As the lumber is dried below 30%, it progressively gets stronger. Most strength properties of dried lumber are typically twice that of wet lumber. This allows dried structural components to have smaller dimensions and lighter weight, an advantage in furniture and structural millwork.

The various end uses elaborated above have different dried-lumber requirements. Considering the end-user’s requirements, Hoadley (1979) indicates that the relative humidity is the “cause” and the equilibrium moisture content the “effect”. Lumber must be dried to target final moisture content within a specified range and allowance (final moisture content distribution). Shrinkage, degree of residual drying stress and degree of allowable drying degrade in the form of warp and checks are specified. Table (2.2) shows a typical lumber products moisture content range.

<table>
<thead>
<tr>
<th>Lumber product</th>
<th>Final moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>3 - 4%</td>
</tr>
<tr>
<td>Furniture cabinets and millwork</td>
<td>7 - 9%</td>
</tr>
<tr>
<td>Framing for construction - studs</td>
<td>15 - 19%</td>
</tr>
<tr>
<td>Glued-laminated timbers</td>
<td>11%</td>
</tr>
<tr>
<td>Other uses</td>
<td>10 - 12%</td>
</tr>
<tr>
<td>Hardwood</td>
<td></td>
</tr>
<tr>
<td>Furniture cabinets and millwork</td>
<td>6 - 8%</td>
</tr>
<tr>
<td>Framing for construction</td>
<td>15 - 19%</td>
</tr>
<tr>
<td>Bending stock</td>
<td>25 - 28%</td>
</tr>
<tr>
<td>Preservative treating stock</td>
<td>20 - 30%</td>
</tr>
<tr>
<td>European export</td>
<td>10 - 12%</td>
</tr>
<tr>
<td>Tropical export</td>
<td>12 - 16%</td>
</tr>
</tbody>
</table>

The challenges in wood drying and the quality of the wood product expected however can only be achieved by proper understanding of the movement of water (moisture) in wood and the mechanics of the drying process.
2.3 Wood drying mechanisms and heat and mass transfer

The wood cell wall is composed of cellulose, hemicellulose (polyoses) and lignin all of which are polymeric (Kollman and Cote 1968, Fengel and Wegener 1989) and the lumen and intercellular spaces contain a considerable amount of sap. The sap however, is a solution of many organic and inorganic materials but from drying standpoint, it is considered as plain water (Simpson 1991). This is often referred to as moisture and expressed in percentage as moisture content. Moisture content \( M \) is defined as the weight of water \( W_w \) in a product expressed as a percentage of the weight of the product in dry or wet basis (Hall 1979). Commonly used for wood is the dry basis where the weight of product is expressed as oven dry weight of wood \( W_{od} \) (Kollmann 1951, Kollman and Cote 1968, Mackay and Oliveira 1989, Skaar 1972, Siau 1984) and often calculated as follows:

\[
M = \frac{W_w}{W_{od}} \times 100 = \frac{W_i - W_{od}}{W_{od}} \times 100 \text{ (Dry basis)} \tag{2.1}
\]

where \( W_i = \) initial or green weight (g).

Moisture content of a living tree is very variable depending on the geographical location and the season (Knuchel 1930, 1935). However, variability is even higher depending on the location within the tree or wood sample. According to Kollmann and Cote (1968) green softwood sapwoods show higher green moisture content than its corresponding heartwoods. The lower part of the stem contains less moisture than the top part of the tree (Knuchel 1935). Another variation from log to log and between and within boards which is very prominent in species like western hemlock may be due to the presence of wet pockets.

The moisture in wood exists in two different forms namely free (capillary) and bound (hygroscopic) which influence the ease of removal, rate of moisture movement and shrinkage (swelling) (Kollman and Cote 1968). The free water which is held by weak
capillary forces occupies the cell lumens and the intercellular spaces, and requires less energy to be removed. Bound water is the water molecules dissolved or adsorbed through hydroxyl groups to the cellulose, hemicellulose and to a lesser extent lignin (Berthold et al. 1994). It is limited by the available number of sorption sites and by the number of water molecules a sorption site can hold. They are held unto the wood by hydrogen bonds and van der Waals’ forces and therefore, require more energy for diffusion and evaporation (Siau 1995). Water vapour exists in the cell lumens and the intercellular spaces, which are not occupied by liquid water (Blass et al. 1994, Panshin and de Zeeuw 1970, Siau 1984). It is assumed that the bound water is not removed until all free water has been evaporated. This point or moisture content level is called the fibre saturation point or $M_{f_{sp}}$ (Tiemann 1906). At $M_{f_{sp}}$ more energy is required to remove moisture from the cell wall than the cell cavity (5% more at 15% moisture content and 15% more at 6% moisture content), shrinkage starts to occur and significant physical and mechanical changes begin to take place (Haygreen and Bowyer 1982, Simpson 1997). The fibre saturation point for most species varies in the range of 25 to 35%, and for practical purposes, 30% is commonly used.

Water will usually move from higher to lower moisture content zone (Simpson 1997), and drying lumber involves moving water/moisture and water vapour from wood into its surroundings in the presence of heat. Increasing the temperature of wood reduces the viscosity of the water and thereby increasing the mass movement of the water. The viscosity of fluids can be described by

$$\eta = Ae^{(B/T+C)} \Rightarrow \eta = f(T) \ (Ns/cm^2) \tag{2.2}$$

where

$\eta =$ viscosity (Ns/cm$^2$)

$T =$ temperature (°C)

A, B and C are constants.
The lumber drying process may be divided into movement of water from the core to the surface and movement of water from the surface into the environment (Vansteenkiste *et al.* 1997). The former process is about 100 to 1000 times slower than the latter (Pagnozzi 1991), which makes it crucial to balance these two phenomena during drying to reduce internal stresses and checks. These two phases consequently set a moisture gradient between the interior (core) and the surface (shell). Moisture or vapour migrates to the surface and evaporates into the circulating air. The evaporation can be slow or swift depending on the equilibrium moisture content and also on the rate of the surrounding air circulation. As wood takes up (adsorption) or loses (desorption) moisture from or to its surroundings when exposed to the same conditions of temperature and relative humidity for sufficiently long time, it attains a dynamic steady moisture balance or equilibrium with its environment. The amount of moisture at this point of balance is known as equilibrium moisture content (Bramhall and Wellwood 1976, Mackay and Oliveira 1989, Panshin and de Zeeuw 1970). The equilibrium moisture content is mainly influenced by relative humidity and temperature of the surrounding air. It fluctuates by changing any of the two environmental conditions. The equilibrium moisture content however, cannot be controlled directly, but indirectly by relative humidity and temperature. The relative humidity being the ratio of partial vapour pressure of the air to the saturated vapour pressure at a prevailing temperature, expressed in percentage or fraction as relative vapour pressure (Equation 2.3).

\[
relative \ humidity \ (H) = \frac{p}{p_o} \times 100 \% \quad \text{or} \quad relative \ vapour \ pressure \ (h) = \frac{p}{p_o} \% \quad (2.3)
\]

where

- \( p \) = partial vapour pressure (Pa)
- \( p_o \) = saturated vapour pressure (Pa)

Wood drying process has been described as an unsteady process of heat, mass and momentum transfer in an orthotropic continuum with variable properties (Martinovic *et al.* 2001) with two major flow processes being heat and mass transfer. Heat transfer incorporates the process of thermal energy movement into the material whilst mass
transfer is the transportation of moisture or fluid from the wood material to air (Lyman 1965). Drying hygroscopic biopolymers like wood is an energy intensive process. The two principal heat transfer modes in wood are conduction and convection. Through conduction heat is moved from areas of high to low thermal levels within the material and by convection thermal energy is exchanged between a fluid (air) and a solid surface (wood). According to Tschernitz and Simpson (1997) for levels of moisture less than 20%, the heat of adsorption increases exponentially as the moisture content drops from 20 to 0%. The energy rate flow is determined by its thermal conductivity coefficient that is 1.5 to 2.8 times greater longitudinally than across the grain, whilst tangential and radial conductivity is about the same. According to Siau (1984, 1995), the thermal conductivity of wood increases with density, moisture content and temperature, and heat transfer from wood surface to center obeys Fourier’s law as follows:

\[
\frac{H}{t} = \frac{KA\Delta T}{L} \text{ (J/s)}
\]  

(2.4)

where

- \( H \) = amount of heat (J)
- \( t \) = time (s)
- \( K \) = thermal conductivity coefficient (W/mK)
- \( A \) = area (m²)
- \( L \) = length (m)
- \( \Delta T \) = temperature differential (K)

Keey et al. (2000) also indicated that the boundary condition at the wood surface is independent of the internal model, but at the surface, the fluxes of water vapour (moisture) and energy may be expressed as follows:

\[
j_{wv} = \beta (p_{vS} - p_{vG})
\]

(2.5a)

\[
E_s = h (T_G - T_S) - h_{wv} j_{wv}
\]

(2.5b)
where:

\[ j_{\text{wv}} = \text{flux of water vapour (kg/m}^2\text{s)} \]
\[ \beta = \text{external mass transfer coefficient (s/m)} \]
\[ p_{\text{vS}} = \text{vapour pressure above surface of board (Pa)} \]
\[ p_{\text{vG}} = \text{partial vapour pressure in the bulk gas (Pa)} \]
\[ E_s = \text{energy flux at surface of board (W/m}^2\text{)} \]
\[ h = \text{external heat-transfer coefficient (W/m}^2\text{K)} \]
\[ T_G = \text{gas temperature (K)} \]
\[ T_S = \text{surface temperature (K)} \]
\[ h_{\text{wv}} = \text{vapour enthalpy for vapour leaving surface (kJ/kg)} \]

From these equations the boundary conditions can be influenced by oscillating the temperature (climate) and therefore be used to affect the heat transfer rate and moisture evaporation to achieve suitable drying results.

The mass transfer which obeys Fick’s law (see equation 2.6) consists of two principal modes, bulk flow (capillary movement) and diffusion. Bulk flow occurs through the interconnected voids of the wood structure and is influenced by static or capillary pressure gradient (Siau 1995) and depends on the permeability of the lumber being dried. The internal moisture conductivity however, depends on the temperature, and instantaneous and initial moisture content of a specimen (Dedic 2000).

\[
\frac{W}{t} = \frac{DAG \rho_w \Delta M}{100L} \quad \text{(g/s)}
\]  

(2.6)

where:

\[ W = \text{mass of water vapour transferred through wood in time } t \text{ (g).} \]
\[ t = \text{time (s)} \]
\[ D = \text{water-vapour diffusion coefficient of wood (cm}^2\text{s}^{-1}) \]
\[ A = \text{cross-sectional area of specimen (cm}^2\text{)} \]
\[ G = \text{specific gravity of wood} \]
\( \rho_w = \text{density of water (1 g/cm}^3) \)
\( \Delta M = \text{moisture differential (\%)} \)
\( L = \text{length (cm)} \)

The other type of mass transfer is diffusion, which is the most important during drying especially below fibre saturation point. Diffusion in wood during drying is driven by moisture content, partial pressure of water vapour (Bramhall 1995), chemical potential (Skaar 1988) and water potential (Cloutier and Fortin 1993). It takes place mainly within the cell wall and as intergas diffusion. This molecular motion can therefore be influenced through relative humidity gradient (vapour pressure) causing movement of water vapour from areas of high to areas of low relative humidity. The molecules moves through both cell walls and cell cavity, by evaporating from cell wall into cell cavity and re-adsorbed into cell wall and repeat the process until it evaporates from the wood surface (Siau 1984). It is the aim of the drying schedules to influence these flow processes as much as to increase drying rate and reduce degrade.

### 2.4 Drying schedule

Kiln drying of wood involves basically adjustments of the interrelationship between temperature, relative humidity and the air velocity in the kiln to suit a desired result. This takes into consideration the properties and history of the wood species, thickness, grade, and end use of dried lumber. This interrelationship forms the basis for constructing a kiln schedule which is a carefully developed compromise between the need to dry lumber as fast as possible for economic efficiency and the need to avoid severe drying conditions that will lead to drying defects (Forest Products Laboratory 1999).

A dry kiln schedule is a series or progressive sequence of air temperature and relative humidity used to direct the whole lumber drying process. Bachrich (1980) outlined four empirical general means of kiln schedule construction namely by experimental methods (trial and error), constant humidity, constant and changing equilibrium moisture contents. By trial-and-error, a schedule is experimented for several times for a particular species to
ascertain suitable results. The constant humidity method maintains a constant relative humidity, but increases the dry bulb temperature ($T_{db}$) if drying rate acceleration is required. For constant equilibrium moisture content schedule, the three physical factors of $T_{db}$, wet-bulb temperature ($T_{wb}$) and relative humidity are operated to maintain constant equilibrium moisture content for the entire drying process. The last type adopts changing equilibrium moisture content which manipulates wood moisture content and air equilibrium moisture content relationship for the best drying. Hart et al. (1990) also based his drying simulation model on the principles that, air-wood heat transfer is directly proportional to air-wood temperature difference as well as direct proportionality between air-wood vapour transfer and air-wood vapour pressure difference. They also based the model on direct proportionality of core-shell moisture movement to moisture gradient. A uniform temperature across board thickness with no boundary layer which allows complete air mixing flowing across the stack was also assumed.

Experience has shown that satisfactory kiln drying can best be accomplished by gradual temperature increase and decreasing relative humidity. This implies very gradual increase in wet bulb depression ($T_{wbdb} = T_{db} - T_{wb}$). High relative humidity is usually maintained at early stages especially with thick timbers and as long as external convection controls the process the lumber surface remains saturated. When internal moisture-transfer rate lags behind external vapour-transfer rate, the surface temperature rises with a falling surface moisture content to maintain a moisture balance (Keey et al. 2000). The $T_{wbdb}$ may then be carefully raised to sustain the drying rate but avoiding a steeper moisture gradient. According to Keery et al. (2000) $T_{wbdb}$ of a typical normal temperature convectional schedule lies within 5 to 10°C whilst high temperature $T_{wbdb}$ may increase above 50°C.

It is important to appreciate within the kiln atmosphere, the difference between the equilibrium moisture content and the instantaneous moisture content of the wood. According to Hansom (1988), this is indicative of the potential rate of moisture removal from the wood surface and that increasing temperature tends to increase rate of moisture flow within the lumber. Using the moisture gradient and equilibrium moisture content Keylwerth (1950) introduced a term called “drying gradient” (DG) used to control the
drying process. Drying gradient he defined as the ratio of the momentary average moisture content of timber to the average equilibrium moisture content to which timber will adjust, if the kiln climate at that moment were to remain constant until hygroscopic equilibrium. It therefore follows:

\[
Drying \ gradient \ (DG) = \frac{M}{M_{emc}}
\]

(2.7)

where

\[M = \text{moisture content (\%)}\]
\[M_{emc} = \text{equilibrium moisture content (\%)}\]

Increasing \(DG\) (steep gradient) means increasing drying rate readily leading to tension stress developments (Hildebrand 1970), which are normally the limiting factor in determining a best schedule. The schedule must therefore be developed so that the drying tension stresses do not exceed the strength of the wood at any given temperature and moisture content. Otherwise, the wood will crack either on the surface or internally or be crushed by forces that collapse the wood cells. As wood dries accompanied by decreasing moisture content, it increases in strength and can tolerate higher temperatures and lower relative humidity. This phenomenon is taken advantage of to increase drying temperature to maintain a reasonably fast drying rate since drying rate decreases with decreasing moisture content. Thus, rapid drying is achieved in kilns by the use of temperatures as high as possible and relative humidity as low as possible but care is taken to ensure tolerable stress development.

The drying process has been demonstrated by many investigators as being a function of average wood moisture content and the kiln atmosphere (mainly temperature and relative humidity) and that the moisture content decreases with time (Hansom 1988). Figure 2.5 illustrates a theoretical drying curve, which assumes only a single set of dry and wet bulb temperatures making up the drying schedule and over given moisture content range. Thus, the schedule does not change temperatures as drying proceeds.
Figure 2.5: Theoretical drying curve (after Hansom, 1988)

where in the graph:

- $M$ = moisture content (%)
- $M_0$ = initial moisture content at time zero (%)
- $M_e$ = equilibrium moisture content of kiln atmosphere (%)
- $DR$ = drying rate (%/hr)

There are two major types of kiln schedules namely moisture content- and time-based schedules. In the moisture content-based schedules, the kiln temperature and relative humidity are changed according to the changing levels of lumber moisture content during drying. This means that the temperature and relative humidity conditions are changed according to changing moisture content levels attained by the lumber during drying. Most hardwood lumber uses moisture content-based schedules where typical schedule might begin at 49°C and 80% relative humidity when the lumber is green. At 15% lumber moisture content, the temperature might be as high as 82°C (Forest Products Laboratory
This method requires continuous monitoring of moisture content during drying. A common industrial method is the use of short kiln samples that are periodically weighed, usually manually. Otherwise, electrodes are imbedded in sample boards to measure change in electrical conductivity with moisture content. This later system, however, is effective to measure values less than 30%. The time-based schedules are a list of temperatures as a function of time normally used when drying softwoods. Unlike softwood schedules hardwood schedules are generally moisture content based schedules. Other schedule type is the cyclical or oscillating, which can be moisture content- or time based but the principle is to oscillate the climate within the kiln.

2.4.1 Kiln climate oscillation schedule and its effect on drying parameters

Wood drying generally induces strains and stresses in lumber and depending on the drying rate at any particular time elastic strain, viscoelastic creep or mechanosorptive strain may occur (Keey et al. 2000). The later strain, which is sometimes referred to as mechano-sorptive creep (Salin 1992) occurs in response to changing moisture content. This strain causes the wood to stretch more than would have occurred with instantaneous or viscoelastic strains. In hygroscopic composite materials, an important coupling effect exists between transient moisture and mechanical stresses, often referred to as the "mechano-sorptive effect" (Grossman 1976). Changing moisture content (cycling climate) in wood contributes to creep and relaxation process as well as mechano-sorptive effect (Ranta-Maunus 1990). Drying initially green beams under load, Leicester (1971) reported that increase in deflection of the beam is due more to the change in moisture content than time. Nakano (1996), also suggested that excess entropy decrease in water desorption process contributes to the deflection recovery in the subsequent adsorption for mechano-sorptive creep. Kollmann and Côte (1968), indicated that sorptive power or hygroscopicity decreases with increasing temperature whilst creep and relaxation increases rapidly at elevated temperatures (Morlier et al. 1991) especially in oscillating climate conditions (Fruewald et al. 2000). With any drying process the elastic limit of lumber is rapidly attained (Welling 1988) leading to plastic deformation and finally to checks (Moren and Sehsted-Persson 1992). Kiln climate oscillation increases the
maximum strain of wood leading to a decrease in stress development and checks. These phenomena and processes can therefore be taken advantage of to cycle or oscillate temperature or climate in a kiln to achieve a faster drying rate at reduced moisture variability and stress development in lumber drying.

Publications on the influence of cycling or oscillating climate on wood and wood composites have been made by several investigators. Most concern drying stress investigations (Dinwoodie et al. 1990, Martensson 1992, Hanhijavi et al. 1995). The principle involves the cycling of temperature ($T_{wb}$ or $T_{db}$) (Terziev et al. 2002), relative humidity (Bengtsson 2001), air velocity or the equilibrium moisture content (Fruewald et al. 2000). The principle of oscillation takes advantage of the viscoelastic and mechano-sorptive behaviour of wood and its hygrothermal activation (Perré 2002) during the drying process.

Though oscillation drying has been practiced for some time now, properly controlled amplitude and frequency oscillation drying processes is fairly new. In 1963, Luboshitz dried seeds by adopting short intervals of heating and cooling varying between 10 and 300s using temperatures from 40 to 150°C. Reduced drying time and quality has been reported by Luikov (1968) using temperature oscillation to dry potatoes and leather. Recent works by Maache-Rezzoug et al. (2002) using cyclical pressure drops in dehydration of collagen gel found a reduction in drying times.

Application of climate cycling in drying wood has been reported by Haygreen (1965). He indicated that regular steam cut-offs and door openings in a batch kiln drying process may accelerate drying of thick hickory and walnut lumber accompanied by steam reduction. A more systematic oscillation drying of wood specifying amplitude and frequency was done by Poskrobko and Vilchinski (1983). They dried 25mm thick oak boards in a 15m$^3$ batch kiln by varying temperatures between 35 and 65°C at 4-hour intervals. The authors found no significant difference in drying time and quality of lumber but a 25% decrease in steam consumption as compared to normal conventional drying. In the early nineties Samuelson and Söderstrom (1991) experimented on 75mm thick pine boards and reported
a 28% decrease in kiln residence time and a less acceptable dried lumber quality compared to conventional drying. As indicated earlier, intermittent drying was also used by Langrish et al. (1992) in drying 27mm thick beech lumber at a temperature amplitude varying between 20 and 60°C. The frequencies of heating and cooling periods were 7 and 17 hours respectively. Their work yielded a higher quality than conventionally dried timber but with longer drying time.

All the oscillation drying methods described above applied the normal conventional temperature, but Vansteenkiste et al. (1997) oscillated the temperature in a high temperature drying (HTD) process of poplar. Temperatures were oscillated within 80 to 120°C range at the frequency of 3 hours. They found an increase in honeycomb, collapse and warping as compared to normal HTD. They attributed the defects to the frequency of oscillation. Edvardsen and Sandland (1999) dried spruce planks (44 and 55mm thick) at 50°C (low temperature- LT) and 110 °C (high temperature-HT) for 96 hours. They then exposed them to two cyclic climatic conditions (wet-20 °C/ 85% relative humidity and dry- 30 °C/ 30% relative humidity). They observed that the high temperature dried wood had lower moisture content and dimensional changes than the low temperature dried samples. However, they said the difference in dimensional changes evened out in the last (fifth) climatic cycle. The dimensional stability in the high temperature dried wood might be due to less hygroscopicity (Sehlstedt-Persson 1995) contributed especially by the hemicellulose (Hillis and Rozsa 1985).

Using moisture content based schedule, Fruewald et al. (2000) oscillated equilibrium moisture content at amplitudes from ±1.5 to ±3 and frequencies between 2 and 4 hours in a small laboratory kiln. The two species dried were pine (500 x 110 x 30mm³) with green moisture content between 84 and 89% and beech (500 x 200 x 60mm³) with green moisture content between 70.6 and 77.6%. The base equilibrium moisture content for the pine was set at 12% with amplitudes of ±1.5 and ±3 for 2 and 4 hours. The base equilibrium moisture content for the beech changed from 19 to 11% during drying at ±2% for 2 and 4 hours. In both cases the oscillation however was done only during the drying phase. Their results show a reduction in drying time but the dried lumber quality of the
softwood was equal to the conventional whilst the thicker hardwood showed a better quality. They also observed an increase in drying rate after 20% lumber moisture content and a lesser core and shell difference as compared to conventional schedule. Although the investigations described above in oscillation drying presented mixed results, there is a high potential in the method for thick lumber.

2.4.2 "Heat-and-vent" kiln drying and drying schedules

Lumber drying began with the air-drying technique with the use of the sun's energy (solar energy). Air drying, however has some limitations like slow drying speed (Kollman and Cote 1968), which leads to longer drying periods and higher insurance premiums emanating from high inventories (Bachrich 1980). Drying a 25mm thick lumber from green to 20% using air-drying as compared to kiln drying the same thickness from green to 6% moisture content, 75 to 90% drying time was saved and about 90 to 99% was saved by kiln drying from 20 to 6% (Kollmann and Cote 1968).

Rapid increasing demands of wood and wood products led to the development of different kiln types and drying methods. The techniques are conventional (heat and vent) and non-conventional which includes dehumidification, conductive vacuum, superheated steam vacuum (SSV), radio frequency vacuum (RFV) and solar kilns. However, about 90 to 95% of wood drying in the world uses the heat and vent technique.

The conventional kiln is a thermally insulated compartmental structure made mostly of aluminium or stainless steel (less used are wood, clay, bricks and cement blocks) designed to specifically control the principal lumber drying parameters temperature, humidity and air velocity. They are classified as compartment- or progressive-type kiln based on their operational techniques. The compartment-type kiln is most common. It is loaded in one operation and lumber remains stationary during drying. This offers the advantage of flexibility in varying the kiln climate to a specified condition and has reasonably uniform instantaneous conditions within the kiln. The kiln parameters can also be controlled by a predetermined schedule that is in turn controlled with heat,
humidification, ventilation and air circulation.

Energy is required in a dry kiln to warm up and evaporate the moisture from lumber and is the largest consumer of energy in many sawmills. Due to the high heat of evaporation of water (2326kJ/kg), large quantities of heat energy are needed to dry lumber. According to Hansom (1988), the total energy required to remove a kilogram of water from lumber consists of 2.4MJ heat of vaporization (T_{db} 50^\circ C), energy used to raise ventilation air to kiln conditions, energy needed to heat kiln and wood to maximum operating temperatures and energy lost through kiln fabric and excess air interchange. It is estimated that a commercial softwood kiln requires about 1.1kJ per 0.24m$^3$ per unit time (Boone and Simpson 1991, Bramhall and Wellwood 1976, Mackay and Oliveira 1989). Energy is transferred to the wood through the air either directly or indirectly. In the indirect principle, heat is conducted in the form of hot fluid (steam, hot water and thermal oil systems) to the kiln through pipes into a radiator, which gives off its heat to the kiln atmosphere. Other kiln construction combines it with electric heat energy. In the control room of the kiln, the dry bulb temperature depicts and controls the heat supply in the kiln.

Air is needed in kilns as a medium of transporting heat to the lumber and removing moisture from wood. However, the process is linked to the wetness or dryness of the kiln atmosphere that is depicted by the relative humidity. The relative humidity is of earnest importance especially during beginning of drying, equalization and conditioning stages of the drying process. Moisture is added to a kiln atmosphere when the relative humidity is lower than desired. In steam heated kilns the moisture is supplied as steam spray, which mixes with the circulating air before reaching the wood. Removal of wood moisture causes a rise in kiln air moisture level with time. Excess moisture is vented either by static or pressure venting system. The number of vents and their sizes are dependent on the amount of water to be removed from lumber (species and size of lumber).
In order to distribute air of controlled temperature and humidity uniformly over lumber throughout a dry kiln, fans are installed to circulate kiln-air. There are two major kiln fan types namely the line- and cross-shaft fan systems. For the fans to effectively function, factors like size, speed, location, and the reversibility of the fan must be considered. The volume of air to be moved is directly proportional to the fan speed with static pressure varying with the square of fan speed whilst the horsepower varies as the cube of fan speed and directly proportional to air density. The speeds of modern kiln fans are not fixed but can be varied thereby varying the airflow velocity in the kiln as the drying progresses. Hansom (1988) indicated an air velocity between 1 and 1.5m/s as recommended for most hardwoods and partly air dried lumber and high temperature kilns require velocities between 3 and 4.5m/s. Use of higher air velocities have been shown to increase rates of lumber drying (Herzberg et al. 1985, Li et al. 1997, Lyman 1965, Price 1981). Simpson (1997) working on 25mm eastern white pine also reported that drying rate increased with air velocity for moisture content above approximately 40% to 50%. The increase he said gradually decreased and tended to level off with air velocities above 3.05 to 3.56m/s and
moisture content below approximately 80% to 90%.

Baffles made of steel or plastic are installed with hinges on the kiln floor and ceiling, wood or plywood panels for the effective direction of the airflow through lumber. This prevents airflow over, under or around the load. Facilitation of airflow across each piece of lumber is achieved by placing stickers of equal size and species and at equal intervals on the layers of lumber.

2.4.3 Kiln schedule stages

Based on the basic drying mechanisms described in section 2.3, kiln drying of lumber can be divided into stages which overlap. Bachrich (1980) indicates that with softwood species the capillary flow as first stage, diffusion of bound water as second stage and the third drying stage as vapour diffusion. However with many investigators the general

Figure 2.7: Relationship between average moisture content and schedule settings
divisions are the heating up (warm-up) time, drying (above and below equilibrium moisture content), equalization, conditioning and lastly the cooling down phase as shown in Figure 2.7.

Depending on species, thickness and initial moisture content, the temperature of the kiln atmosphere is set to rise to a certain point (usually 4 to 24 hours) whilst maintaining a high humidity to protect the lumber from defects especially checking. After the heating up temperature is reached, it is allowed to stay until the temperature gradient in the timber approximately equalizes. This phase is split into heating up of the air and the warming up of the load by some researchers (Brunner-Hildebrand 1987). It is followed by the main drying phase in which, the relative humidity is gradually reduced to create a moisture gradient in the profile of the timber. The drying phase is greatly influenced by the species, thickness of the boards, the desired quality and the kiln air velocity. Brunner-Hildebrand, (1987) subdivides this part into drying above and below equilibrium moisture content. During drying above equilibrium moisture content only free water from the cell lumen and cavities is being removed and the drying rate is high and constant which is commonly known as constant rate period (CRP). Experience shows that high relative humidity is used two thirds of this period \( T_{wb} \approx 2 \ldots 5^\circ C \). The corresponding equilibrium moisture content is normally between 16% and 20% with drying gradient of between 1.5 and 2. For the last third of this period the wet bulb depression is increased which leads to a rise of the drying gradient and a decreasing equilibrium moisture content.

At the period below fibre saturation point the timber is more resistance to drying, therefore a higher drying gradient is applied to remove water from small capillaries and bound water and the lumber begins to shrink. This period is commonly called falling rate period (FRP-divided into first and second). At this stage the load is able to reach equilibrium moisture content according to the climate in the kiln. The control of the drying process can be done by moisture content measurements or \( T_{db} \) and \( T_{wb} \).

Equalization phase is used to even out the moisture content distribution within board and between boards of the load. Boone et al. (1988) and Culpepper (1990) suggest an
equalization step when the moisture content difference exceeds about 3% from the wettest to the driest board at the end of drying. This phase is more common in hardwood drying. Whilst in conditioning high humidity and temperature are applied to relief stress and minimize drying degrade as well as evening out the moisture content differences within a board. This phase is sometimes ignored especially in high temperature drying. The final cooling stage is applied to cool down the load to almost ambient conditions within the still closed kiln to avoid surface checks and accompanying quality decrease. (Brunner-Hildebrand 1987, Henderson 1951, Kollmann 1955, Pratt 1974).

2.5 Conventional drying of Western Hemlock and its difficulties

Pacific coast hemlock has difficulties in drying to the desired moisture content and drying quality. The most dominant problems encountered in drying the lumber are wide variation in final moisture content after drying (Kozlik 1970, Kozlik et al. 1972, Kozlik and Hamlin 1972, Avramidis and Mackay 1988, Oliveira and Mackay 1991, Li et al. 1997), drying defects like internal checking (Kozlik and Hamlin 1972, Oliveira and Mackay 1991) and extended drying times (Kozlik 1970, Kozlik et al. 1972). This predicament in drying has been largely attributed to the presence of wet wood (wet pockets) in heartwood of the pacific coast hemlock (Kozlik 1970, Kozlik et al. 1972, Ward 1986) and therefore its wide initial moisture content variation. Kozlik in 1970 found that wet pockets of hemlock have higher initial moisture content. The initial moisture contents of normal heartwood and wet wood of some 54 wood samples were compared. The results are found in Table 2.3.

<table>
<thead>
<tr>
<th></th>
<th>Average green moisture content</th>
<th>Range of green moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal heartwood</td>
<td>66%</td>
<td>33% - 152%</td>
</tr>
<tr>
<td>Wetwood</td>
<td>153%</td>
<td>108% - 186%</td>
</tr>
</tbody>
</table>

Table 2.3: Average moisture content of hemlock wetwood (after Kozlik 1970 tabularized)

The results also indicated that, out of the 54 samples, only five of the normal heartwood
was found to have initial moisture content above 100 % (Kozlik et al. 1972). The high moisture content of the normal heartwood might be attributed to the presence of sapwood. Chafe (1996) found a high variability in the initial moisture content and relatively dry sapwood zone surrounding the wet wood. Furthermore, in the green wood, density and the green moisture content increased towards the pith with no significant relationship between these properties. Since there exists normally a negative relationship between density and moisture content, the abnormality also indicated the presence of wetwood.

Permeability that depicts the ease of fluid flow under the influence of pressure gradient (Ward 1986, Siau 1971) is one of the most important characteristics of wood and affects the rate of drying. By comparing average initial permeability of three wood types of western hemlock to water, Lin et al. (1973) found sapwood to be $9.6 \times 10^{-6} \text{m}^2$, normal heartwood $4.4 \times 10^{-8} \text{m}^2$ and wet-wood (wet pockets) was $6.64 \times 10^{-6} \text{m}^2$. The permeability of sapwood was attributed to differences in hydrostatic pressure during testing. That of wetwood was due to the extractives being transported and deposited on pit membranes by water, thereby creating an almost impermeable pit membrane. Schroeder and Kozlik (1972) confirmed this by reporting a higher extractive content mostly the lignan, conidendrin in wetwood than sapwood and normal heartwood of PCH. Regardless of using steady or unsteady state techniques, longitudinal permeability in PCH to water was highest in sapwood and slightly higher in wetwood than normal heartwood (Lin and Lancaster, 1973). The aspiration of the wet wood pits is also quiet characteristic of PCH (Kozlik et al. 1972, Lin et al. 1973).

Earlier research in drying PCH to average final moisture content of 19% was found to have a wide range of moisture content between 8 and 25% or more (Dedman and Van Dusen 1965, Kozlik 1963). By drying therefore lumber with wetwood especially, some of the boards will be over-dried and others will not be well dried (under-dried). This leads to cost of sorting and re-drying the under-dried pieces and cost of the defects due to over-drying. Re-drying operations can increase kiln-drying cost to about 40% (Ward 1984) and Forest Products Laboratory (1999) gave an approximation of about 25%.
Drying lumber with wet pockets may lead to uneven final moisture content distribution and develop defects, but the most severe problem is slow drying rate (Chafe 1996, Ward 1986). A typical kiln-drying times for drying PCH dimension lumber to 19% moisture content for instance, are 78h for normal heartwood (65% green moisture content), 115h for sapwood (170% green moisture content) and for wetwood 160h (145% moisture content) (Simpson 1991). In a work by Kozlik et al. (1972) with PCH lumber, it was reported that comparing the evaporable water of sinker- and normal heartwood, the normal heartwood reached lower moisture content in the shortest time. The total drying rate of wet wood was about 60% slower than the normal heartwood (Kozlik and Ward 1981).

2.6 Some methods to alleviate drying difficulties in pacific coast hemlock

Salamon (1966) dried a 50mm thick PCH with conventional, low-high combined and constantly high drying schedules. The low-high schedule started at the conventional drying temperatures and after reaching fibre saturation point, higher temperatures above 100°C were applied. In the other schedule, a constantly high temperature of 104.4°C was used. Degrade was found to be highest in the constantly high conventional schedule and least in the low-high temperature schedule. Saving in drying time was 33% in high temperature schedule and 10% in low-high temperature schedule compared to the conventional type. In 1969, Sato and Hoshide applied relatively high (105°C) and low (80°C) temperatures to 4 meter long PCH baby squares (105 x 105mm²) using a conventional kiln. They observed severe shrinkage and twist in the dried lumber with a higher degrade in the high temperature schedule. Avramidis and Mackay (1988) using normal conventional schedule dried 90.5 x 90.5mm PCH squares timber from 71% average green moisture content to 18% average final moisture content within 160 hours with less degrade. Core and shell final moisture content difference was between 4 and 6%.

Presteaming before drying of wetwood has also been investigated and it indicates an increase in permeability and overall drying rate (Kozlik 1970). The work of Kozlik and
Hamlin (1972) confirmed this result. Avramidis and Oliveira (1993) working with unsorted PCH however, recorded no significant increment in drying rates. There was rather a reduction in the difference between core and shell final moisture content with increasing presteaming times after drying and a significant increase in shrinkage with increase in presteaming duration. They also reported that after an extended presteaming the variation in moisture content and shrinkage decreased without adversely affecting the overall dried wood quality. It must be taken into accounts that, this work was on normal PCH with no indication of the presence of wetwood.

In another work, Kozlik and Hamlin (1972), found that high temperature drying above 100°C decreased the total drying time. Degrade was not increased and final moisture content was more uniform. The total drying time was reduced by 50% compared to the conventional drying (Kozlik and Ward 1981). Nevertheless, increase in drying temperature, results in a decrease in tensile stress (Kozlik 1976) and increase in shrinkage although wet wood had the least shrinkage compared to conventional drying.

Zhang et al. (1996) investigated the effect of basic density on drying characteristics. They dried pure western hemlock baby squares between 174 and 204 hours from green moisture content of 59 to 64% to a final moisture content of 19%. From the same green moisture content to 13% final moisture content the residence time was found to be between 229 and 292 hours. They indicated a short residence time for low basic density specimen with fast average drying rate between 0.156 and 0.241%/hour. The basic density effect on final moisture content variability within lumber was not significant. Adopting changing vertical air gaps in kiln stacks and changing air velocities on thick PCH squares, Li et al. (1997) reported that kiln residence times could be reduced for baby squares of the same basic density. Vertical air gaps, however, decreases the lumber volume a dry kiln can hold and therefore reducing profits. The enumerated research makes it inevitable to investigate further into schedules that could solve the drying difficulties of thick PCH without changing kiln hardware or increasing labor cost.
2.7 Shrinkage and drying defects

According to Ward and Simpson (1997), drying defects may be any characteristic or deficiency that occurs during a drying process of wood or wood product, which decreases the product’s intended value. Drying degrade which is more specific on the other hand, denotes drying defects that reduce the grade or value of a piece of lumber (Bramhall and Wellwood 1976). In order to understand the occurrences of certain drying defects the knowledge of shrinkage and swelling is inevitable.

Shrinkage (equation 2.8) is not a defect but the aftermath of removing water from a hygroscopic material like wood. As mentioned earlier loss of moisture from wood below fibre saturation point leads to shrinkage. On the other hand when wood cell walls adsorbs or gain moisture it swells. Swelling and shrinkage in small pieces of stress free wood is therefore exactly opposite (Haygreen and Bowyer 1982). The S2 layer of a wood cell wall being the thickest of the walls contributes the most to the overall shrinkage and its molecular orientation determines how shrinking as well as swelling occurs. It is actually the most dominant factor that contributes to the various drying defects, because most wood and wood products are dried to moisture content below the fibre saturation point. Shrinkage is expressed in percentage as follows:

\[
\% \text{ Shrinkage} = \frac{\text{decrease in dimension or volume}}{\text{original dimension or volume}} \times 100\% \tag{2.8}
\]

The property of anisotropy causes a higher wood shrinkage tangentially than radial. This differential shrinkage is due to the restraining influence of the wood rays in the radial direction as well as the helical arrangements of the microfibrills in the radial and tangential cell walls (Kollmann et al. 1968). Morath (1931), also pointed out that the differential transverse shrinkage is due to the alternation of early wood and late wood in the annual growth rings. Shrinkage in the tangential and radial directions is more than in longitudinal direction. This is owing to the fact that in the longitudinal direction the microfibril orientation in the S2 layer is almost parallel to the long axis, which, therefore,
causes no substantial swelling or shrinkage. The measure at which wood shrinks in the three dimensions is given below:

<table>
<thead>
<tr>
<th></th>
<th>Maximum longitudinal shrinkage</th>
<th>Maximum radial shrinkage</th>
<th>Maximum tangential shrinkage</th>
<th>Tangential shrinkage is generally 1.5 to 2 times greater than radial shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum longitudinal shrinkage</td>
<td>0.1% to 0.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum radial shrinkage</td>
<td>2.1% to 7.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum tangential shrinkage</td>
<td>4.7% to 12.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Forest Products Laboratory (1999), most problems associated with defects after drying may be categorised as rupture of wood tissue, warp, uneven moisture content or discoloration. Rupture is shrinkage-based defect on the wood as it dries. During drying the surface of the wood dries first and creates a moisture gradient between shell and core. Owing to the fact that the shell is drying, shrinkage will commence, but the core will still be above the fibre saturation point. As a result tensile stress leading to deformation causing cracking (Sehlstedt-Persson 1995) is induced in the shell of the lumber as it pull itself together and therefore brings about a compression within the core (Mackay and Oliveira 1989).

An abrupt change in relative humidity and temperature easily causes abrupt changes in surface moisture content setting up moisture gradient leading to dynamic stresses in the lumber being dried. As the resulting stresses exceed the strength of the lumber, shrinkage-induced defect occurs. Some of the rupture defects are casehardening, checking, splits, collapse, honeycombs, ring failure, and checked and loose knots.

Casehardening occurs when a permanent surface stretch called ‘tension set’ develops and defined as the tendency of dried wood to deform (into a cup shape) after re-sawing and equalizing of the moisture content (Ranta-Maunus et al. 1992). As the core starts drying below the fibre saturation point, it also starts shrinking and relieves some of the shell tensile stress. However, the shell, which is in tension set, restrains this process. This
condition causes a reverse in the stresses; the core turns to be under tensile stress, while the shell reverses into compressive stress. Casehardening could be prevented through the maintenance of sufficiently high relative humidity to prevent the surface from drying too fast especially in the early drying stages (Bramhall and Wellwood 1976).

Checking can occur on the surface, interior and/or end of the lumber. A check is the occurrence of separation of wood cells, along the length of a lumber in the longitudinal direction. This is due to three factors namely, shrinkage difference between surface (shell) and interior (core), radial and tangential directions and between normal and reaction wood. Checking is caused when the unequal stresses between the shell and core that occurs in casehardening, becomes so severe that the lumber cannot withstand (Bramhall and Wellwood 1976, Mackay and Oliveira 1989).

Surface checks are those that occur in the wood rays of flat sawn faces of a board. They may occur in mineral streaks or resin ducts. These are caused when the aforementioned shell tension stresses exceeds the tensile strength of the wood perpendicular to the grain. At the early stages of drying if the equilibrium moisture content is low, surface checks can occur. These checks may penetrate to the inner parts of the wood as the dry zone spreads into the interior and cause at this point an internal check. After the stress reversal, the surface checks may close up, however the internal check will remain and causes rapture type defect called honeycomb. These checks may be minimised and or alleviated by maintaining high relative humidity at the early drying stages. This on one hand will maintain higher surface moisture content to prevent shrinkage and on the hand increase the plasticity of the wood to accommodate the stresses (Keey et al. 2000).

Another type of check is the end check, which is due to the rapid drying of the wood along the grain than across it. The permeability of wood in the longitudinal direction is about 50 to 100 times greater than in transverse direction (Stamm 1964). Exposure of the end boards leads to rapid diffusion of moisture along the wood grain. Using end coats, which are moisture resistant, may prevent or reduce longitudinal moisture movement (Rasmussen 1961, Wengert and Lamb 1994). The use of stickers flush with end boards
also helps to reduce these defects. The reduction of excessive air circulation may also help minimise this defect.

According to Ward and Simpson (1997), warping is any diversion of the face or edge of a lumber from the flatness. It can occur in one or more of four forms, which are bow, crook, twist, cup, and diamonding. Shape deformations can be caused by differential shrinkage in tangential, radial and longitudinal directions. The effect of the inherent properties of wood could also lead to warping. Use of proper kiln schedule can also help reduce warping.

Wood is dried with target moisture content, usually to the level suitable for the next processing step or end use. This is mostly not achieved due to positive or negative deviation from the moisture content. It can also be due to a very wide variation of moisture content within a charge. Wide initial moisture content variation also can lead to uneven final moisture content. Mackay and Oliveira (1989) indicate that this may be the greatest single problem of western hemlock. This problem occurs also, when species of different permeability and cell wall thickness are dried together. In order to alleviate some of these problems pre-sorting is necessary especially with different permeability and wet pockets (Ward and Simpson 1997, Milota et al. 1993).
Chapter 3

Methodology

3.1 Materials

A total of forty two green timbers of 7.32m long each of western hemlock (few specimens of amabilis fir were found) were obtained from a local sawmill. They were rough sawn, pencil wane with no through shake and free of heart center. These timbers were cut from logs located in the BC coastal forest region. The green timber had an average cross sectional area of 115 x 115mm$^2$. These dimensions were chosen because after drying and planning it reaches the customer dimensions of 105 x 105mm$^2$. Timbers delivered were not sawn according to any particular pattern and no separation was made with reference to sapwood and heartwood.

Due to the length of the available cold storage facility each piece was cut into two unequal (3.1m and 4.22m) parts and shrink-wrapped with plastic. In order to reduce any drying, the two piles were stored in a five meter long refrigerator kept at a constant temperature of 8°C until further processing.

3.2 Pre-drying specimen preparation

The specimens of timber in the pile were numbered from 1 to 42 and each piece marked and divided into seven equal parts. Each part was 975mm long and was denoted with a letter starting from (A) at one end to (G) at the other as seen in Figure 3.1. Since the timber was randomly chosen from the chain, the load was considered a representative of the production population. From each end a piece of 150mm in length was marked (S) and discarded.
Each drying run (charge) comprised of forty two 975mm specimens and each of the 42 specimens to be dried, were cut from the end of the long piece as illustrated in Figure 3.2. Run 1 was composed of specimens (A₁) to (A₄₂) (only ‘A’ specimen) cut from specimens 1 to 42, respectively. The rest were again shrink-wrapped and placed back in the refrigerator. For the determination of the initial moisture content (Mᵢ), moisture content specimens (called ‘cookies’) of 25.4mm thick were cut from the two ends of each specimen and labelled (A) and (B) as indicated in figure 3.3 leaving 915mm as green kiln specimen.

Figure 3.2: Sawing pattern of green timbers and drying specimens.
Figure 3.3: Sample of green specimen prepared for kiln and ‘cookies’.

Visual evaluation was carried out on each kiln specimen to record surface checks, wane and shake and other visible pre-drying defects. A line perpendicular to the horizontal axis dividing the specimen into two equal parts was drawn on one of the four surfaces indicating the top of the piece and also used to measure thickness and width for further shrinkage calculations. Both ends of the kiln specimens were immediately coated with polyvinyl acetate (PVA) sealant to avoid end drying before and during the kiln-drying and shrink-wrap. The ‘cookies’ were placed in plastic bags and sealed to avoid changes in green moisture content. The procedure was repeated for the specimens for each run reducing each long piece after a run.

Figure 3.4: Volumetric determination using water displacement method.

The ‘cookies’ were weighed with a digital balance (0.01mm) (Mettler PM 4600 Delta
Range) and the volume determined by water displacement method as shown in Figure 3.4. They were then oven-dried (Blue M B-2730-Q) at 103 ±2°C for 24 hours. Weights of all oven-dried ‘cookies’ were taken and together with their green weights, their initial moisture content were calculated using equation 2.1. The average green moisture content of each kiln specimen was then determined from cookies (A) and (B) and the average green moisture content of the charge calculated from all 42 specimens.

3.3 Dry kiln and data acquisition

For the drying process, a laboratory-scale dry kiln capable of holding about 0.73m$^3$ (0.9 x 0.9 x 0.9m$^2$) as shown in Figure 3.5 located at the premises of Forintek Canada Corporation, Western Laboratory was used. This is a conventional heat and vent kiln made of aluminum and electrically heated with two fans (Model 4F182) sitting on its top. The fans are not reversible, so the air flow was unidirectional. Aluminum stickers of thickness 19mm were placed at the ends of the specimens perpendicular to the longitudinal axis. The specimens were stacked in such a way to have only horizontal gaps (Figure 3.5). Baffles that hang from the top of the kiln were used to prevent air movement over the load. The kiln is equipped with a load cell unit which takes the weight change as the timber dries. There are three resistance temperature devices (RTD), one of which measured the outlet $T_{db}$ and the other the inlet $T_{db}$ with the third measuring $T_{wb}$. The relative humidity was controlled by the steam boiler and a venting system. Thus the boiler automatically starts when more humidity is required with vents closed. It shuts down when less humidity is desired as the vents open. The relative humidity is registered and depicted by $T_{wb}$ whose feedback is sent to the boiler. The whole process was fully computer monitored and controlled using software called Intellution Version 5.02-10.94. With this software, the schedule is put into the computer with the initial moisture content and the target moisture content and the rest of the drying process is automatic.
3.4 Drying schedule strategy and drying process

An existing time-based drying schedule developed by Avramidis and Oliveira in a report by Aune (2001) was adopted with changes made in the $T_{wb}$ and $T_{db}$. This was used as the control schedule (see Table 3.1). Using a visual basic program (Microsoft excel) the interrelationships between drying temperature, relative humidity and equilibrium moisture content were calculated and tabulated. Oscillations of the $T_{wb}$ and $T_{db}$ temperature values about the mean (control schedule values) were introduced and oscillating drying schedules constructed (see Tables 3.1 to 3.5). In all one control and four oscillating schedules were completed.
Table 3.1: Run 1 (Control) - starting at 60°C/53°C without oscillation

<table>
<thead>
<tr>
<th>Description</th>
<th>$T_{db}$ (°C)</th>
<th>$T_{wb}$ (°C)</th>
<th>$T_{wbdl}$ (°C)</th>
<th>$M_{emc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat up</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d1</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d2</td>
<td>80</td>
<td>65</td>
<td>15</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 3.2: Run 2 (TDB-H) – starting at 60°C/53°C and oscillating $T_{db}$ at 6°C for 8hrs

<table>
<thead>
<tr>
<th>Description</th>
<th>$T_{db}$ (°C)</th>
<th>$T_{wb}$ (°C)</th>
<th>$T_{wbdl}$ (°C)</th>
<th>$M_{emc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat up</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d1</td>
<td>60 +/-6</td>
<td>53</td>
<td>7 +/-6</td>
<td>10.5</td>
</tr>
<tr>
<td>d2</td>
<td>80 +/-6</td>
<td>65</td>
<td>15 +/-6</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 3.3: Run 3 (TWB-H) - starting at 60°C/53°C and oscillating $T_{wb}$ at 6°C for 8hrs

<table>
<thead>
<tr>
<th>Description</th>
<th>$T_{db}$ (°C)</th>
<th>$T_{wb}$ (°C)</th>
<th>$T_{wbdl}$ (°C)</th>
<th>$M_{emc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat up</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d1</td>
<td>60</td>
<td>53 +/-6</td>
<td>7 +/-6</td>
<td>10.5</td>
</tr>
<tr>
<td>d2</td>
<td>80</td>
<td>65 +/-6</td>
<td>15 +/-6</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 3.4: Run 4 (TDB-L) - starting at 60°C/53°C and oscillating $T_{db}$ at 3°C for 4hrs

<table>
<thead>
<tr>
<th>Description</th>
<th>$T_{db}$ (°C)</th>
<th>$T_{wb}$ (°C)</th>
<th>$T_{wbdl}$ (°C)</th>
<th>$M_{emc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat up</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d1</td>
<td>60 +/-3</td>
<td>53</td>
<td>7 +/-3</td>
<td>10.5</td>
</tr>
<tr>
<td>d2</td>
<td>80 +/-3</td>
<td>65</td>
<td>15 +/-3</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 3.5: Run 5 (TWB-L) - starting at 60°C/53°C and oscillating $T_{wb}$ at 3°C for 4hrs

<table>
<thead>
<tr>
<th>Description</th>
<th>$T_{db}$ (°C)</th>
<th>$T_{wb}$ (°C)</th>
<th>$T_{wbdl}$ (°C)</th>
<th>$M_{emc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat up</td>
<td>60</td>
<td>53</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>d1</td>
<td>60</td>
<td>53 +/-3</td>
<td>7 +/-3</td>
<td>10.5</td>
</tr>
<tr>
<td>d2</td>
<td>80</td>
<td>65 +/-3</td>
<td>15 +/-3</td>
<td>6.2</td>
</tr>
</tbody>
</table>
A completely randomized design with 5 treatments and 42-specimens/kiln-charge was used (Table 3.6). The treatments were two temperatures (wet bulb $-T_{wb}=53^\circ C$ and dry bulb $-T_{db}=60^\circ C$) oscillating at two amplitude and frequency combinations of $3^\circ C/4$hours and $6^\circ C/8$hours respectively and the control. The control (Run 1) was set at $T_{wb}$ 53$^\circ C$, $T_{db}$ 60$^\circ C$ without oscillation. In two schedules (Runs 3 and 5), the $T_{wb}$ was oscillated whilst $T_{db}$ remained as the control. In the other schedules (Runs 2 and 4) $T_{db}$ was oscillated, maintaining the $T_{wb}$ at control. Runs 2 and 3 were experimented with the higher amplitudes and frequency combination and Runs 4 and 5 with the lower. Due to time constraints and the schedule for the drying facilities, treatment replications could not be done. All results were tested with the analysis of variance test at 95% confidence interval.

**Table 3.6:** Completely randomized design table

<table>
<thead>
<tr>
<th>Observation</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_A42</td>
<td>Y_B42</td>
</tr>
<tr>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Y_A1</td>
<td>Y_B1</td>
</tr>
</tbody>
</table>

where A $=>$ Control, B $=>$ TDB-H, C $=>$ TWB-H, D $=>$ TDB-L and E $=>$ TWB-L

All runs targeted a final moisture content of 15% without a conditioning period. This was done in order that the effect of the schedules on stresses (casehardening) will not be dampened or eliminated. The air velocity in the kiln was kept at a constant 2.54m/s.

### 3.5 Post-drying measurements and evaluation

At the attainment of the programmed target moisture content ($M_f$) the kiln automatically stopped. The specimens in the kiln were allowed for about 12 hours to cool down to ambient temperature. Each dried specimen was reweighed and the thickness and width were taken with a pair of callipers at the same position as in the green. Visual evaluation for surface and end checks, and splits were measured and recorded. All the 42 specimens were immediately sawn as illustrated in Figure 3.6. Each specimen was marked into four
divisions and five 'cookies' of 25.4mm thick were sawn from the specimen at positions indicated in figure 3.6 and placed in plastic bags to avoid moisture content change.

**Figure 3.6:** Sawing pattern of cookies after drying

**Figure 3.7:** (a) Sawing pattern for the detection of residual stress (b) Schematic diagram showing method of quantifying displacement of prongs in drying stress test (*after Simpson*, 1987).
Specimens labelled CS were used for core and shell final moisture content, HD for casehardening and MS for average final moisture content determination, the latter determined by the gravimetric method. The HD specimens were further cut into prongs of equal thickness perpendicular to the top face as shown in Figure 3.7 (a). The prongs were left to stay for 24 hours at ambient temperature to detect residual stresses. The residual stress was quantified as indicated in Figure 3.7 (b) thus, prong position = (a+b)/c (Simpson 1987).

![Diagram](image)

**Figure 3.8 (a) and (b):** Sawing pattern for core and shell (CS) final moisture content determination ((a) – after Forest Products Laboratory, 1999).

The CS specimens were also cut into shell and core parts as indicated in Figure 3.8, weighed and immediately placed in an oven at 103 ± 2°C for 24 hours after which the final moisture content was determined by gravimetric method.
4.1 Initial moisture content and basic density distributions

Altogether, two hundred and ten (210) specimens were used in this study. The initial moisture contents are indicated in Table 4.1 and their distributions are shown in Figure 4.1. The initial moisture content ranged from 33.9 to 186.5% with an overall average of 61.6%, with the greater part of the timber ranging between 35 and 80% and having a coefficient of variation (CoV) of 44%. Nielson et al. (1985) reported an average initial moisture content of pure western hemlock to be about 55% for heartwood, and 143% for sapwood. The five kiln-charges averaged between 54.1% and 67%. Also 7% of the total specimens were found to contain pockets of rot and 6% with wormholes. The high maximum initial moisture content and large variation may either be attributed to these defects and/or to the presence of wet pockets (Kozlik 1970) and high sapwood moisture content.

The highest average initial moisture content of 67% was measured in Run 2 with a standard deviation of 33.1% and the widest range was found in Run 1. The high initial moisture content variability has been known to be one of the problems of western hemlock, which leads to uneven final moisture content and may result in under-dried or

<table>
<thead>
<tr>
<th>Run</th>
<th>Average</th>
<th>Std. dev.</th>
<th>CoV</th>
<th>Min</th>
<th>Max</th>
<th>(Min)-(Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1(Control)</td>
<td>60.6</td>
<td>27.8</td>
<td>45.9</td>
<td>35.4</td>
<td>177.5</td>
<td>176.5</td>
</tr>
<tr>
<td>Run 2(TDB-H)</td>
<td>67.0</td>
<td>33.1</td>
<td>49.4</td>
<td>34.7</td>
<td>169.7</td>
<td>135.0</td>
</tr>
<tr>
<td>Run 3(TWB-H)</td>
<td>64.8</td>
<td>33.1</td>
<td>51.0</td>
<td>34.6</td>
<td>186.5</td>
<td>151.9</td>
</tr>
<tr>
<td>Run 4(TDB-L)</td>
<td>57.0</td>
<td>18.6</td>
<td>32.6</td>
<td>35.3</td>
<td>122.6</td>
<td>87.4</td>
</tr>
<tr>
<td>Run 5(TWB-L)</td>
<td>54.1</td>
<td>16.6</td>
<td>30.8</td>
<td>33.9</td>
<td>103.4</td>
<td>69.5</td>
</tr>
</tbody>
</table>
Figure 4.1: Histogram and cumulative frequency of initial (green) moisture content for each drying run.
over-dried timber. Comparing the kiln-charges, runs 2 and 3 had the highest standard deviation and coefficient of variation. Using one-way analysis of variance, however, it was found that there was no significant difference between their averages (Table 4.2).

Table 4.2: Analysis of variance table for initial moisture content

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>4837.748</td>
<td>4</td>
<td>1209.437</td>
<td>1.687</td>
<td>0.154</td>
<td>2.415696</td>
</tr>
<tr>
<td>Within Groups</td>
<td>146906.9</td>
<td>205</td>
<td>716.6191</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>151744.7</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on oven-dried weight and wet volume, basic density ($\rho_b$) of each sample was determined and the average values and range are indicated in Table 4.3 and shown in Figure 4.2. The results indicate a $\rho_b$ range between 302 and 511 kg/m$^3$ being comparable to the results obtained by other researches. Zhang et al. (1996) reported a $\rho_b$ range of western hemlock from 316 to 563 kg/m$^3$ whilst Li et al. (1997) indicated between 261 and 540 kg/m$^3$. The average $\rho_b$ for all runs was 380.4 kg/m$^3$. According to Zhang et al. (1996) who worked on $\rho_b$ pre-sorting, this average falls under low basic density western hemlock timber. However, individual specimens at the high extreme of the range may be considered to have high $\rho_b$. Since amabilis fir and western hemlock grow and are normally harvested together, there is the possibility that the specimen with very low $\rho_b$ may be amabilis fir. Avramidis and Oliveira (1993) and Zhang et al. (1996) also reported

Table 4.3: Mean, maximum, minimum and range of basic density (kg/m$^3$) of each drying run (Std. dev. = standard deviation, CoV = coefficient of variation).

<table>
<thead>
<tr>
<th>Run</th>
<th>Average</th>
<th>Std. dev</th>
<th>CoV</th>
<th>Min</th>
<th>Max</th>
<th>(Min)-(Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1(Control)</td>
<td>381</td>
<td>34.2</td>
<td>9.0</td>
<td>302</td>
<td>498</td>
<td>196</td>
</tr>
<tr>
<td>Run 2(TDB-H)</td>
<td>387</td>
<td>40.3</td>
<td>10.4</td>
<td>334</td>
<td>511</td>
<td>177</td>
</tr>
<tr>
<td>Run 3(TWB-H)</td>
<td>381</td>
<td>30.9</td>
<td>8.1</td>
<td>324</td>
<td>454</td>
<td>130</td>
</tr>
<tr>
<td>Run 4(TDB-L)</td>
<td>378</td>
<td>26.3</td>
<td>7.0</td>
<td>341</td>
<td>470</td>
<td>129</td>
</tr>
<tr>
<td>Run 5(TWB-L)</td>
<td>375</td>
<td>26.0</td>
<td>6.9</td>
<td>338</td>
<td>446</td>
<td>108</td>
</tr>
</tbody>
</table>
Figure 4.2: Histogram and cumulative frequency of basic density for each drying run.
that $\rho_b$ affects drying time, drying rate and core and shell moisture content difference. Therefore a drying run with high $\rho_b$ variation may result in a large percentage of under-dried or over-dried timber. In this experiment run 2 has a relatively higher standard deviation of $\rho_b$ when compared to runs 4 and 5. Due to this variation in $\rho_b$, the effect of oscillation schedule on the timber's drying characteristics may be overlapped by the $\rho_b$ influence. However, the influence may be minimal owing to less $\rho_b$ variation.

4.2 Timber drying and oscillation drying schedule

4.2.1 Schedule effect on kiln residence times and drying rate

The drying schedules used were control (without oscillation-base temperatures- 53 and 60°C), TDB-H ($T_{db}$ oscillated at 6°C/8hrs), TWB-H ($T_{wb}$ oscillated at 6°C/8hrs), TDB-L ($T_{db}$ oscillated at 3°C/4hrs) and TWB-L ($T_{wb}$ oscillated at 3°C/4hrs). Figure 4.3 shows the curves resulting from the schedules. As shown in Table 4.4, the kiln residence times ranged between 248 hours (10.3 days) and 314 hours (13.1 days).

<table>
<thead>
<tr>
<th>Schedule Type</th>
<th>Control</th>
<th>TDB-H</th>
<th>TWB-H</th>
<th>TDB-L</th>
<th>TWB-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln residence time (hr)</td>
<td>287</td>
<td>300</td>
<td>314</td>
<td>248</td>
<td>293</td>
</tr>
<tr>
<td>Kiln residence time estimated between 54% &amp; 19% moisture content (hr)</td>
<td>244</td>
<td>242</td>
<td>252</td>
<td>216</td>
<td>240</td>
</tr>
<tr>
<td>Average drying rate (%/hr)</td>
<td>0.147</td>
<td>0.164</td>
<td>0.145</td>
<td>0.156</td>
<td>0.133</td>
</tr>
<tr>
<td>Initial moisture content (%)</td>
<td>60.6(27.8)</td>
<td>67.0(33.1)</td>
<td>64.8(33.1)</td>
<td>57.0(18.6)</td>
<td>54.1(16.6)</td>
</tr>
<tr>
<td>Final moisture content (%)</td>
<td>16.6(8.7)</td>
<td>17.0(8.8)</td>
<td>16.7(7.9)</td>
<td>17.1(6.3)</td>
<td>14.3(4.1)</td>
</tr>
<tr>
<td>$M_{core-shell}$ (%)</td>
<td>11.8(12.6)</td>
<td>10.4(12.5)</td>
<td>12.1(12.9)</td>
<td>11.1(8.5)</td>
<td>8.0(5.8)</td>
</tr>
<tr>
<td>Casehardening (%)</td>
<td>0.094</td>
<td>0.089</td>
<td>0.106</td>
<td>0.136</td>
<td>0.092</td>
</tr>
<tr>
<td>Thickness shrinkage between 30 and 15% M (%)</td>
<td>2.94</td>
<td>2.73</td>
<td>3.20</td>
<td>2.62</td>
<td>2.54</td>
</tr>
<tr>
<td>Width shrinkage between 30 and 15% M (%)</td>
<td>2.90</td>
<td>2.90</td>
<td>2.88</td>
<td>2.20</td>
<td>2.65</td>
</tr>
<tr>
<td>Basic density (kg/m$^3$)</td>
<td>381(34.2)</td>
<td>387(40.3)</td>
<td>381(30.9)</td>
<td>378(26.3)</td>
<td>375(26)</td>
</tr>
</tbody>
</table>
Figure 4.3: Drying, temperature and equilibrium moisture content curves for each drying schedule.
Comparing the oscillation drying schedules, those with low amplitude and frequency combinations had shorter kiln residence times than those with higher amplitude and frequency combinations. The schedule oscillating the $T_{db}$ at lower amplitude (TDB-L), with slightly lower initial moisture content had about 17% shorter drying time than the one oscillating $T_{db}$ at higher amplitude, 14% than control, 15% than the one oscillating $T_{wb}$ at low amplitude and 21% shorter kiln residence time than the schedule with the oscillating $T_{wb}$ at higher amplitude. The TWB-L schedule also resulted in about 7 and 2% reduction in kiln residence time, when compared to TWB-H and TDB-H respectively, but took 2% longer time relative to control schedule. The drying curve was normalised (Figure 4.6) and kiln residence times for all schedules were estimated between 54 and 15% moisture content (Table 4.4). It was observed that all oscillation schedules except TWB-H resulted in a shorter kiln residence time than the control. The drying time of TDB-L was 10%, 10.7%, 11.5% and 14% shorter than the TWB-L, TDB-H, Control and TWB-H respectively.

The drying rates against average instantaneous moisture content of each drying run are shown in Table 4.4 and Figure 4.4. They indicate an average drying rate for all runs to range between 0.133 and 0.164%/hour. Contrary to the kiln residence times, the average drying rate of the drying run using TDB-H schedule was the highest during the drying process. In all the drying runs, the percentage increases of TDB-H schedule compared to TWB-H and TWB-L were 13 and 23% respectively whilst it was 12% faster than control run. There was only 5% difference between average drying rates of the $T_{db}$ oscillated schedules and were both higher than the $T_{wb}$ oscillated schedules as well as the control.

Estimating drying rates during the period above fibre saturation point (assuming 30%) shows a near similar trend as the average for the whole drying process. However, as indicated in Table 4.5, the average drying rate of TWB-H became the highest below the fibre saturation point at 0.143%/hr. This might be because, before the 30% moisture content the drying rate became negative and temporary condensation might have taken place which then contributed to overall high drying rate below 30%. The TWB-L on the other hand recorded the lowest drying rate. Comparing the curves, it was observed that
Figure 4.4: Drying rate against average moisture content excluding the 24 hour heat-up period for each drying run.
Table 4.5: Estimated average drying rates from 54% to 30% and between 30 and 15% moisture contents of each drying run.

<table>
<thead>
<tr>
<th>Schedule Type</th>
<th>Control</th>
<th>TDB-H</th>
<th>TWB-H</th>
<th>TDB-L</th>
<th>TWB-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average drying rate estimated from 54% to 30% M (%/hr)</td>
<td>0.163</td>
<td>0.180</td>
<td>0.146</td>
<td>0.178</td>
<td>0.164</td>
</tr>
<tr>
<td>Average drying rate between 30 &amp; 15% M (%/hr)</td>
<td>0.124</td>
<td>0.127</td>
<td>0.143</td>
<td>0.133</td>
<td>0.105</td>
</tr>
</tbody>
</table>

The effect of oscillation was more pronounced above the fibre saturation point. Also the drying process of the lower amplitude schedules approached rapidly that of the control whilst the higher amplitudes especially the TWB-H had negative drying rate at certain points (see Figure 4.4).

In order to reduce noise due to the oscillating nature of the curves, cumulative drying curves as shown in Figure 4.5 were plotted. The cumulative drying rate was calculated by dividing the change in moisture content from the start to momentary moisture content by the corresponding time interval. Also since the initial moisture contents of all runs were not the same, for comparison purpose the moisture contents were normalised by taking the ratio of the initial and the momentary moisture content \((M/M_i)\) as illustrated in Figure 4.6.

Through extrapolation and estimation from the normalised drying rate curves it was realised that all the drying rates started being almost parallel to each other and to the horizontal axis between 50% and 54% of their individual initial moisture contents. For TDB-H and TWB-H this point was at about 54% corresponding to momentary moisture content of 35% and 33% and at a cumulative drying rate of 0.182 and 0.141%/hr respectively. The control and TWB-L were about 51% corresponding to 29 and 28% moisture content at a rate of 0.154 and 0.146%/hr respectively. For TDB-L the point was estimated at about 50% of its initial moisture content being 27% and at a drying rate of 0.159%/hr.

55
Figure 4.5: Cumulative drying rate against average moisture content during drying for each drying run.
Figure 4.6: Drying curves (above) and cumulative drying rate curves (below) for each drying run.
4.2.2 Schedule effect on final moisture content and its distribution

The average, range, standard deviation and coefficient of variation of the final moisture content are shown in Table 4.6. Figures 4.7 and 4.8 also illustrate the final moisture content, variation and distribution. The final moisture content ranged between 9.3 and 59.1% with the average ranging from 14.3 to 17.1%.

Table 4.6: Mean, maximum, minimum and range of the final moisture content (%) for each drying run (Std. dev. = standard deviation, CoV = coefficient of variation)

<table>
<thead>
<tr>
<th>Run</th>
<th>Average</th>
<th>Std. dev.</th>
<th>CoV</th>
<th>Min</th>
<th>Max</th>
<th>(Min)-(Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 (Control)</td>
<td>17.0</td>
<td>8.7</td>
<td>51.1</td>
<td>9.9</td>
<td>59.1</td>
<td>49.2</td>
</tr>
<tr>
<td>Run 2 (TDB-H)</td>
<td>16.6</td>
<td>8.8</td>
<td>53.1</td>
<td>9.7</td>
<td>44.4</td>
<td>34.7</td>
</tr>
<tr>
<td>Run 3 (TWB-H)</td>
<td>16.7</td>
<td>7.9</td>
<td>47.0</td>
<td>9.3</td>
<td>40.0</td>
<td>30.7</td>
</tr>
<tr>
<td>Run 4 (TDB-L)</td>
<td>17.1</td>
<td>6.3</td>
<td>36.7</td>
<td>9.3</td>
<td>47.7</td>
<td>38.4</td>
</tr>
<tr>
<td>Run 5 (TWB-L)</td>
<td>14.3</td>
<td>4.1</td>
<td>28.3</td>
<td>10.2</td>
<td>32.2</td>
<td>22.0</td>
</tr>
</tbody>
</table>

The extreme maximum final moisture content value of 59% indicates the presence of wet pocket. The standard deviation was between 4.1 and 8.8%. All except the timber of the TWB-L schedule with average final moisture content of 14.5% had quite close average final moisture content ranging between 16.6 and 17.1%. The standard deviations for the control (8.7%) and TDB-H (8.8%) were quite different from TWB-L (7.9%) and TDB-L (6.3%) and far from TWB-L (4.1%). However, based on the one-way analysis of variance shown in Table 4.7, there were no significant differences observed between the treatment means. This might be partly due to the variation within runs in the initial moisture contents.

Table 4.7: Analysis of variance table for final moisture content

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between schedules</td>
<td>230.4011</td>
<td>4</td>
<td>57.60027</td>
<td>1.069418</td>
<td>0.372693</td>
<td>2.415696</td>
</tr>
<tr>
<td>Error</td>
<td>11041.57</td>
<td>205</td>
<td>53.86133</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11271.97</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.7: Histogram and cumulative frequency of final moisture content for each drying run.
As shown in Figure 4.8, it was observed that the schedules TDB-H, TWB-H and TWB-L resulted in narrower final moisture content distributions compared to the control and TDB-L. The coefficient of variation also indicates a lesser variation in the $T_{wb}$ oscillated schedules as compared to their corresponding counterparts in the $T_{db}$ oscillated schedules and the control. Relating the change in coefficient of variation between the means of the initial and final moisture contents, both high and low $T_{wb}$ oscillated schedules decreased by 8 percentage points. On the contrary, the moisture content coefficient of variation of TDB-H, TDB-L and control specimens increased by 7, 13 and 11 percentage points, respectively. This indicates a reduction in moisture content variation between timbers of the $T_{wb}$ oscillated schedules. This is also evident in Figures 4.9 and 4.10 which show that both $T_{wb}$ oscillated schedules had a far higher reduction from the initial moisture content variation than the control. TDB-H also had more reduction in final moisture content variation as compared to control. The reduction recorded in TDB-L however, was only slightly higher than the control.

The differences between the means of the initial and final moisture contents ranged between 40 and 50% (Table 4.8). There were no significant differences found between their means when tested with a one-way analysis of variance (Table 4.9).

**Table 4.8**: Mean, maximum, minimum and range of the difference between initial and final moisture content (%) for each drying run ($Std. dev. = standard deviation, CoV = coefficient of variation$).

<table>
<thead>
<tr>
<th>Run</th>
<th>Average</th>
<th>Std. dev.</th>
<th>CoV</th>
<th>Min</th>
<th>Max</th>
<th>(Min)-(Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1(Control)</td>
<td>43.6</td>
<td>19.9</td>
<td>45.7</td>
<td>20.0</td>
<td>118.4</td>
<td>98.4</td>
</tr>
<tr>
<td>Run 2(TDB-H)</td>
<td>50.4</td>
<td>25.1</td>
<td>49.8</td>
<td>24.1</td>
<td>136.4</td>
<td>112.3</td>
</tr>
<tr>
<td>Run 3(TWB-H)</td>
<td>48.1</td>
<td>25.8</td>
<td>53.7</td>
<td>20.1</td>
<td>146.8</td>
<td>126.7</td>
</tr>
<tr>
<td>Run 4(TDB-L)</td>
<td>39.8</td>
<td>13.8</td>
<td>34.7</td>
<td>22.3</td>
<td>83.5</td>
<td>61.2</td>
</tr>
<tr>
<td>Run 5(TWB-L)</td>
<td>39.8</td>
<td>13.6</td>
<td>34.2</td>
<td>22.5</td>
<td>84.9</td>
<td>62.4</td>
</tr>
</tbody>
</table>
Table 4.9: Analysis of variance table for the difference between the means of the initial and the final moisture contents.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between schedules</td>
<td>3924.431</td>
<td>4</td>
<td>981.1077</td>
<td>2.369685</td>
<td>0.053778</td>
<td>2.415696</td>
</tr>
<tr>
<td>Error</td>
<td>84875.04</td>
<td>205</td>
<td>414.0246</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>88799.47</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the grading rules of the National Limber Grades Authority (NGLA 1991), seasoned air or kiln dried timber above 19% is considered under-dried or wet. Under-dried timber must be re-dried leading to increased production cost and profit reduction. Wide final moisture content variation has been reported by several researchers to be a characteristic problem in kiln-drying of PCH (Knutson 1968, Kozlik 1970, Zhang et al. 1996, Li et al. 1997, Avramidis and Hao 2003).

![Figure 4.8](image.png)

**Figure 4.8**: Variation in the final moisture content for each drying run.

In this study more wets were recorded in the $T_{db}$ oscillated schedules than in the $T_{wb}$ schedules. As is evident in Table 4.10, there were greater percentage of under-dried ($M > 19\%$) timbers in all the runs than over-dried ($M > 10\%$). In total 20% of all specimens were wets whereas only 4% were recorded as over-dried. The drying run with the TWB-L schedule had the least percentage of under-dried amounting to 7% whilst TDB-L with
Figure 4.9: Comparison of initial and final moisture content distribution for each run.
Figure 4.10: Initial (above) and final (below) moisture content distribution for each run.
20% under-dried was the highest. There were no over-dried timber found by the TDB-L schedule specimens, whilst the TWB-H had the highest under-dried of 7%. The low percentage of both under- and over-dried specimens by the TWB-L schedule may partly be attributed to the low initial moisture content and coefficient of variation.

<table>
<thead>
<tr>
<th>Run</th>
<th>$M &lt; 10%$</th>
<th>$M &gt; 19%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 (Control)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Run 2 (TDB-H)</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Run 3 (TWB-H)</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Run 4 (TDB-L)</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Run 5 (TWB-L)</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

4.2.3 Schedule effect on the core and shell moisture content differences

The difference between final core and shell moisture content is very important especially for timbers purposed for remanufacturing. The average range of core and shell difference was between 8.0 and 12.1% with standard deviation between 5.8 and 12.9% (Figure 4.11). The overall higher difference in core and shell might be due to wet pockets. Higher amplitude as well as control schedules resulted in greater standard deviations compared to the lower amplitude schedules. The difference in core and shell final moisture content in TWB-L schedule was observed to be 28% lower than the corresponding low amplitude TDB-L schedule whilst it was 23%, 34% and 32%, less than the TDB-H, TWB-H and control respectively. Similar relationships were also found in the standard deviations. This might be partly due to the low final moisture content of the TWB-L. One-way analysis of variance indicated no significant difference between the means of their differences (Table 4.11).
Table 4.11: Analysis of variance table for the core and shell moisture content difference.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between schedules</td>
<td>440.137</td>
<td>4</td>
<td>110.0342</td>
<td>0.936488</td>
<td>0.443752</td>
<td>2.415696</td>
</tr>
<tr>
<td>Error</td>
<td>24086.8</td>
<td>205</td>
<td>117.4966</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>24526.9</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.11: The difference between core and shell final moisture content for each drying run.
Unlike the final moisture content, the core and shell final moisture content difference of TDB-H schedule was 14% less than the TWB-H with a corresponding lower standard deviation. This might be explained from the fact that, during falling rate period of drying where most drying takes place in the core, diffusion which increases with temperature becomes the dominant moisture transfer mechanism. Therefore increasing the $T_{db}$ will have a greater effect on transferring moisture from the center to the surface than decreasing relative humidity through decreasing $T_{wb}$. Although the TDB-L had a higher difference than TDB-H, it resulted in a lower standard deviation. Considering the distribution of difference in core and shell as seen in Figure 4.10, the larger percentage of all the runs fall below 20% whereas the TDB-H seems to have greater percentage of its specimens having core and shell final moisture content difference below 15%.

4.2.4 Schedule effect on internal stresses (casehardening)

Casehardening is an important quality assessment tool especially in the remanufacturing sector of timber processing. Prong test was used to evaluate the internal stresses or casehardening in the timber after drying with various drying schedules. Since there were no vertical gaps in the charges, most evaporation was assumed to be from top and bottom of specimens. This will induce moisture gradient in the vertical direction, hence internal stresses occurring mostly vertically. Casehardening was therefore evaluated only in the vertical direction. Degrees were assigned to the severity of the casehardening as follows; slightly casehardened (0.001-0.100), medium casehardened (0.101 - 0.200) and severe casehardened (0.201- 0.300). The frequency of a particular degree per drying run is indicated in Table 4.12. Figure 4.12 also illustrates the severity of casehardening of the prongs after a 24-hour period.

In these experiments, specimens of all runs showed no reverse casehardening but different degrees of casehardening were observed. It must be noted however that there was no conditioning period in any of the runs, so casehardening was very likely to occur.
Table 4.12: The severity and occurrence of casehardening in each drying run.

<table>
<thead>
<tr>
<th>Run</th>
<th>Slightly casehardened 0.001-0.100 (1°)</th>
<th>Casehardened 0.101 - 0.200 (2°)</th>
<th>Severe casehardened 0.201- 0.300 (3°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>%</td>
<td>Number</td>
</tr>
<tr>
<td>Run 1(Control)</td>
<td>22</td>
<td>52</td>
<td>17</td>
</tr>
<tr>
<td>Run 2(TDB-H)</td>
<td>27</td>
<td>64</td>
<td>10</td>
</tr>
<tr>
<td>Run 3(TWB-H)</td>
<td>21</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Run 4(TDB-L)</td>
<td>14</td>
<td>33</td>
<td>19</td>
</tr>
<tr>
<td>Run 5(TWB-L)</td>
<td>22</td>
<td>52</td>
<td>19</td>
</tr>
</tbody>
</table>

Categorizing the casehardening in all the runs, it was observed that all the specimens of the lower amplitude oscillated schedules showed some degree of casehardening whereas 2% each of the high amplitude schedules and the control showed no casehardening. Of the total population 23% exhibited 3° casehardening out of which 42% resulted from specimens of TDB-L schedule (21% of that run). Out of the specimens from TDB-H, TWB-H, TWB-L and control schedules, only 10, 12, 2 and 5% respectively showed 3° casehardening. It was also observed that about 64% of specimens from TDB-H schedule had only slight casehardening indicating a 22, 48, 19 and 19% lesser degree of casehardening than TWB-H, TDB-L, TWB-L and control respectively.

Figure 4.12: Prongs showing levels of casehardening after 24 hours.
Using the formula by Simpson (1987) as explained in chapter 3, the magnitude of the casehardening ranged from zero to 0.296 and averaged from 0.089 to 0.136 with standard deviation between 0.055 and 0.076. The specimens of the TDB-L schedule (Figure 4.13) showed the highest average which was 34%, 22%, 32% and 31% greater than the average casehardening found in TDB-H, TWB-H, TWB-L and control respectively. This might partly be due to the fact that it had the highest number of wets. Therefore during the 24-hour waiting period of the prongs, the exposed core may dry to the ambient conditions leading to shrinkage, hence increasing the magnitude of a “pseudo-casehardening”. The specimens of TDB-H schedule however, had the lowest average casehardening and resulted in 16% and 5% less casehardening than TWB-H and the control schedules respectively. On the contrast the high amplitude $T_{wb}$ oscillated schedule had 9% less internal stresses compared to the TWB-L.

Figure 4.13: Average and standard deviations of casehardened specimens after 24 hours.

Analysing the results with a one-way analysis of variance indicated a significant
difference between casehardening means (Table 4.13). A further Tukey multiple range test (Appendix B1), showed that the specimens from TDB-L schedule is significantly different from all other schedules. The casehardening of specimens from the TWB-H schedule was also significantly different from those of the TDB-H, TWB-L and the control. Specimens from control were also significantly different from those of the TDB-H schedule. These differences indicate mixed effects of oscillation drying on casehardening as a drying characteristic.

Table 4.13: Analysis of variance table for casehardening.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between schedules</td>
<td>0.061639</td>
<td>4</td>
<td>0.01541</td>
<td>3.344781</td>
<td>0.01162</td>
<td>2.415696</td>
</tr>
<tr>
<td>Error</td>
<td>0.944458</td>
<td>205</td>
<td>0.00461</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.006097</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 Shrinkage of timber

Shrinkage indicates one of the hygro-mechanical behaviour of wood that occurs mostly after the fibre saturation point is reached. Although shrinkage itself is not a defect, it might induce several drying defects. Reduction and controlled shrinkage can therefore reduce drying defects. The actual volumetric shrinkage ranged from a minimum of 1.02% by TDB-L specimen to a maximum of 14.26% indicated by TWB-L. The average was from 4.11 to 5.33% with a standard deviation between 1.61 and 2.10%. The average values were fairly consistent with one reported by Zhang et al. (1996). The absolute values seem to show that the $T_{db}$ oscillated schedules resulted in less volumetric shrinkage than the $T_{wb}$ and control schedules. However, analysis of variance indicated (Table 4.14) a significant difference only in the actual width shrinkage means. Using Tukey multiple range test, it was observed that the actual width shrinkages of specimens from the low amplitude $T_{db}$ oscillated schedule were significantly different (Appendix B2).
Table 4.14: Analysis of variance table for actual width shrinkage

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>17.995274</td>
<td>4</td>
<td>4.498185</td>
<td>3.39908</td>
<td>0.010199</td>
<td>2.415696</td>
</tr>
<tr>
<td>Within Groups</td>
<td>271.25963</td>
<td>205</td>
<td>1.3232177</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>289.2549</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Due to the anisotropic nature of wood, differential shrinkage occurs during drying processes. Also because all runs ended with different final moisture contents, the magnitude of shrinkage will differ. Shrinkages were therefore estimated for final moisture content of 15% for all runs based on the assertion that shrinkage decreases linearly in the hygroscopic range and that fibre saturation point was at 30%. The average actual and estimated percentage volumetric, thickness, and width shrinkages are hence indicated in Table 4.15 and illustrated in Figure 4.14.

Table 4.15: The actual ($S_v$) and estimated ($s_v$) average shrinkage at final moisture content for each drying run.

<table>
<thead>
<tr>
<th>Run</th>
<th>Volumetric (%)</th>
<th>Thickness (%)</th>
<th>Width (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_v$</td>
<td>$s_v$</td>
<td>$S_v$</td>
</tr>
<tr>
<td>Run 1(Control)</td>
<td>5.21</td>
<td>6.01</td>
<td>2.55</td>
</tr>
<tr>
<td>Run 2(TDB-H)</td>
<td>4.90</td>
<td>5.48</td>
<td>2.44</td>
</tr>
<tr>
<td>Run 3(TWB-H)</td>
<td>5.33</td>
<td>6.01</td>
<td>2.85</td>
</tr>
<tr>
<td>Run 4(TDB-L)</td>
<td>4.11</td>
<td>4.78</td>
<td>2.25</td>
</tr>
<tr>
<td>Run 5(TWB-L)</td>
<td>5.32</td>
<td>5.15</td>
<td>2.63</td>
</tr>
</tbody>
</table>

It can be observed from the derived shrinkages that the specimens from the TWB-H and control showed the same highest volumetric shrinkage. They resulted in 10, 26 and 17% greater volumetric shrinkage than TDB-H, TDB-L and TWB-L respectively and were greater in the thickness shrinkage. Both of the higher amplitude schedules and the control indicated equal width shrinkages which were greater than those of both lower amplitude schedules. In all the shrinkages both high amplitude schedules were greater when compared to specimens from the lower amplitude counterparts.
4.4 Timber quality

All the specimens were visually evaluated before and after drying. Of the total population 7.1% were found to have pockets of rot whilst 6.2% showed worm holes. A couple of the specimens were also identified with wet-pockets, shake, wane and one specimen was with heart center. Because these were identified before drying and are natural characteristics of wood, they were not considered as drying defects.

After drying there were no internal checks (honey comb), collapse or unsound knots found. However, surface checks and splits were identified and quantified and some timbers were also found with end checks. Due to the length of the specimens which was 910mm, it was impracticable to grade and evaluate the timber according to the NGLA (1991) rules or any such grading systems and rules.
Table 4.16: Degrade classification of dried timber for each drying run.

<table>
<thead>
<tr>
<th>Run</th>
<th>A-Grade</th>
<th>B-Grade</th>
<th>C-Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>(%)</td>
<td>Number</td>
</tr>
<tr>
<td>Split</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1 (Control)</td>
<td>36</td>
<td>86</td>
<td>0</td>
</tr>
<tr>
<td>Run 2 (TDB-H)</td>
<td>36</td>
<td>86</td>
<td>4</td>
</tr>
<tr>
<td>Run 3 (TWB-H)</td>
<td>39</td>
<td>93</td>
<td>1</td>
</tr>
<tr>
<td>Run 4 (TDB-L)</td>
<td>25</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>Run 5 (TWB-L)</td>
<td>41</td>
<td>98</td>
<td>0</td>
</tr>
<tr>
<td>Surface checks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1 (Control)</td>
<td>31</td>
<td>74</td>
<td>2</td>
</tr>
<tr>
<td>Run 2 (TDB-H)</td>
<td>30</td>
<td>71</td>
<td>4</td>
</tr>
<tr>
<td>Run 3 (TWB-H)</td>
<td>27</td>
<td>64</td>
<td>5</td>
</tr>
<tr>
<td>Run 4 (TDB-L)</td>
<td>34</td>
<td>81</td>
<td>3</td>
</tr>
<tr>
<td>Run 5 (TWB-L)</td>
<td>32</td>
<td>76</td>
<td>6</td>
</tr>
</tbody>
</table>

It is however, very important to evaluate the effects of the schedules on surface checks and splits since they are directly affected by change in magnitude and time of application of both temperature and relative humidity. Also according to NGLA (1991) standards surface checks are not used in grading construction timber, it has therefore been incorporated in this study for comparison purposes. The lengths of the surface checks and splits on the timber were divided and graded as follows: A – no or slight degrade (0-100mm); B – medium degrade (101-400mm) and C – high degrade (401-910mm). The results of the grading classification are shown in Table 4.16.

The overall dried timber quality in both split and surface checks was high as illustrated in Figure 4.15. Degrade through checks was observed to be greater than split degrade. Regarding splits the grade (A) percentage quality ranged between 60 and 98%. The $T_{wb}$ oscillated schedules showed higher quality timber than the $T_{db}$ and control schedules. The least percentage splits were recorded in the timbers of the TWB-L schedule whilst the opposite was true for the TDB-L schedule. Only timber dried with the TDB-L showed
lower quality than the control. This might be due to high internal stresses which occurred with the timber of this schedule (see Figure 4.12).
Chapter 5

Conclusions

The basic objective of this study was to explore the effect of oscillating drying schedules on the drying characteristics of thick hemlock timbers. The conclusions are summarized as follows:

1. Oscillating dry and wet bulb temperatures of the drying schedule in a conventional kiln drying process increased the drying rate and shortened drying time for thick hemlock timbers. Oscillating dry bulb at higher amplitude and frequency increased the average drying rate by 12% compared to control. On the other hand the kiln residence time decreased between 10 and 14% by the lower amplitude dry bulb oscillated schedule when compared to the control.

2. The overall impact of oscillating drying temperatures on drying rate was more pronounced above the fibre saturation point than below especially at the early stages of the drying process.

3. Oscillation drying schedule reduced final moisture content variation in both high and low amplitude and frequency schedules especially in the wet bulb oscillated schedules.

4. The low amplitude dry bulb oscillated schedule showed a significantly higher core and shell final moisture content variation. However, no statistically significant differences were found between the rest of the schedules and the control.

5. Drying stresses in the timber increased when oscillating the dry bulb temperature at lower amplitudes but no significant effect on timber stresses in the other schedules.

6. Width shrinkage in the baby square hemlock timber was significantly reduced in the specimens from the low amplitude schedules.
From this study, it is the opinion of the author that oscillation drying strategy using conventional drying method has a very high potential especially for hemlock baby square timbers. Furthermore the application of this strategy in the industry for steam operated kilns does not require any change in hardware than a minor adjustment in the kiln controlling software. Any software which can be looped or altered during a drying process might be capable to handle and operate using oscillating drying strategy. However, there is the need for a full industrial scale research into optimizing the timing of the start of oscillation in the drying process as well as the magnitude of the amplitude and frequency combinations.
References


Forest Products Management Development Institute. 1998. Nature of Wood CD. University of Minnesota. USA.


Hansom, O. P. 1988 Contemporary Timber Drying. TBL 60, Timber Research and Development Association (TRADA), Buckinghamshire. UK. 84 pp


Kininmonth, J.A. 1974. Timber Drying in New Zealand, Wellington, New Zealand Forest Service 42 pp


Determination of kiln-load weight at target moisture content of 15%

During the drying process the whole kiln charge rested on a load cell. At time intervals change in weight is registered and automatically monitored by a computer. At the reach of the target moisture content of 15%, the kiln automatically shuts down. This final target moisture content is the average of all the individual specimens in the kiln and is calculated as follows;

For Run1 the initial moisture content is and the green weight were 60.6 % and 309.1 kg respectively. These data were fitted to the equation below to calculate the oven-dry weight of the total kiln load.

\[
\text{over-dry weight} = \frac{\text{green weight of load}}{1 + \text{initial moisture content}}
\]

\[
\text{oven-dry weight for Run 1} = \frac{309.1}{1 + 60.6\%} = 192.5 \text{ (kg)}
\]

The weight corresponding to the target moisture content of 15% is calculated as;

weight at 15% moisture content = 1.15 x (oven dry weight) therefore for Run1 weight at 15% moisture content = 1.15 x 192.5 (kg) = 221.3 (kg)

Table of target weight for each drying run.

<table>
<thead>
<tr>
<th>Run</th>
<th>M_i (%)</th>
<th>Green weight (kg)</th>
<th>Oven-dry weight (kg)</th>
<th>Target weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Run 1) Control</td>
<td>60.6</td>
<td>309.1</td>
<td>192.5</td>
<td>221.3</td>
</tr>
<tr>
<td>(Run 2) TDB-H</td>
<td>67.0</td>
<td>328.8</td>
<td>196.9</td>
<td>226.4</td>
</tr>
<tr>
<td>(Run 3) TWB-H</td>
<td>64.8</td>
<td>319.8</td>
<td>194.1</td>
<td>223.2</td>
</tr>
<tr>
<td>(Run 4) TDB-L</td>
<td>57.0</td>
<td>302.2</td>
<td>192.5</td>
<td>221.4</td>
</tr>
<tr>
<td>(Run 5) TWB-H</td>
<td>54.1</td>
<td>297.8</td>
<td>193.3</td>
<td>222.2</td>
</tr>
</tbody>
</table>
One-way analysis of variance of casehardening and Tukey multiple range test.

Hypothesis:  
H₀:  μ₁ = μ₂ = μ₃ = μ₄ = μ₅  
Hₐ: Mean casehardening are not the same in specimens from all schedules, where μ₁, μ₂, μ₃, μ₄ and μ₅ are the means of Control (Run1), TDB-H (Run2), TWB-H (Run3), TDB-L (Run4) and TWB-L (Run 5).

α (significant level) = 0.05

Results from one-way analysis of variance (ANOVA)

<table>
<thead>
<tr>
<th>Schedules</th>
<th>Count</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>42</td>
<td>3.946708</td>
<td>0.09396924</td>
<td>0.004546</td>
</tr>
<tr>
<td>TDB-H</td>
<td>42</td>
<td>3.755095</td>
<td>0.08940702</td>
<td>0.004458</td>
</tr>
<tr>
<td>TWB-H</td>
<td>42</td>
<td>4.465633</td>
<td>0.10632459</td>
<td>0.005838</td>
</tr>
<tr>
<td>TDB-L</td>
<td>42</td>
<td>5.697135</td>
<td>0.13564607</td>
<td>0.005163</td>
</tr>
<tr>
<td>TWB-L</td>
<td>42</td>
<td>3.855714</td>
<td>0.09180271</td>
<td>0.00303</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between schedules</td>
<td>0.061639109</td>
<td>4</td>
<td>0.01540978</td>
<td>3.344781</td>
<td>0.011162</td>
<td>2.415796</td>
</tr>
<tr>
<td>Error</td>
<td>0.944457882</td>
<td>205</td>
<td>0.00460711</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.006096992</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Because F_{critical} > F_{calculated} there is a significant difference between the casehardening means. In order to determine which means are significantly different Tukey multiple range test is applied.

Tukey multiple range test

Ranking of sample means in descending order:

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>0.13564607</td>
<td>0.106325</td>
<td>0.09396924</td>
<td>0.09180271</td>
<td>0.08940702</td>
</tr>
<tr>
<td>Schedule</td>
<td>TDB-L</td>
<td>TWB-H</td>
<td>Control</td>
<td>TWB-L</td>
<td>TDB-H</td>
</tr>
</tbody>
</table>
Formula for Tukey test: 

\[ q = \frac{\bar{X}_b - \bar{X}_a}{SE} \quad \text{where} \quad SE = \sqrt{s^2 / n} \]

\( \bar{X}_a \) and \( \bar{X}_b \) are the means of the samples being compared,

\( n \) is the size of the samples = 42, and

\( s^2 \) is the mean square error (MS) from ANOVA table = 0.00460711

The critical value of \( q(\alpha, \nu, k) \) is determined from the "Studentised range"

where: \( \nu = \text{error degree of freedom} \)

\( k = \text{the total number of means being tested} \)

For each comparison, if \( q_{\text{critical}} \geq q_{\text{calculated}} \) then \( H_0 \) is rejected and there is a significant difference between those means.

\( q(0.05, 205, 5) \) determined from the"Studentised range" tables = 3.858

Comparison results of Tukey test:

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Difference</th>
<th>SE</th>
<th>( q )</th>
<th>( q(0.05,205,5) )</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDB-L vs. TDB-H</td>
<td>0.046239056</td>
<td>0.000711</td>
<td>65.0436452</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TDB-L vs. TWB-L</td>
<td>0.043843361</td>
<td>0.000711</td>
<td>61.6736644</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TDB-L vs. Control</td>
<td>0.041676831</td>
<td>0.000711</td>
<td>58.6260458</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TDB-L vs. TWB-H</td>
<td>0.029321486</td>
<td>0.000711</td>
<td>41.2460043</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TWB-H vs. TDB-H</td>
<td>0.016917571</td>
<td>0.000711</td>
<td>23.7976410</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TWB-H vs. TWB-L</td>
<td>0.014521876</td>
<td>0.000711</td>
<td>20.4276601</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TWB-H vs. Control</td>
<td>0.012355346</td>
<td>0.000711</td>
<td>17.3800416</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>Control vs. TDB-H</td>
<td>0.004562225</td>
<td>0.000711</td>
<td>6.41759941</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>Control vs. TWB-L</td>
<td>0.002166530</td>
<td>0.000711</td>
<td>3.04761859</td>
<td>3.858</td>
<td>Accept ( H_0 )</td>
</tr>
<tr>
<td>TWB-L vs. TDB-H</td>
<td>0.002395695</td>
<td>0.000711</td>
<td>3.3699808</td>
<td>3.858</td>
<td>Accept ( H_0 )</td>
</tr>
</tbody>
</table>

Overall conclusion: \( \mu_4 \neq \mu_3 \neq \mu_1 = \mu_2 = \mu_5 \)

Conclusion:

1. Oscillating schedule has effect on casehardening.
2. Specimens from TDB-L schedule had the highest internal stresses.
3. Internal stresses in TWB-L specimens were also higher than control.
4. Oscillating the dry bulb at high amplitudes reduced internal stresses.
One-way analysis of variance of width shrinkage and Tukey multiple range test.

Hypothesis:  
\[ H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 \]
\[ H_A: \text{Mean width shrinkage is not the same in specimens from all schedules.} \]

where \( \mu_1, \mu_2, \mu_3, \mu_4 \text{ and } \mu_5 \) are the means of Control (Run1), TDB-H (Run2), TWB-H (Run3), TDB-L (Run4) and TWB-L (Run 5).

\( \alpha \) (significant level) = 0.05

Results from one-way analysis of variance (ANOVA)

<table>
<thead>
<tr>
<th>Width Shrinkage</th>
<th>Count</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>42</td>
<td>105.4743</td>
<td>2.5112928</td>
<td>1.182027</td>
</tr>
<tr>
<td>TDB-H</td>
<td>42</td>
<td>109.1065</td>
<td>2.5977749</td>
<td>1.635799</td>
</tr>
<tr>
<td>TWB-H</td>
<td>42</td>
<td>106.929</td>
<td>2.5459283</td>
<td>1.400139</td>
</tr>
<tr>
<td>TDB-L</td>
<td>42</td>
<td>79.47678</td>
<td>1.8923043</td>
<td>1.119663</td>
</tr>
<tr>
<td>TWB-L</td>
<td>42</td>
<td>114.9917</td>
<td>2.7378988</td>
<td>1.278461</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>17.995274</td>
<td>4</td>
<td>4.4988185</td>
<td>3.399908</td>
<td>0.010199</td>
<td>2.415696</td>
</tr>
<tr>
<td>Within Groups</td>
<td>271.25963</td>
<td>205</td>
<td>1.3232177</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>289.2549</td>
<td>209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Because \( F_{\text{critical}} > F_{\text{calculated}} \) there is a significant difference between the casehardening means. In order to determine which means are significantly different Tukey multiple range test is applied.

**Tukey multiple range test**

Ranking of sample means in descending order:

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>2.7378988</td>
<td>2.5977749</td>
<td>2.5459283</td>
<td>2.5112928</td>
<td>1.8923043</td>
</tr>
<tr>
<td>Schedule</td>
<td>TWB-L</td>
<td>TDB-H</td>
<td>TWB-H</td>
<td>Control</td>
<td>TDB-L</td>
</tr>
</tbody>
</table>
Formula for Tukey test: \[ q = \frac{\bar{X}_A - \bar{X}_B}{SE} \] where \( SE = \sqrt{s^2/n} \)

\( \bar{X}_A \) and \( \bar{X}_B \) are the means of the samples being compared, 
n is the size of the samples = 42, and 
\( s^2 \) is the mean square error (MS) from ANOVA table = 1.3232177

The critical value of \( q(\alpha, \nu, k) \) is determined from the "Studentised range" where: 
\( \nu = \text{error degree of freedom} \)
\( k = \text{the total number of means being tested} \)

For each comparison, if \( q \text{ critical} \geq q \text{ calculated} \) \( H_0 \) is rejected and there is a significant difference between those means.

\( q(0.05, 205, 5) \) determined from the "Studentised range" tables = 3.858

<table>
<thead>
<tr>
<th>Comparison B vs. A</th>
<th>Difference</th>
<th>SE</th>
<th>( q )</th>
<th>( q(0.05, 205, 5) )</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWB-L vs. TDB-L</td>
<td>0.845595</td>
<td>0.204177</td>
<td>4.141479</td>
<td>3.858</td>
<td>Reject ( H_0 )</td>
</tr>
<tr>
<td>TWB-L vs. Control</td>
<td>0.226606</td>
<td>0.204177</td>
<td>1.109851</td>
<td>3.858</td>
<td>Accept ( H_0 )</td>
</tr>
<tr>
<td>TWB-L vs. TWB-H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TWB-L vs. TDB-H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDB-H vs. TDB-L</td>
<td>0.705471</td>
<td>0.204177</td>
<td>3.455193</td>
<td>3.858</td>
<td>Accept ( H_0 )</td>
</tr>
<tr>
<td>TDB-H vs. Control</td>
<td>0.086482</td>
<td>0.204177</td>
<td>0.423564</td>
<td>3.858</td>
<td>Accept ( H_0 )</td>
</tr>
<tr>
<td>TDB-H vs. TWB-H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDB-H vs. TDB-L</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TWB-H vs. TDB-L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control vs. TDB-L</td>
<td></td>
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</tr>
</tbody>
</table>

Overall conclusion: \( \mu_1 = \mu_2 = \mu_3 = \mu_4 \neq \mu_5 \)

Conclusion:

1. Specimens from TDB-L schedule had the lowest width shrinkage.
2. Width shrinkage from TDB-L specimens were significantly different from TWB-L specimens but no difference found in the rest.
3. Oscillation had therefore no significant effect on width shrinkage.