Chapter 2

LITERATURE REVIEW

2.1 Rubberwood

The wood from rubber tree stems (*Hevea brasiliensis*) has become the raw material for a wide variety of end products of varying quality, substituting timber from the natural forests. Rubberwood becomes available from agricultural plantations when replanting is carried out after 25 to 30 years because of declining latex yield.

Although rubberwood (sometimes called hevea wood) is a relatively inexpensive and mass-produced timber, it is now being used and marketed in many applications in which higher-value, less available hardwoods such as teak *(Tectona grandi*s) have traditionally been used. These include furniture, flooring, wood panels and indoor building components. It is not durable enough, however, for use in some situations requiring the durability of teak, such as boat building, bulwarks, construction and transmission line poles.

The availability of rubberwood in large quantities is partly a result of the trees' undemanding site requirements, and mainly from the fact that rubberwood is a by-product of a crop grown for latex production. An additional, vital factor for the availability of rubberwood is, at least in Malaysia, strong governmental support and incentives to ensure the continuing supply of latex through replanting of rubber plantations.

Most of the technical problems in processing and utilization of rubberwood have been overcome by the Southeast Asian countries over the past 20 years and the timber has been successfully marketed internationally. Rubberwood has thus become a Southeast Asian success story. It is even more important than teak as a plantation timber in Southeast Asia (Killmann, W. and Hong, L.T., 2000).

Until recently the most important product from the rubber tree was its latex and efforts to improve the tree concentrated upon increasing the latex yield. Typically following an exploitation period of about 30 years the trees are felled for replanting with higher yielding clones. Until recently, most of the timber was used as fuel. With the depleting of tropical forests, leading to a shortage of timber for many industrial and engineering uses, attention has turned towards rubberwood as an alternative source of timber. (Sekhar, A.C., 1995). A 30-year-old cultivated hevea tree is about 30 m tall with an average branch-free bole of 3 m. The diameter at breast height (DBH) may reach about 30 cm. The stem tends to taper. Young rubber trees have a smooth brown-green bark. The constantly tapped portions of the stem may develop with age into a latex-smeared cortex. (Killmann, W. and Hong, L.T., 2000)

More than 80 percent of the 7.2 million hectares of plantations established worldwide for latex production in 1999 are in Southeast Asia; 70 percent of the total (or 5.2 million ha) are in Indonesia, Malaysia and Thailand (FAO, 1999). For decades, Malaysia had the largest area, followed by Indonesia and Thailand.

Table 2-1 Rubber plantation area of major producing countries worldwide ('000 ha)

Country	**1981**	**1991**	**1999**
Indonesia	1564	1878	2269

Malaysia	1620	1610	1420
Thailand	1269	1420	1555
Vietnam	85	221	380
Philippines	54	87	98
Myanmar	47	39	48
Cambodia	10	35	39
China	n.a.	420	390
Sri Lanka	230	198	158
India	194	306	374
Asia total	**5073**	**6214**	**6731**
Liberia	107	20	28
Nigeria	73	268	225
Cameroon	28	41	53
Côte d’Ivoire	17	42	60
West Africa total	**225**	**371**	**366**
Guatemala	16	15	27
Brazil	n.a.	50	59
Latin America total	**16**	**65**	**86**
World	**5314**	**6650**	**7183**

Source: http://apps.fao.org

Fresh, sawn rubberwood is white to creamy in colour, sometimes with a pinkish tinge, and has a fairly straight grain. It turns yellowish after seasoning. Heartwood and sapwood are not distinguishable. Pores are large and scattered and show radially and tangentially as brown lines. Improper tapping practices cause an interruption in the normally homogeneous creamy colour. If the tapper accidentally cuts through the cambium, deposits and fungi introduced by the knife cause a black stain along the growth rings, which is considered a defect in the timber. In addition, the traumatic reaction of the cambial tissue produces a callus.

This eco-friendly Rubber-wood (*Hevea brasiliensis*) is an excellent timber to use and its various attributes are outlined here:

APPEARANCE

Color	Pale cream to yellowish brown. Oxidative discoloration can be limited by rapid production sequence and vacuum drying
Grain pattern	Mostly straight. A cross section of rubberwood shows few concentric markings reminiscent of growth rings. These markings combined with the large vessels in structure give an attractive appearance with clear patterns on the longitudinal surface.
Structure	Uniform in structure with an excellent 'Timber' feel.

Figure 2-1 Appearance of rubberwood.

Source : www.andamans.com/RubWd.htm

Table 2-2 Physical and mechanical properties of Rubberwood comparing with Teak.

Properties	Rubberwood (MC 15%)	Teak (MC12%)
Density	460-650 kg/m^3	480-850 kg/m^3
Modulus of rupture (MOR)	66 N/mm^2	86-170 N/mm^2
Modulus of elasticity (MOE)	9240 N/mm^2	10500-15600 N/mm^2
Compression		
• parallel to grain	32 N/mm^2	55 N/mm^2
• perpendicular to grain	5 N/mm^2	6.5 N/mm^2
Shear	11 N/mm^2	11 N/mm^2
Hardness (Janka)	4350 N	4500 N

Source: Killmann.W.and Hong.L.T. (2002)

Rubberwood has traditionally been used as a cheap source of fuel wood in most of the countries where rubber plantations are abundant. It is also used industrially for brick burning and tobacco curing. Because of its lack of durability, the wood was not traditionally used as timber except in timber-scarce countries, such as India and Sri Lanka, where it has been used for general utility purposes. Some processing problems had to be overcome, as described above, before rubberwood could be widely marketed. Being naturally non-durable, rubberwood is not economically usable without preservative treatment. Through research and development efforts, protective measures have been prescribed which are now routine for rubberwood processing.

Rubberwood's favourable woodworking and timber properties make it suitable for a wide scope of applications. Salleh (1984) reported 61 different products made from rubberwood. Its most important uses are in furniture and furniture parts, parquet, panelling, wood-based panels (particle board, cement-and gypsum-bonded panels, medium density fibreboard) and kitchen and novelty items, and as sawntimber for general utility and fuel. The favourable qualities and light colour of rubberwood make it a good substitute for ramin *(Gonystylus bancanus* Baill.), a timber noted for its quality for furniture and other applications. The natural colour of rubberwood is one of the principal reasons for its popularity in Japan, where it is increasingly used to replace more traditional timbers, e.g. *Fagus* spp. and *Quercus* spp., in a wide variety of applications. A disadvantage of rubberwood is the smaller sizes available compared with timber from forest species. Boards normally have a maximum length of 1800 mm and thickness of up to 50 mm. For larger end products such as table tops, the timber is usually laminated or fingerjointed.

2.2 The Theory and Practice of Wood Drying

Wood products should be dried to a final moisture content (MC) about mid-range of the expected MC of its surroundings. These can vary considerably by product, geographic location, and the intended use of the product (e.g., whether it will be used inside or outside).

Wood products used outside but protected from direct precipitation will stabilize with the surrounding environment at about 12% MC in the humid southern states of the United State, but may stabilize to as low as 6% MC in the arid Southwest. Hardwood furniture, all paneling, and other products used in heated buildings are estimated to stabilize at about 8% MC. Wood products to be used inside buildings that are only occasionally heated should be dried to about 18% MC.

2.2.1 Problems in Drying Wood

There are some negative aspects to drying wood, including:

1. The great amount of energy that must be expended to drive the water out of wood. As much as 80% of the total energy requirement for a sawmill can be used in the drying operations.

2. The possibility of drying defects. As wood dries, it shrinks in several dimensions. If wood is not correctly dried, the dimensional changes will cause drying defects, including checks, splits, warp, casehardening, and honeycomb.

Some explanations of these two items are warranted because of their importance in the wood drying process.

- **Effect of Drying Temperature**

High temperatures reduce the strength of wood in two ways. First, there is an immediate and reversible effect. For example, wood is weakened when heated from 24 to 116 °C but regains strength if immediately cooled to 24°C. The second effect occurs over time and is permanent. When wood is heated for long times at high temperatures, 'it is permanently weakened; the loss of strength remains after the wood is cooled. Both effects are greater at high moisture content than at low moisture content. The permanent effect is caused by a combination of time, temperature, and moisture content. Strength loss increases as any one of these factors increases.

The immediate-reversible effect of high-temperature drying is important in the development of drying defects that result from breakage or crushing of wood cells. When the drying stresses become greater than the strength of the wood, this type of drying defect develops. This is why high temperatures early in drying are dangerous. The weakening effect of high temperatures coupled with high moisture content can cause the wood to fracture or be crushed. High-temperature drying for long periods, particularly early in drying when the moisture content is high, may not result in breakage or crushing-type drying defects, but it can cause a permanent loss in strength or other mechanical properties that affect product performance in end use. In general, stiffness is not greatly reduced by high-temperature drying, but bending strength may be reduced by as much as 20% (Simpson, W.T., et al., 1991).

Most defects or problems that develop in wood products during and after drying can be classified under one of the following categories:

- **End Checks and Splits**

End checks usually occur in the wood rays, but on end-grain surfaces. They also occur in the early stages of drying and can be minimized by using high relative humidity or by end coating. End checks occur because moisture moves much faster in the longitudinal direction than in either transverse direction. There, the ends of boards dry faster than the middle and stresses develop at the ends. Ends checked lumber should not be wetted or exposed to high relative humidity before any further drying, or the checks may be driven further into the board (Simpson, W.T., et al., 1991).

The tendency to end check becomes greater in all species as thickness and width increase. Therefore, the end-grain surface of thick and width lumber squares, and gunstocks should be end coated with one of the end coatings available from kiln manufacturers and other sources. To be most effective, end coatings should be applied to freshly cut, unchecked ends of green wood.

End splits often results from the extension of end checks further into a board. One way to reduce the extension of end checks into longer splits is to place stickers at the extreme ends of the boards. End splits are also often caused by growth stresses and are therefore not a drying defect. End splits can be present in the log or sometimes develop in boards immediately after sawing from the log.

- **Warp**

Warp in lumber is any deviation of the face or edge of a board from flatness or any edge that is not at right angles to the adjacent face or edge (squares). It can cause significant volume and grade loss. All warp can be traced to two causes, differences between radial, tangential, and longitudinal shrinkage in the piece as it dries, or growth stresses. Warp is also aggravated by irregular or distorted grain and the presence of abnormal types of wood such as juvenile and reaction wood. Most warp that is caused by shrinkage difference can be minimized by proper stacking procedures. The effects of growth stresses are more difficult to control, but centain sawing techniques are effective.

- **Discoloration**

The use of dried wood products can be impaired by discolorations, particularly when the end use requires a clear, natural finish. Unwanted discolorations can develop in the tree, during storage of logs and green lumber, or during drying. Discolorations may also develop when light, water, or chemicals react with exposed surfaces of dried wood. This section is mainly concerned with discolorations that develop in clear, sound wood before or during drying. Any discolorations beyond the control of the drying and related processing operations, such as mineral stain and decay in the tree, will be mentioned only when they might form the focal points for initiation of drying defects. Drying discolorations have been traditionally classified in association with fungal attack or chemicals in the wood. Also, the formation of unwanted color will vary with complex interactions of tree species, type of wood tissue, and drying conditions. Successful control of discolorations depends upon the ability of the dry kiln operator to recognize differences in the wood quality of the species being dried and environmental factors that will initiate discoloration.

To prevent discolorations, the dry kiln operator must know the wood species and determine the wood type (sapwood, heartwood, or wetwood). The third and sometimes hardest step is to determine if the causal are primarily chemical or microbial.

Hence, it may sometimes be economically necessary to remove discolorations that cannot be surfaced off on the planer. Some stains may be removed with a bleaching agent, but some trial and error method is often required to find the most effective agent for a particular stain. Bleaching operations can be costly in terms of handling and redrying the wood. To be effective, the bleaching treatment may have to be so severe that significant amount of natural color is also eliminated. Of course, the bleached wood cannot be resurfaced without exposing interior discolorations.

If the stain is not too deep, it can often be removed or reduced in intensity with hydrogen peroxide. A concentrated aqueous solution of oxalic acid will bleach out chemical sapwood stains but not sapwood stains caused by mold fungi. A laundry bleach of 5 percent sodium hypochlorite solution can sometimes be used effectively (Simpson, W.T., et al., 1991).

2.2.2 Water and Wood

The water or *moisture content* (MC) of wood is expressed, in percent, as the weight of water present in the wood divided by the weight of dry wood-substance. MC may be greater than 100% because the weight of water in the wood can be larger than the weight of dry wood-substance.

Moisture content on dry and wet basis is defined as follows:

On dry basis,

Moisture content (percent)

$$= \frac{\text{Weight of water in wood}}{\text{Weight of total dry wood}} \times 100 \qquad (2\text{-}1)$$

On wet basis,

$$\text{Moisture content (percent)} = \frac{\text{Weight of water in wood}}{\text{Weight of total dry wood and water}} \times 100 \qquad (2\text{-}2)$$

Green (freshly cut) wood may have an MC as low as 30% to as high as 250%. Sapwood usually has a higher MC than heartwood. Average green wood MC may vary considerably from one tree to another, among boards cut from the same tree, and with the time of year the tree is cut.

Most of this water must be removed in order to obtain satisfactory performance from wood that is to be processed into consumer and other types of useful products.

When the tree dies from natural causes—such as fire, insects, disease, ice, snow, or wind damage—the wood immediately begins to lose some of its moisture to the surrounding atmosphere. When a tree is converted to logs, lumber, veneer, and chips, the wood immediately starts to dry. If drying continues long enough, the dimensions and the physical properties of the wood begin to undergo change.

Because wood is made up of various kinds of cells, some water remains within the structure of the cell walls even after it has been manufactured into lumber or other wood-based products. The physical and mechanical properties, resistance to biological deterioration, and dimensional stability of any wood-based product are all affected by the amount of water present.

To understand drying, we need to know that water is contained in wood cells in two ways: Wood can hold moisture in the cell *lumen* (cavity) as liquid or “free” water, or as adsorbed or “bound” water attached to the cellulose molecules in the cell wall. Figure 2-2 shows these two conditions. The occurrence of free water does not affect the properties of wood other than its weight. Bound water, however, does affect many properties of wood, and is more difficult to remove in the drying process.

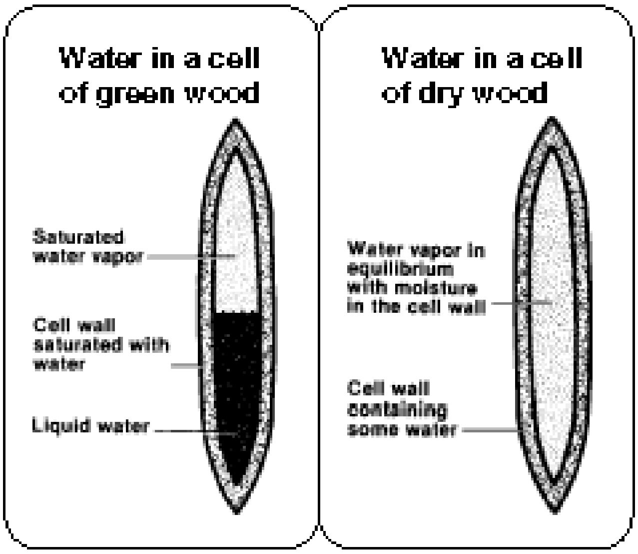

Figure 2-2 Two ways water is contained in wood.

Source: Haygreen, J.G. and J.L. Bowyer. 1996."Forest Products and Wood Science." Iowa State Univ. Press, Ames, IA. 484 pp.

Green wood is considered to be in the condition where the cell walls are saturated and lumen contains a variable amount of liquid water. During drying, free water leaves the cell lumen first. When the cell lumen is completely empty, but the cell wall remains saturated with the more tightly held bound water, wood is said to be at the *fiber saturation point* (FSP).

FSP is about 28 to 30% MC. The FSP is of particular interest because changes in shrinkage and strength occur below this point**.** It is only when bound water begins to leave the cell walls that the wood begins to shrink and its strength begins to increase. Related to wood shrinkage, the FSP is commonly considered to be 30% MC, but for strength property calculations, FSP is taken as 25%.

Actually, all wood—not in direct contact with water—gains or loses moisture by adsorption and evaporation in an attempt to reach a state of balance or equilibrium with the atmospheric conditions within which it is stored or used. This state of equilibrium depends upon the relative humidity of the surrounding air and is called the *equilibrium moisture content* (EMC).

The EMC depends mainly on the relative humidity and temperature of the surrounding air, although species and previous moisture history have a slight effect on EMC. The relationship of EMC to relative humidity and temperature is shown in Figure 2-3. If, for example, wood is kept in air at 60°C (141°F) and 65 % relative humidity, it will eventually either gain or lose moisture until it reaches approximately 10 % moisture content.

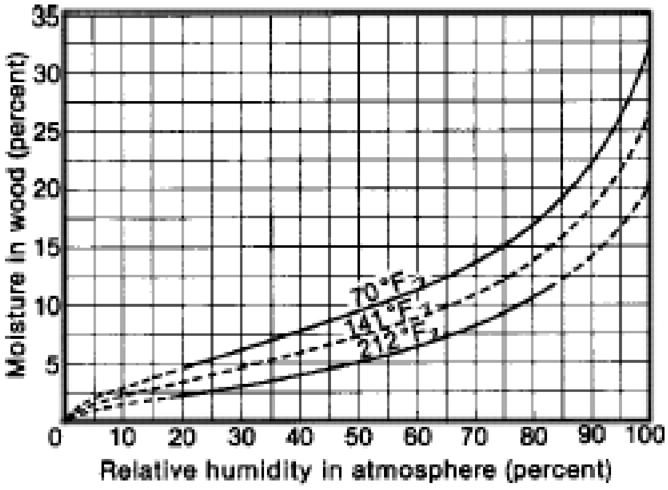

Figure 2-3 Relation of the equilibrium moisture content of wood to the relative humidity of the surrounding atmosphere at three temperatures.

Source: Simpson, W.T., et al. 1991."Dry Kiln Operator's Manual."Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

The process of drying focuses on producing wood with an MC about the same as the equilibrium value for the intended service environment. When wood is dried during manufacture, all the liquid water in the cell lumen is removed. The cell lumen always contains some water vapor, however. The amount of water remaining in the cell walls of a finished product depends upon the extent of drying during manufacture and the environment into which the product is later placed. After once being removed by drying, water will recur in the lumen only if the product is exposed to liquid water. This could result from placing wood in the ground or using it where it is in contact with rain or condensation.

2.2.3 Drying Concepts

Drying is the removal of water from wood. However, unlike many wet materials that must be dried, wood must be dried at specified rates to avoid *degrade* (value loss). If degrade were no concern, lumber could be dried in minutes.

The dimensions of a wood specimen do not vary with MC if the MC value is above the FSP (except in the case of a drying problem called “collapse”). Below the FSP, however, substantial dimensional changes occur with MC changes.

Macroscopically, the dimensional change with MC is *anisotropic* (referring to the fact that wood has very different properties parallel to the grain versus the transverse direction). As the MC decreases, wood shrinks; conversely, as the MC increases, wood swells or grows larger.

Loss of water results in changes in many of the properties of wood, such as strength and both thermal and electrical conductivity. Of perhaps greater importance is the fact that moisture loss from the cell walls (i.e., below FSP) results in shrinkage. The basic cause of drying degrade is wood shrinkage, often 5% or more.

To complicate things, wood shrinks different amounts in different directions. Shrinkage parallel to the annual growth rings *(tangential shrinkag*e) is twice as much as shrinkage perpendicular to or across the annual rings *(radial shrinkag*e). Shrinkage along the grain (vertical direction in a standing tree), also known as *longitudinal shrinkag*e, is so small—usually less than 0.1%—that it is ignored in most cases. Shrinkage along the grain is important for juvenile, compression, and tension wood where longitudinal shrinkage may be as much as 3%.

In drying from the FSP to the oven-dry condition, wood will shrink an average of 8% of its green dimension tangentially (parallel to growth rings) and about 4% radially (across the growth rings).

As wood dries, then, from the outside inward, it also begins shrinking, or trying to shrink, from the outside inward. Changes in MC result in strain and strain-induced stresses, the magnitudes of which are sufficiently large to produce configurational strain known as *warp* and *fractur*e. Specific types of warp are cup, bow, twist, and crook. Specific types of fracture are checking and splitting. Figure 2-4 illustrates various types of warp that develops in boards during drying.

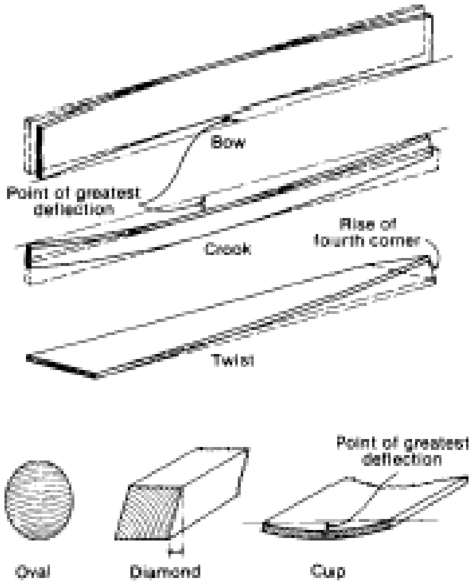

Figure 2-4 Various types of warp that develop in boards during drying.

Source: Simpson, W.T., ed. 1991."Dry Kiln Operator's Manual."Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

Because of this anisotropic shrinkage, the resultant shape of a given wood specimen after drying—compared with the green-cut shape—will depend on the original orientation of the specimen with respect to the cylindrical coordinates of the tree. The directional variations in wood shrinkage are illustrated in Figure 2-5. To minimize directional variations in use, wood needs to be dry enough to match the service environment.

Therefore, the key philosophy behind drying, as it is practiced today, is to control drying conditions so that shrinkage and resultant stresses and strains are controlled, which in turn will control degrade.

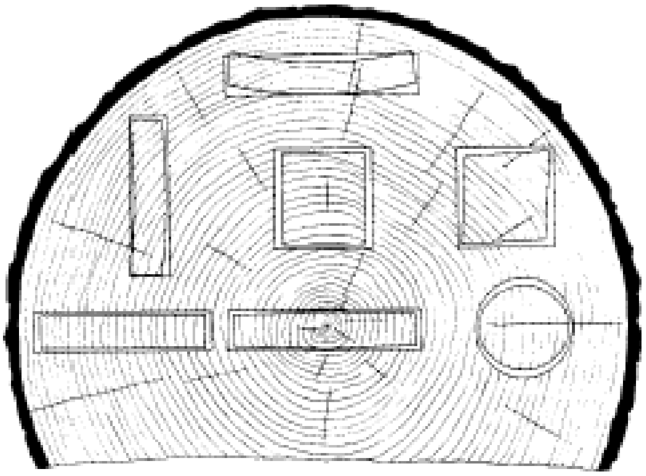

Figure 2-5 Characteristic shrinkage and distortion of flats, squares, and rounds as affected by the direction of annual growth rings. (The dimensional changes shown are somewhat exaggerated.)

Source: Simpson, W.T., et al. 1991. "Dry Kiln Operator's Manual." Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

2.2.4 Factors Influencing the Drying of Wood

The factors which will be described are those which affect wood when dried in air (in the open or in a kiln).

2.2.4.1 Vapour Pressure and Relative Humidity

To understand how wood dries in air it is necessary to introduce some terminology. When air holds the maximum possible amount of vapour, the vapour exerts what is called the saturation vapour pressure. If the water vapour present is less than this maximum then the air can take up more moisture. The ratio of actual vapour pressure to the saturation vapour pressure at any given temperature, expressed as a percentage, is called the relative humidity (RH).

When a piece of wet wood is exposed to air which is not already saturated (i.e. its relative humidity is less than 100%), evaporation takes place from its surface. At a given temperature the rate of evaporation is dependent on the vapour pressure difference between the air close to the wood and that of the more mobile air above this zone.

2.2.4.2 Temperature

The temperature of a piece of wood and of the air surrounding it will also affect the rate of water evaporation from the wood surface. With kiln drying, warm or hot air is passed over the timber and at the start of the drying process the temperature differential between the air and the wet wood will usually be large. As a result, heat energy will be transferred from the air to the wood surface where it will raise the temperature of both the wood and the water it contains. Water, in the form of vapor, will then be lost from the wood surfaces, provided the surrounding air is not already saturated with moisture. This results in the development of a moisture content gradient from the inside to the outside of the wood. As the temperature is raised this increases not only the steepness of this moisture gradient, but also the rate of moisture movement along the gradient and the rate of loss of water vapor from the surface of the wood.

To illustrate the effect of temperature on drying rate, a piece of wood with a moisture content of 16% at the surface and 40% at the core will generally have moisture gradients at 50 and 80 which are, respectively, four and eight times greater than that at 20°C.

With kiln drying, higher temperatures also increase the capacity of the air for moisture. An advantage of this is that less air needs to be heated and exhausted from the kiln. In addition, higher temperatures allow more rapid conditioning of a timber load to a uniform final moisture content.

Unfortunately the considerable benefits obtainable by raising the drying temperature cannot always be fully exploited because there are limits to the drying rates which various wood species will tolerate without degrade.

In the drying of many species, especially medium density and heavy hardwoods, shrinkage and accompanying distortion may increase as the temperature is raised. So with species which are prone to distort it is normal to use comparatively low kiln temperatures. A few species are liable to collapse and/or honeycomb if dried at high temperatures. Many tend to darken appreciably and, in resinous timbers, drying at temperatures above about 50°C causes the resin to exude on to the wood surface, although this may not necessarily be detrimental for all products or uses. Finally, since high temperature drying may cause a slight loss in impact strength, it is not advisable to exceed about 60°C when drying timber for items such as tool handles and sports goods.

2.2.4.3 Air Movement

If the air surrounding a piece of wet wood is stagnant and of small volume, it will soon become saturated and evaporation of moisture from the wood will stop. Even when there is a continuous stream of air passing over the wood, the layer of air in immediate contact with the wood will move more slowly and have a higher vapour pressure than the main stream. This is known as the 'boundary layer effect'. With increasing air velocity in the main stream this effect decreases and evaporation rates from the wood surface increase, particularly when the air flow is turbulent rather than laminar. An increase in air speed can therefore be regarded as equivalent to a reduction of the humidity barrier near the wood surfaces.

Since air passing through a stack of wet wood gives up heat and takes up moisture, it is bound to be cooler and more humid where it emerges than where it enters, and the drying rate is, therefore, slower on the air outlet than on the air inlet side of the stack. The faster the air speed and the narrower the stack, the smaller is the difference between the two sides. For this reason fairly high air speeds are desirable in a drying kiln, particularly when the timber being dried is very wet and loses its moisture readily. In most modern kilns, the uniformity of drying is further improved by reversing the direction of air flow through the kiln load at regular intervals.

2.2.4.4 Movement of Moisture in the Wood

When water evaporates from the surface of a piece of wet wood, the moisture content in the outer zone is lowered and moisture begins to move outwards from the wetter interior. In practical terms this movement of moisture can be accepted as being a combination of capillary flow and moisture diffusion, a process which is resisted by the structure of the wood, particularly in dense hardwood species. If the rate of water loss by evaporation exceeds the rate at which moisture from the wet interior can pass to the surface, the moisture gradient within the wood becomes progressively steeper. As the outer layers dry below the fiber saturation point, their tendency to start shrinking is resisted by the wetter interior so that stresses develop. If these stresses become large, they can lead to a number of drying defects.

In both air and kiln drying, the establishment of a moisture gradient is unavoidable and indeed desirable, for in any particular piece of wood at a given temperature the rate of movement of moisture up to the surface is proportional to the steepness of the gradient. The skill in timber drying lies in controlling the rate of evaporation to match the rate at which moisture is reaching the surface; the aim is to maximize the moisture gradient without damaging the timber. (www.mtc.com.my/)

2.3 Drying Method

According to Simpson, et al. (1991) although many methods of drying timber have been tried over the years, only a few of these enable drying to be carried out at a reasonable cost and with minimal damage to the timber. The most common method of drying is to extract moisture in the form of water vapor. To do this, heat must be supplied to the wood to provide the latent heat of vaporisation.

2.3.1 Air Drying or Seasoning

In air drying, sawmill products are stacked outdoors. Control of drying rates is limited, and great care must be taken to avoid degradation. The drying time is a function of the climate; in damp coastal areas wood dries slowly, whereas in arid regions, it dries rapidly.

2.3.2 Kiln Drying

Drying wood in an insulated chamber and circulating air over it is called kiln drying. For most end uses of wood, all of the free water and much of the bound water should be removed. To accomplish this in a shorter period of time, or in more humid environments, a dry kiln must be used to dry the wood. Almost all commercially produced lumber is dried in a kiln before it is finally put in use.

2.3.2.1 Pre-dryers

Commercial wood drying operations sometimes use a pre-dryer to dry green wood to a MC of around 25% before drying the wood to a lower moisture content in a dry kiln. Pre-dryers are usually referred to as a type of low temperature kiln. Temperatures typically range from 24 to 38°C, and relative humidities typically range from 60 to 90%. Pre-dryers have been used for more than 25 years in the northern latitudes of the United States where air drying conditions are unfavorable. More recently, pre-dryers have become established in other areas to shorten the air drying times of some hardwoods. Pre-dryers have controlled ventilation to regulate the drying rate. Other advantages of pre-drying over air drying are:

1. brighter lumber,
2. more uniform MC throughout the wood,
3. reduction in drying defects, and
4. one-third or more reduction in drying times.

Unless large amounts of lumber are to be dried, building, energy, and maintenance costs can make air drying a preference over a pre-dryer.

2.3.2.2 Dehumidification Dry Kiln

Dehumidifiers can be viewed as a type of low temperature wood dryer although temperatures can reach as high as 71°C. Dry kilns that operate at these temperatures are capable of drying most wood species at maximum drying rates. Dehumidification kilns can dry wood to a low MC of 5 or 6%. Dehumidification kilns operate in the following manner:

1. humidity (moisture in the kiln) is removed by condensation on the cold coils of
2. a heat pump dehumidifier;
3. liquid Freon is evaporated in the coils and then cools;
4. water is condensed from the moist air drawn across these evaporation coils;
5. the evaporated Freon gas is compressed and the pressurized gas attains
6. temperatures as high as 118°C;
7. dehumidified air is passed over the hot coils to provide useful energy for drying

8. the lumber.

Vents are not needed in dehumidification kilns, as they are in steam kilns. Vents can be used as an extra control, especially to help control temperatures in the drying cycle.

2.3.2.3 Solar Drying Kiln

The advantage of solar kilns is the free and often abundant energy available, but the disadvantage is that there is a cost to collecting free energy. This free energy is also low-intensity energy, which often limits the operating temperature of a solar kiln to about 54°C unless expensive special solar collectors are used. Another advantage of solar kilns is that relatively small, simple, and inexpensive kilns are possible, and this level of technology is often well suited to small-scale operations. Solar kilns can operate by direct solar collection (greenhouse type) or by indirect solar collection where the collector is isolated in some way from the drying compartment. They can operate with solar energy alone or with supplemental energy. There are 2 types of solar kilns:

1. **Direct collection or greenhouse**

a) Solar only, which is typified by wide diurnal (within a 24-hour period) and day to-day changes in temperature and relative humidity.

b) Solar with supplemental energy, which is typified by the ability to follow a drying schedule and has large nighttime heat losses because of the low insulating ability of the transparent cover.

2. **Indirect collection or isolated drying compartment**

a) Solar only, where the diurnal change in temperature and relative humidity can be reduced by energy storage and decreased heat losses at night.

b) Solar with supplemental energy, where scheduled drying is possible and nighttime losses are minimized. A solar kiln design for northern latitudes is shown in Figure 2-6.

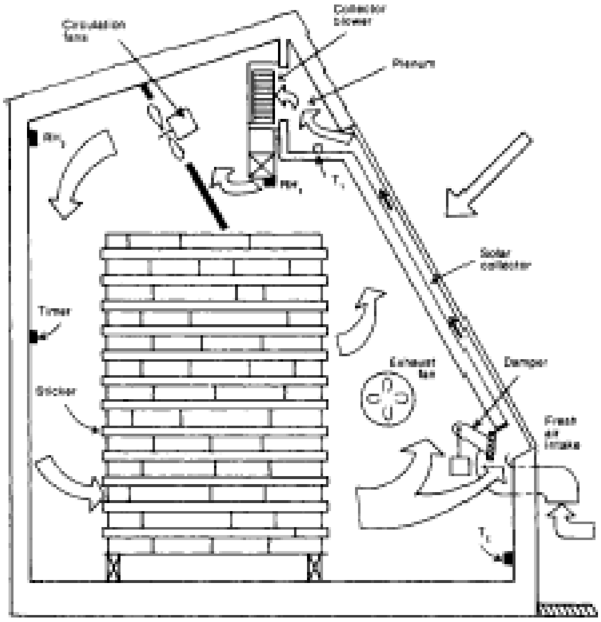

Figure 2-6 Solar kiln design for northern latitudes, showing inexpensive control system.

Source: Simpson, W.T., et al,. 1991. "Dry Kiln Operator’s Manual."Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

2.3.2.4 Steam Kiln Drying

In a steam dry kiln, fans are used to circulate air at speeds as high as 2 meters per second. Drying temperatures can reach 82°C. Heat is supplied from an oil, gas, or wood waste-fired boiler.

Although drying the wood products before shipment adds value to the product and lowers transportation costs, it can also be one of the most expensive operations in terms of energy used. The ideal situation is for a wood product mill to use its own wood waste to fire a boiler for kiln operations, thus reducing fuel costs.

Temperature and humidity are carefully controlled during the drying cycle using drying schedules designed for the species, size, and condition of the wood. It is beyond the scope of this publication to discuss individual species and drying schedules. Heated air is circulated over the wood, and the water on the wood surface evaporates, raising the humidity of the air. When the humidity of the air exceeds the level specified by the drying schedule, the warm, moist air is vented to the outside, and cool, drier air is brought in. Each time moist air is vented, all the energy from the boiler is also lost. The venting and reheating of the exchanged air consumes up to 80% of the energy required to dry lumber.

2.3.2.5 Vacuum Drying

Vacuum drying of lumber is not a new idea, and, in fact, it has been considered since the turn of the century. However, vacuum drying did not come into use until the 1970’s because it was considered uneconomical. The principal attraction of vacuum drying is that the lowered boiling temperature of water in a partial vacuum allows free water to be vaporized and removed at temperatures below 100°C almost as fast as it can at high-temperature drying at above 100°C at atmospheric pressure. Drying rate is, therefore, increased with out the dangers of defects that would surely develop in some species during drying above 100°C. Vacuum drying is essentially high-temperature drying at low temperatures. During the early 1970’s, the economic outlook for vacuum drying became more favorable, largely because of the increased costs of holding large inventories of lumber during long drying processes. This is particularly true in the drying of thick, refractory, high value species, which can be safely dried in a vacuum kiln in a small fraction of the time required in a conventional kiln.

The main difference between the several types of vacuum kilns currently on the market is the way in which heat is transferred to the lumber. Convective heat transfer in a partial vacuum is almost nonexistent. In one common type of vacuum kiln, there are alternate vacuum and atmospheric pressure cycles. Heat is applied to the lumber convectively at atmospheric pressure, and then a vacuum cycle is applied to remove water at low temperature. These cycles are alternated throughout the drying. Another common type of vacuum kiln maintains a vacuum throughout the entire drying process, and the heat is transferred to the lumber by direct contact with steam-heated platens or by electrically heated conductive blankets that contact the lumber. A third type employs high frequency electrical energy to heat the lumber. In all types, water is removed from the drying chamber by pumps (Simpson, W.T., et al., 1991).

2.3.2.6 High-temperature Dry Kilns

High-temperature dry kilns operate at temperatures of 93 to 116°C. Air velocities usually exceed 4 meters per second. Vents are usually kept closed since control of the relative humidity is not essential.

This type of kiln was developed to dry softwoods. Commercial high-temperature kilns can dry large quantities of lumber in one day. However, only a few species of easily dried hardwoods can be dried in this fashion (www.ca.uky.edu/agc/ pubs/for/for55/for55.htm).

2.4 Superheated Steam Drying

2.4.1 Definition of Superheated Steam

Steam was heated to a temperature higher than the boiling point corresponding to its pressure. It cannot exist in contract with water, nor contain water and resembles a perfect gas; --call also surcharged steam, anhydrous steam and steam gas.

2.4.2 Benefits of Using Superheated Steam(Pronyk,C and Cenkowski, S, 2003)

The use of superheated steam as a drying medium has many potential benefits to the consumer and industry:

- Use of superheated steam can lead to energy saving as high as 50 to 80% over use of hot air or flue gases. These saving can be achieved due to higher heat transfer coefficients and the increased drying rates in the constant and falling periods if the steam temperature is above the inversion temperature. The constant drying rate period is also longer in superheated steam drying thus providing high drying rates for longer period of time. These higher drying rates will increase the efficiency of the processing operation potentially leading a reduction in equipment size or an increase in output. High thermal efficiency is usually achieved only if the exhaust steam is collected and used elsewhere in the processing operation.
- Use of superheated steam as the drying medium instead of hot air means that there is an oxygen free environment during drying. That means there is no

oxidative or combustion reactions during drying (no fire or explosion hazards). The oxygen free environment also produces improved product quality (no scorching).

- Most superheated steam dryers are designed as a closed system where the exhaust may be collected and condensed. In this way toxic or expensive compounds are removed and collected before they reach the environment thus reducing air pollution. In this same way, dust from the process can be collected.
- Processing in superheated steam allows concurrent blanching, pasteurisation, sterilisation and deodorisation of food products during drying.

Even with these proven benefits utilisation of superheated steam as a drying medium is not wide spread due to a lack of understanding about superheated steam and its effect on products during drying.

2.4.3 Properties of Superheated Steam Drying

Superheated steam is steam that has been given additional sensible heat to raise its temperature above the corresponding saturation temperature at a given pressure. Unlike saturated steam, a drop in temperature will not result in condensation of the steam as long as the temperature is still greater than the saturation temperature at the processing pressure. The moisture evaporated from the product becomes part of the drying medium and does not need to be exhausted, thus allowing for recycling of the drying medium, provided sensible heat is added. When the drying process is looked at, there are some distinct differences between superheated steam and air as the drying medium. The superheated steam drying process can be broken into three distinct periods.

1. The first periods begins when superheated steam comes into direct contact with the product being dried. The superheated steam raises the product’s temperature to the boiling temperature at the processing pressure by giving the product a portion of its sensible heat. During this period if there is not sufficient sensible heat in the superheated steam, some condensation may occur on the product, or in the drying chamber.
2. The second period is the constant rate period where the internal resistance to moisture diffusion is less than the external resistance to water vapour removal from the product surface. In hot air drying, the rate depends on the convective transfer of

heat from the air to the product and diffusion of moisture from the product to the air through a boundary layer surrounding the product. However, in drying with superheated steam, the moisture does not have this diffusive resistance to movement through the boundary layer and moisture moves by bulk flow only. As well, evaporation of water into superheated steam is greater than into dry air except when the temperature of superheated steam approaches the saturation temperature. The constant rate period is longer than for air-drying under similar conditions. These properties will have an effect on the drying rate in superheated steam versus hot air drying.

3. The third period, called the falling rate period begins as the drying rate decreases and the product's temperature rises to that of the superheated steam. In this period, the internal resistance to moisture transport is greater than the external resistance. The drying rate is usually greater for superheated steam than for air drying because the product temperature is greater allowing for greater moisture diffusion in the product. As well, casehardening may not occur and the product dried in superheated steam is more porous. It has been claimed that one of the limitations for using superheated steam for drying is that products cannot be temperature sensitive because of the high temperature experienced with superheated steam processing.

2.4.4 Previous Researches

In general the drying time will be reduced up to 50% in comparison with the regular drying process. The drying quality will be maintained at the same level.

Johansson et. al. (1997) studied high temperature convective drying of single wood chip with air and superheated steam and reported that the differences between drying in air and superheated steam respectively, can be assigned to the physical properties of the drying medium. The period of constant drying rate which is comparatively short in air drying becomes more significant with increasing humidity of the drying medium and is clearly visible in pure superheated steam drying. The maximal drying rate is higher in air drying, and shorter drying times are obtained since the heat flux to the wood chip particle increases with increasing amounts of air in the drying medium. The period of falling drying rate can be divided into two parts: in the first, the drying rate is dependent upon the humidity of the drying medium whereas in the second, there is no such correlation. The influence of intergas diffusion in air drying was found to be of minor importance.

Aly (1999) replaced the conventional air-drying of milk powder with superheated steam drying. In his work, Aly operated the superheated steam in a recycle mode where evaporated water is purged and compressed in a two-stage mechanical vapor compressor (MVC). The purged compressed steam is used to boost the superheated steam temperature from the circulating exit up to the required inlet temperature of the dryer. This process helped to reduce the energy consumption of the plant.

Li, et al. (1999) studied superheated steam impingement drying of tortilla chips which were dried at different superheated steam temperatures and heat transfer coefficients and reported that the steam temperatures had greater effect on drying curve than the heat transfer coefficient within the range of study. The microstructure of the samples after steam drying showed that higher steam temperature resulted in more pore and coarser appearance. The modulus of deformation and the shrinkage of tortilla chips correlated with moisture content. A higher steam temperature caused less shrinkage and a higher modulus of deformation. Comparison of the superheated steam drying and air drying revealed that at elevated temperatures the superheated steam provided higher drying rate.

Pang and Dankin (1999) studied the drying rate and temperature profile for superheated steam vacuum drying versus moist air-drying of softwood lumber (*Pinus radiata*) and found that the superheated steam produced a significantly faster drying rate than the hot moist air.

Moreira (2001) studied tortilla chips and potato chips have been impingement dried using hot air and superheated steam and declared that at higher temperatures (above 130°C), tortilla chips dry faster when using superheated steam compared to hot air (at the same condition). Impingement drying with superheated steam can produce potato chips with less color deterioration and less nutritional losses (Vitamin-C) than drying with hot air. Potato chips dry faster at high superheated steam temperature and high convective heat transfer coefficients.

Thiam, Milota and Leichti (2002) studied the effect of high temperature drying on bending and shear strengths of Western hemlock 38 mm by 140 mm (2 in.

by 6 in.) dimension lumber and concluded that the time required to dry western hemlock lumber by conventional schedule (82°C) was 48 hours; the accelerated schedule (116°C) resulted in a drying time approximately 24 hours, a 50 % reduction and the mean bending strength or stiffness of western hemlock dried by conventional schedule and accelerated schedule had no significant.

Bekhta and Niemz (2003) investigated effected of high temperature at 100, 150 and 200°C on mechanical properties and color of Spruce wood. The results show that heat treatment mainly resulted in darkening of wood tissue and reduction of its mechanical properties.

Bengtsson and Kliger (2003) studied bending creep of dried Spruce wood and compared betwwen temperature at 115 and 70°C. They found that high temperature dried wood had smaller bending creep deformations than the low temperature dried wood.