FINAL REPORT

Pilot-Scale Superheated Steam Drying of Rubberwood

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Pilot-Scale Superheated Steam Drying of Rubberwood

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Wood and Pulp Research Program
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EXECUTIVE SUMMARY

A 2.4 m x 2.4 m x 2.4 m (13.8 m^3 or 488 ft^3) pilot-scale rubberwood drying kiln was constructed and injected with superheated steam and hot air to study the effect of the hybrid system on the drying rate and mechanical properties of the wood. A total of 300 pieces of rubberwood boards each with dimensions of 1 m long x 3 in. wide x 1 in. thick were stacked in 1 m x 1 m x 1.7 m (60 ft^3) pallet. The stack was impinged with alternating cycles of superheated steam and hot air.

For the optimum condition, the following schedule was carried out: (1) saturated steam at 100°C was used during the first 6 hours of drying to prevent the wood surface from drying too quickly while minimizing the moisture gradient between the center and wood surface, (2) superheated steam at 105°C was used in alternating cycle with hot air (80°C) during the main drying stages to rapidly remove the free water and majority of the bound water inside the wood, and (3) hot air was used continuously during the final stages of drying to reduce the relative humidity inside the chamber making it possible for the removal of the residual bound water. This process successfully reduced the drying time to less than 3 days without causing significant amount of defects which compared favorably to the conventional hot air drying process of 7 – 8 days. Moreover, results of the mechanical properties compared to the conventional drying process revealed that both the shear parallel to grain and the hardness for the superheated steam in combination with hot air drying were slightly higher than the conventional drying values, while the compression perpendicular to grain and the modulus of elasticity (MOE) were substantially higher than that of the conventional drying process indicating that the wood dried using superheated steam can withstand a high breaking force. However, the compression parallel to grain and the modulus of rupture (MOR) values were significantly lower than those from the literature. Even though these properties were lower than the conventional process, they were substantially higher than the literature values. Therefore, using superheated steam in conjunction with hot air presents a substantial saving in operating time and energy consumption compared to the conventional method while retaining the desired mechanical properties of the wood.

บทคัดย่อ

โครงการวิจัยนี้ได้สร้างเครื่องอบไม้ยางขนาดความยาว 2.4 เมตร x 2.4 เมตร x 2.4 เมตร (13.8 ลบ.ม.หรือ 488 ลบ.ฟ.)เพื่อศึกษาผลกระทบของการอบแบบผสมผสานระหว่างไอน้ำร้อนยิ่งยวดและลมร้อนต่อการอบไม้ยางพารา โดยการนำไม้ยางพารา 300 ชิ้น ที่มีขนาดความยาว 1 เมตร ความกว้าง 3 นิ้ว และความหนา 1 นิ้ว มาเรียงเป็นกองที่มีความกว้าง 1 เมตร x 1 เมตร x 1.7 เมตร (60 ลบ.ฟ.) เพื่อทำการอบโดยการสับเปลี่ยนระหว่างไอน้ำร้อนยิ่งยวดกับลมร้อน

งานวิจัยนี้พบว่า ตารางอบที่เหมาะสมที่สุดประกอบด้วย (1) การอบด้วยไอน้ำร้อนที่อุณหภูมิ 100 องศาเซลเซียส เป็นเวลานาน 6 ชั่วโมง ในขั้นตอนแรกเพื่อไม่ให้การแห้งตัวของผิวไม้เร็วเกินไป ซึ่งจะก่อให้เกิดความแตกต่างระหว่างความชื้นในตัวไม้กับตัวผิวไม้มากเกินไป (2) การอบด้วยไอน้ำร้อนยิ่งยวดที่อุณหภูมิ 105 องศาเซลเซียส สับเปลี่ยนกับลมร้อนที่ 80 องศาเซลเซียส ในช่วงหลักของกระบวนการอบเพื่อทำให้น้ำในส่วนของ free water และบางส่วนของ bound water ระเหยออกมาจากตัวไม้และ (3) การใช้ลมร้อนในช่วงสุดท้ายของการอบเพื่อลดความชื้นสัมพัทธ์ในห้องอบและทำให้น้ำในส่วนของ bound water ที่ตกค้างอยู่สามารถเคลื่อนที่ออกมาจากตัวไม้ได้

กระบวนการดังกล่าวสามารถลดระยะเวลาในการอบทั้งหมดให้เหลือต่ำกว่า 3 วัน โดยไม่ทำให้เกิดการสูญเสียท่อนไม้จากการแตกร้าวหรือการคดงออย่างเป็นนัยสำคัญ โดยทั่ว ๆ ไปแล้วการอบแบบ conventional จะใช้เวลา 7-8 วัน นอกจากนี้การทดสอบ mechanical properties x 2.4 m x 2.4 m (13.8 m^3 or 488 ft^3) พบว่าค่า shear strength parallel to grain เท่ากับ 16.22 MPa, ค่า compression parallel to grain เท่ากับ 39.9 MPa, ค่า compression perpendicular to grain เท่ากับ18.32 MPa, ค่า the modulus of rupture เท่ากับ 84.2 MPa, ค่า modulus of elasticity เท่ากับ 12678 MPa และค่า hardness เท่ากับ 56.92 N. ดังนั้นระบบการอบแห้งแบบผสมผสานจึงไม่มีผลต่อค่า shear strength parallel to grain แต่อย่างไร ในขนะเดียวกัน ค่า compression strength parallel to grain และค่า MOR มีค่าลดลง 24.23% และ 21.35% ตามลำดับ แต่อย่างไรก็ตาม ค่า MOE และ ค่า hardness มีค่าเพิ่มขึ้น 30.41% กับ16.4%.ตามลำดับ

เพราะฉะนั้นการอบด้วยไอน้ำยิ่งยวด จะสามารถลดต้นทุนทางด้านพลังงานและด้านการดำเนินการอบ โดยไม่มีผลกระทบต่อ mechanical properties ของไม้ยางพารา

ABSTRACT

A 2.4 m x 2.4 m x 2.4 m (13.8 m^3 or 488 ft^3) pilot-scale rubberwood drying kiln was constructed and injected with superheated steam and hot air to study the effect of the hybrid system on the drying rate and mechanical properties of the wood. A total of 300 pieces of rubberwood boards each with dimensions of 1 m long x 3 in. wide x 1 in. thick were stacked in 1 m x 1 m x 1.7 m (60 ft^3) pallet. The stack was impinged with alternating cycles of superheated steam and hot air.

For the optimum condition, the following schedule was carried out: (1) saturated steam at 100°C was used during the first 6 hours of drying to prevent the wood surface from drying too quickly while minimizing the moisture gradient between the center and wood surface, (2) superheated steam at 105°C and 110°C was used in alternating cycle with hot air (80°C) during the main drying stages to rapidly remove the free water and majority of the bound water inside the wood, and (3) hot air was used continuously during the final stages of drying to reduce the relative humidity inside the chamber making it possible for the removal of the residual bound water. This process successfully reduced the drying time to less than 3 days without causing significant amount of defects which compared favorably to the conventional hot air drying process of 7 – 8 days.

Results of the mechanical tests showed that the shear strength parallel to grain was 16.22 MPa, the compression parallel to grain was 39.9 MPa, the compression perpendicular to grain was 18.32 MPa, the modulus of rupture was 84.2 MPa, the modulus of elasticity was 12678 MPa , and the hardness was 56.92 N. Consequently, the hybrid drying system using superheated steam and hot air had no significant effect on the mean shear strength parallel to grain; however; the mean compression strength parallel to grain was reduced by 24.23% and the mean MOR by 21.35%. Nonetheless, the mean MOE was increased by 30.41% and the mean of hardness by 16.4%. Therefore, using superheated steam in conjunction with hot air presents a substantial saving in operating time and energy consumption compared to the conventional method while retaining the desired mechanical properties of the wood.

ACKNOWLEDGMENTS

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In addition, I would like to thank the Department of Chemical Engineering and the Faculty of Engineering at the Prince of Songkla University for providing the necessary facilities, equipment, and services. Finally, most of all, this project could not have taken place without the generous funding, helpful suggestions, and timely encouragements from the Thailand Research Fund (TRF) and its wonderful people. To all of you, thank you and I hope this project will lead to fruitful advancement of the wood drying industry in Thailand.

TABLE OF CONTENTS

CHAPTER I
INTRODUCTION

Background and Rationale

Wood from the rubber tree is the major source of timber in Southern Thailand. The tree (*Hevea brasiliensis*) is typically harvested between 25 and 35 years of its growth so that the diameter is less than 200 mm (according to a source from Asia Plywood Factory). It is delivered in short lengths (approximately 1 meter long) and, after sawing, has to be glue laminated to get useful plank dimensions.

For glue lamination to be effective, the timber must be dried. However, if the rubberwood is dried too quickly, it will split, crack, warp, cup or check due to unrelieved moisture stresses. Hence, the drying of rubberwood requires an optimum drying rate, while reducing power consumption of the process.

Timber drying is traditionally carried out using warm air. The process may be carried out in a kiln or in "stacks" of "packets" in the open air. The latter process is largely uncontrolled so that the sun's radiation or a prevailing wind can set up moisture stresses that may distort the wood. Rubberwood is usually arranged in stacks and dried in a 400-600 m^3 chambers at temperatures of 80-100°C. The drying time varies from 7 to 16 days depending on the thickness of the lumber. After several days, a mist of water droplets is introduced into the drying kiln (along the side walls) and is circulated using fans. The process helps to maintain a good moisture distribution within the boards and to reduce moisture stress by temporarily increasing the relative humidity in the chamber. If the temperature of the drying kiln is too high, the moisture stress may lead to cracking due to large moisture gradient within the board. However this method of humidity control is generally somewhat crude and inefficient. As a consequence, the desired result is not always achieved and energy usage is seldom optimal.

Therefore, the process of drying wood using the conventional air-drying method is both time-consuming and inefficient. Using a high temperature for drying can cause both the destruction of the wood structure and warping from increased moisture stress. Superheated steam drying has been studied as an alternative to air-drying. Results showed by impinging superheated steam alternately with hot air, the drying time for single board drying and multiple boards drying can be reduced to less than 2 days compared to the conventional 6 to 8 days for 1 inch thick boards (Yamsaengsung and Buaphud, 2006). More importantly, the physical and mechanical properties were not significantly affected by the high temperature of the superheated steam.

Nonetheless, the usefulness of this study cannot be concluded without performing pilot scale operations. An energy efficient and cost effective pilot scale drying kiln must be constructed and operated successfully before the application of this technology to the drying industries of Thailand. Therefore, this research is vital to the improvement of the drying process in Thailand, which in turn will allow the country to compete with regional neighbors in the wood processing and furniture making market.

CHAPTER II
LITERATURE REVIEW

2.1 Properties of Rubberwood

Rubberwood, Parawood or Heveawood (*Hevea brasiliensis*) is a light hardwood with an air-dry density ranging from 560 – 640 kg/m^3. It is grown predominately in Asia (90% of the world total) and is also found in Africa (6%) and Latin America (3%). Rubberwood is used in construction, flooring, furniture, and as a source of chipboard and pulp for papermaking. Moreover, it is considered a by-product of natural rubber or latex production (source: http://www.irrdb.com). After 25 –30 years, the trees cease to produce an economical level of latex. Thus, they are cleared and the soil is prepared for replanting. The timber from this plant is whitish yellow when freshly cut and seasons to pale cream color, often with Pinkish tint (source: ITC). The wood is easy to saw, cross-cut, plane turn, and bore, producing smooth surfaces. Before use, the timber is treated with preservatives and dried. Rubberwood has low shrinkage, making it very dimensionally stable. Tables 2.1 – 2.3 show the Appearance, Working Properties, and Physical & Chemical Properties of rubberwood, respectively.

Table 2.1 Appearance of rubberwood.

Characteristic	Description
Color	Creamy white
Structure	Uniform with excellent "timber" feel
Texture	Moderately course but even
Grain Pattern	Very little (mostly straight to shallowly interlocked)
Sapwood	Not distinct
Figure	Cross section shows vague concentric markings with resemble growth rings. The marking s combined with the large vessels visible to the eye gives the timber an attractive appearance.

Table 2.2 Working property of rubberwood.

Property	**Description**
Machine Nailing	Easy to saw, machine, plane, turn, and bore. The resultant surfaces are fairly smooth
Wood Bending	Moderate wood bending properties. With a 25 mm thickness, the bending radius is approximately 500 mm. After setting, the bends are very stable.
Staining	Due to its light color and very uniform structure, the wood can be stained easily to any desired color and finish.
Chemical Applications	Resistant to many fungal, bacterial and mould attacks. Absence of dead knots, stains, fungi, sapwood and discoloration. Generally, wood preservative chemicals are added via **Vacuum Pressure Impregnation**. For example, 'Disodium Octaborate Tetrahydrate', commercially known as (Timbor), effectively protects the lumber from insect and termite infestation.

Table 2.3a Physical and chemical properties of rubberwood.

Property	**Description**
Average Air Dry Density	560 – 640 kg/m^3 at 16% MC (moisture content dry basis)
Density at 12% M.C.	600 – 620 kg/m^3 (light)
Relative Density	0.63 – 0.66 (Moderately heavy timber)
Modulus of Elasticity	9,700 N/mm^2 at 12% MC
Static Bending	66 N/mm^2 at 12% MC
Shear Parallel to Grain	11 N/mm^2
Volume shrinkage	Negligible (comparable to Dark Red Meranti) **Tangential Shrinkage Coefficient**: 1.2% **Radial Shrinkage Coefficient**: 0.8%
Chemical Composition	Similar to hard wood, but has a higher content of extractive compounds, starch and soluble carbohydrates.
Weight	Comparable to Oak and Teak with a density of 0.55 to 0.65 g/cm^3
Strength	Fairly good, Binding strength at 65 N/mm^2
Compression Strength	**Parallel to Grain**: 32 N/mm^2 **Perpendicular to Grain**: 4.69 N/mm^2
Effective Substitute for	Asian Ramin, Meranti, Agathis, Merbau, Kapur, Teak, African Sapelli, Iroko, Kosipo & Obeche, Latin (South) American Imbula & Virola, Lauan, Nyatoh

Table 2.3b Strength of rubberwood.

Property	Description	
Green Density	682 kg/m^3	
Hardness	On tangential surface On radial surface On end surface	485 kgs 590 kgs 975 kgs
Compression Parallel to Grain	Average compressive strength Type of failure	620 kg/cm^2 Crushing
Static Bending Test	Average flexural strength Type of failure	734 kgs/cm^2 Simple tension
Sheer Parallel to Grain	Average sheer strength along radial face Average shear strength along tangential surface	88.6 kg/cm^2 115 kg/cm^2
Nail Withdrawal Strength	Average load on radial face Average load on tangential face Average load on cross surface	145 kg 204 kg 140 kg
Screw Withdrawal Strength	Average load on radial face Average load on tangential face Average load on cross surface	310 kg 400 kg 200 kg
Tensile Perpendicular to Plane	Average tensile strength along radial surface Average tensile strength along tangential face	44 kg/cm^2 55 kg/cm^2
Tensile Parallel to Grain	Average tensile strength	1267 kg/cm^2

Source: Adapted from http://www.bnswood.co.th/profile.htm.

2.2 The Wood Drying Process

Before wood boards can be used to make furniture or in construction, it but be dried to approximately 8 – 16% MC (moisture content dry basis) to increase the physical properties of the wood and prevent the growth of microorganisms. Generally, there are categories of drying: the commonly used procedure of air-drying and kiln-drying, and the specialized techniques using chemicals, solvents, vacuum retorts, solar energy dehumidifiers, high frequency generators, etc. (Bousquet, 2000).

Drying is the removal of water from wood; however, unlike many wet materials, wood must be dried at specified rates to avoid *degradation* of the material. The dimensions of the wood specimen do not vary with MC above the Fiber Saturation Point (FSP), but substantial dimensional changes do occur below the FSP. Macroscopically, the dimensional change with MC is *anisotropic* (referring to the fact that wood has 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. The loss of water changes many of the wood properties, such as strength and both thermal and electrical conductivity. More importantly, the loss of moisture from the cell walls (i.e., below FSP) results in **shrinkage**. To complicate things, wood shrinks different amounts in different directions. Shrinkage parallel to the annual growth rings (*tangential shrinkage*) is twice as much as shrinkage perpendicular to or across the annual rings (*radial shrinkage*). Shrinkage along the grain (vertical direction in a standing tree), also known as *longitudinal shrinkage*, is so small – usually less than 1.0% – that it is ignored in most cases. In drying from FSP to the over-drying condition, wood will shrink an average of 8% tangentially and 4% radially (Bousquet, 2000).

Furthermore, as wood dries from outside inward, it also begins to shrink. The changes in MC result in strain and strain-induced stresses which lead to ***warp*** or ***fracture***. The special types of warp are cup, bow, twist, and crook. Specific types of fracture are checking and splitting. 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 degradation of the wood.

Figure 2.1 through 2.4 illustrate the directional variations of wood shrinkage and the different types wood deformation (source: Wengert and Meyer, 1993).

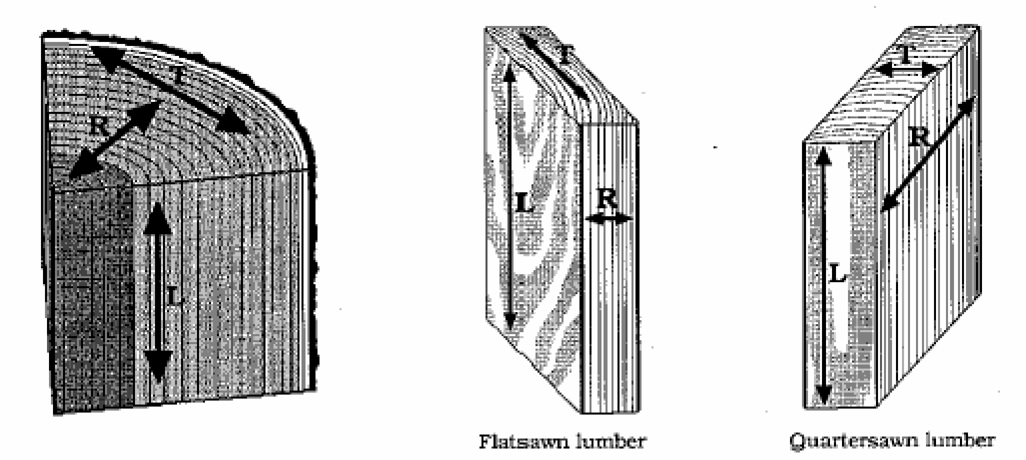
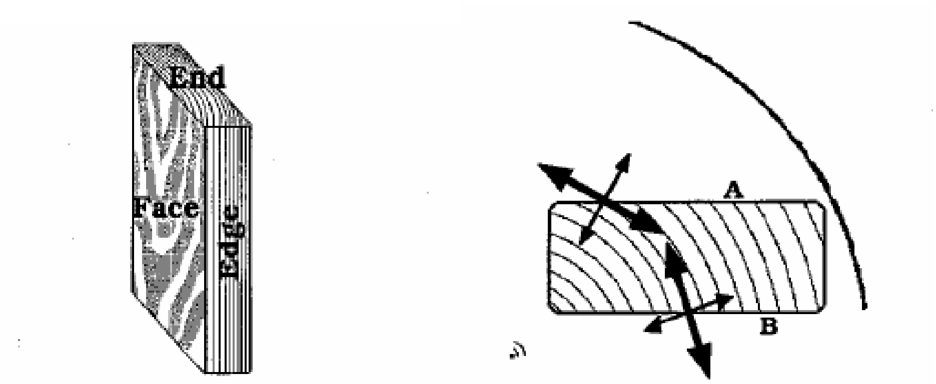


Figure 2.1: Shrinkage directions in wood: L = Longitudinal, R = Radial, T = Tangential.



(a) **(b)**

Figure 2.2: (a) The different surfaces of lumber are referred to as ends, edges, and faces, without regards to grain pattern. (b) Radial and tangential shrinkage directions in relation to the original board's original position in the tree. The large arrows represent tangential shrinkage and the small arrows represent radial shrinkage. A = bark face, or sap face; B = heart face.

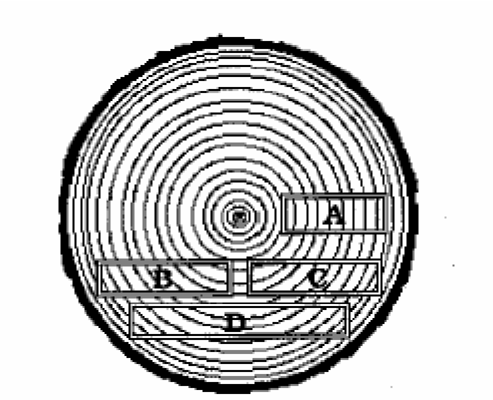
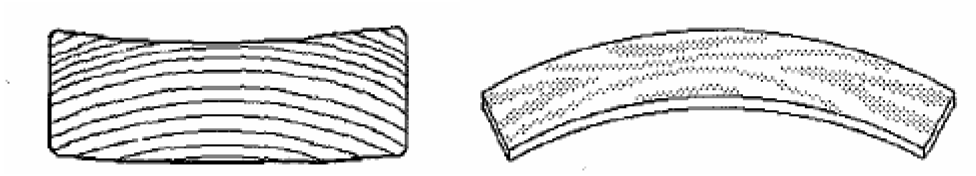


Figure 2.3: Boards A, B, and C are susceptible to crook, or side bend, while board D is not since both edges are equidistant from the core, and the rings are centered, edge-to-edge.



(a) **(b)**

Figure 2.4: (a) End view of a cupped, flatsawn board. (b) Face view of a crook board where one edge shrinks more, longitudinally, than the other.

2.3 Why Wood is Dried

There are many reasons to dry wood. Some of the major reasons are discussed below.

1. Minimize changes in dimension:

Since wood will shrink and swell with changes in MC, it is dried to the desired MC and then placed in a reasonably stable environment. Further changes in dimension will be undetectable.

2. Improve strength properties:

Increase in strength properties begins when the FSP is reached, except for toughness or shock resistance which decreases.

3. Prevent stain and decay:

Usually, fungal attacks are limited when wood MC is 20% or less. Infected wood is sterilized at 66°C or greater. Wood can be re-infected if rewetted. No insect attack occurs at 10% MC or less, except for dry wood termites and some beetles.

4. Prepare for further treatment:

- **Gluing**: Wood needs to be stress free, with no checks or splits. Examples of target MCs are:
  - Laminated timber: 10 – 12% MC
  - Softwood plywood: 3 – 5% MC
  - Furniture, interior millwork: 6 – 8% MC
- **Preservation:** Specifications for treatment of various wood products by pressure processes have been developed. Specification limits include pressures,

temperatures, and time of conditioning and treatment to avoid conditions that would cause damage to the wood. They also contain minimum requirements for handling wood after treatment to provide quality product.

- **Fire retardants:** To meet the specifications in the building codes and various standards, fire-retardant-treated lumber and plywood is wood that has been pressure-treated with chemicals to reduce its flame-spread characteristics. Various target MCs are part of the specifications.
- **Paint and finishes:** The recommended MC for wood used in exterior applications varies somewhat depending on climatic conditions. The safe range is generally from 9 – 14% MC. If the MC exceeds 20% when the wood is painted, the risk of blistering and peeling is increased.
- **Reduce product weight:** Shipping cost by rail and truck are controlled by the weight of the product. Kiln drying is highly preferred over air drying when the following are considered.
    - maintain shipping schedule
    - reduce drying costs in some cases due to land rent and financial charges connected with air drying
    - attain a low MC (e.g. below 12 to 15%).

2.4 Transport Phenomena during Wood Drying

In terms of fundamental knowledge of the drying process, heat and mass transfer at the surface are known to determine the *initial rate* of drying. Later, after the surface water is removed, the rate of drying is controlled by the rate at which moisture diffuses to the surface of the wood. This period is referred to as the *falling rate* of drying. As drying proceeds, the initial rate of drying gradually decreases until the cellulose of the wood comes to equilibrium with the drying air above it. The initial high rate can be increased by the following:

1. Reducing the humidity of the drying medium
2. Increasing its turbulence over the surface

The ***rate of moisture diffusion*** through the wood can be increased by

1. Raising the temperature of the wood
2. Ensuring that all moisture is evaporated from the surface exposed to the drying medium
3. Ensuring that the bordered pit structure between the cells is open

If the temperature is raised too high, (or the operating pressure is reduced), the water in the pores of the wood reaches its boiling point. The sudden phase change usually destroys the cell structure. *Ptylosis* is the process by which the lignins in the wood harden and seal the bordered pit structure. It starts as soon as the tree is cut. In general, steaming the wood with wet saturated steam keeps the pit structure open. If this is followed by drying, very high rates can be achieved without damage occurring from the moisture stress. This is because moisture is able to move freely between the cells.

In order to understand the transport phenomena during the wood drying process, the following terminologies are presented below followed by the discussion of the movements of moisture in wood and the stages of the drying process.

2.4.1 Moisture in Wood

The amount of moisture contained in a freshly cut green lumber can vary considerably from one species to the next. The average moister content ranges from 72% MC in Western white birch to 175% MC in Black cottonwood. At the cellular level, moisture can exist in wood cells in three forms:

1. As liquid in cell cavities or the lumen (**Free Water**)
2. As water vapor in the air of the cell cavities not totally filled by free water
3. As chemically bound water (**Bound Water**) absorbed by the cell wall structure.

Wood with a higher specific gravity will typically have thicker cell walls and smaller cavities. Wood materials are considered hygroscopic and consist of bound water. During most conventional drying processes, i.e. oven drying and frying, the removal of bound water causes shrinkage of the material. Figure 2.5 shows the differences between hygroscopic and non-hygroscopic material. The hygroscopic material on the right contains interstitial bound water within the solid structure, while the non-hygroscopic material in the left does not.

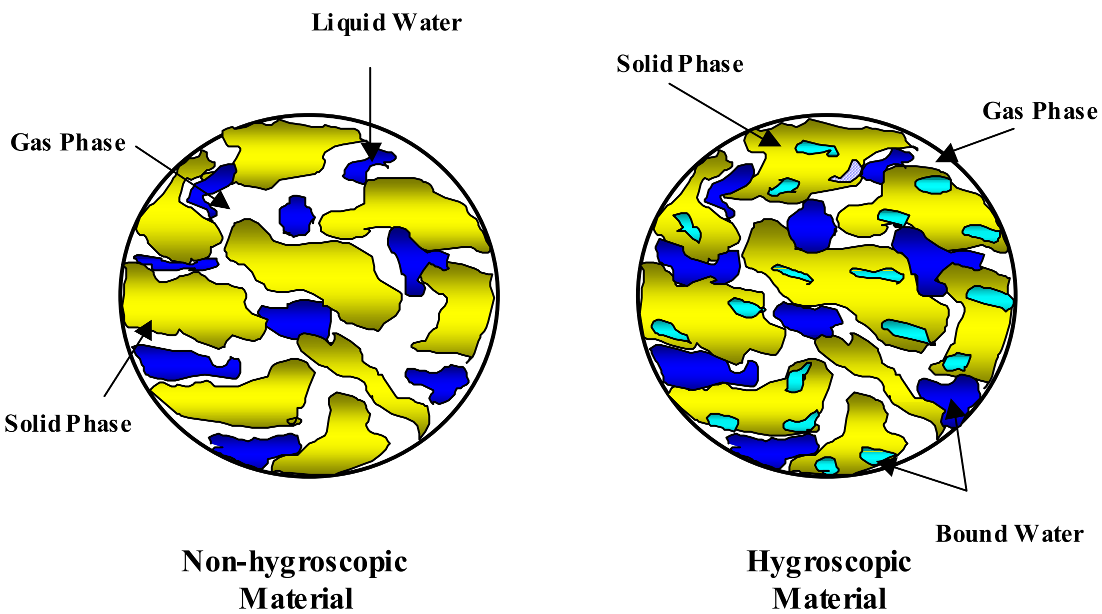


Figure 2.5: Schematic of hygroscopic and non-hygroscopic material.

2.4.2 Moisture Content

The lumber industry defines the moisture content as the weight of water held in the wood expressed as a percentage of the weight of the oven-dry wood (Bone Dry Weight). More typically, it is expressed as the amount of water contained in the wood divided by the oven-dry weight and multiplied by 100. This value is known the moisture content dry basis and is represented by the initials MC in this research. The equation for calculating MC is shown below.

$$MC(\%) = \frac{(wet\ weight - oven\ dry\ weight)}{oven\ dry\ weight} x(100) \qquad (Eq.2.1)$$

Even though not very common, the moisture content value sometimes can be expressed as wet basis, or the amount of water contained in the wood divided the total wet weight of the wood. Equation 2.2 shows the definition of MC wet basis (w.b.) and Equations 2.3 and 2.4 illustrate the conversion from % dry basis (% d.b.) to % wet basis (% w.b.). To prevent confusion, the symbol MC in this research refers specifically to the moisture content dry basis.

$$MC(\%) = \frac{(wet\ weight - oven\ dry\ weight)}{weight\ weight} x(100) \qquad (Eq.2.2)$$

$$MC(\%\ w.b.) = \frac{MC(\%\ d.b.)}{100 + MC(\%\ d.b.)} x(100) \qquad (Eq.2.3)$$

$$MC(\%\ d.b.) = \frac{MC(\%\ w.b.)}{100 - MC(\%\ w.b.)} x(100) \qquad (Eq.2.4)$$

2.4.3 Fiber Saturation Point (FSP)

The fiber saturation is a key concept for understanding the drying of lumber. Key points to consider about the fiber saturation point are:

1. The FSP is defined as the level of moisture content at which the cell wall is fully saturated with bond water but no free water is present in the cell cavity.
2. For practical purposes, the FSP is generally considered to be 30%.
3. The FSP is a concept based on the cellular level – an entire piece of wood cannot be at the FSP.
4. The cell walls, in a fully saturated state, will not shrink. Shrinkage commences below the FSP.
5. Above the FSP, there is practically no change in cell volume and strength.

2.4.4 Movement of Moisture in Wood

The movement of moisture in wood is the result of two fundamental processes: **capillary action** and **diffusion**. These processes act simultaneously to move liquid water and water vapor. The following concepts are considered to help describe this capillary action phenomenon:

1. Capillary action acts on the free liquid in the cell cavities
2. It is similar to the effect of sucking water through a straw
3. Causes the free water to be pulled through the cavities and openings ("pits") in the cell walls
4. Moisture movement is relatively fast and easy compared to diffusion
5. If the capillary action is to strong, it can "collapse" the wood cells
6. Capillary action plays a larger role in the early stages of drying.
7. Capillary action increases with the permeability of the wood and temperature.
8. Capillary action requires the least energy and is the most rapid form of moisture movement.
9. It requites a continuity of water from the surface to the core of the lumber.

Diffusion, on the other hand, plays a larger ole in the latter stages of drying, or the falling rate period. The mechanisms of diffusion are listed below:

1. Diffusion occurs both across the cell cavity and through the cell walls.
2. The driving force behind diffusion is a differential in vapor pressure.

3. Moisture will move from an area of high concentration (high vapor pressure) to an area of low concentration (low vapor pressure).
4. Diffusion does not require a continuity of water from the surface to the core of the lumber.
5. Bound water moves through the pores of the wood via diffusion.
6. The removal of bound water from the surface of the wood cavities requires humidity below that of the FSP

2.4.5 Stages of Drying

During the drying process, the rate of moisture removal varies significantly. This change in the moisture content causes a moisture gradient to develop within the lumber leading to the development of internal stresses.

1. Early stages of drying

When freshly sawn lumber is allowed to dry, the moisture content of the outermost cells of wood drops below the fiber saturation point. The outermost cells begin to shrink and as drying progresses, more cells will start to shrink. While the internal fully swollen cells resist the pulling together of the shrinking cells (tension forces), the cell at the core of the lumber are put under compressive forces from the shrinking shell. As drying continues, the tension forces in the shell can exceed the elastic limits of the wood and the cells will develop “tension set” and further shrinkage of the shell will be temporarily resisted. This is commonly called casehardening. If tension forces continue to increase, they may exceed the strength of the wood and result in a rupture of the wood called a check. Wood is particularly susceptible to checking in the early stages of drying if the rate is too high, leading to weakening of the wood. Therefore, it is important to keep temperatures relatively low and humidity relatively high.

2. Approaching 30 percent average moisture content

As the average moisture content of wood approaches 30 percent, the cells in the core of the lumber begin to dry below the FSP. As these cell shrink, they allow the cells in the shell to pull together, relieving the tension forces that were built up during the early stages. If no pre-existing checks are present the relative humidity can begin to be lowered. Once the core cells begin to shrink, the stresses that were set up during the initial stage of drying begin to reverse. The shell develops compressive stresses and the core develops tension stresses because the shell resists shrinkage of the core. Temperatures are typically not increased until the average moisture content drops below 30%.

3. Final stages of drying

As the moisture content decreases below 30%, the wood becomes stronger and the core continue to lose moisture. At this point, it is safe to increase the temperature and the decrease the humidity to maintain an acceptable drying rate. A maximum temperature and minimum humidity are generally set at 71°C and 25% to 31% relative humidity.

The final stage of drying involves equalizing the moisture content within the wood to relieve the drying stresses. Equalizing requires raising the humidity to a level that will continue to promote drying but will prevent over-drying. The ***conditioning*** step is required to relieve the compressive stresses that were developed in the shell after stress reversal. This requires elevated temperature and humidity to effectively relieve stresses without raising the average moisture content significantly.

2.5 Drying Technology

2.5.1 Conventional Drying Techniques

- **Air Drying –** Wood is exposed to the outside environment, possible protected only from direct rainfall with portable roofs or by a shed.

- **Forced Air Drying –** Wood is exposed to the outside environment, but fans are used to provide circulation in addition wind. Wood is also protected from rainfall.

- **Low-Temperature Drying –** Wood is exposed in a building, with temperatures as high as 54°C, but usually between 26 and 43°C. Humidity may be partially controlled using vents. Circulation is provided by fans with an average velocity of about 500 feet per minute (fpm). There are three types of low-temperature dryers: (1) solar-heated or solar dryer: low cost; (2) dehumidifier dryer: very good control system, but expensive; and (3) steam-heated dryer: medium cost, but control is usually not as precise.

- **Conventional Kiln Drying –** Wood is exposed in a permanent, insulated structure with temperatures as high as 93°C, with humidity control provided by steam spray and vents. Circulation is provided by fans with velocities from 250 to 400 fpm. (The word "kiln" drying can be used for both low- and high-temperature drying.) An example of a typical rubberwood drying factory is shown in Figures 2.6 through 2.11.

- **High-Temperature Drying –** Wood is exposed as in kiln drying, except the temperature range is 100 to 115°C and research has been conducted at temperatures above 148°C. Velocities are usually above 800 fpm.

Figure 2.6: Woods are sawn into 1 meter long pieces.

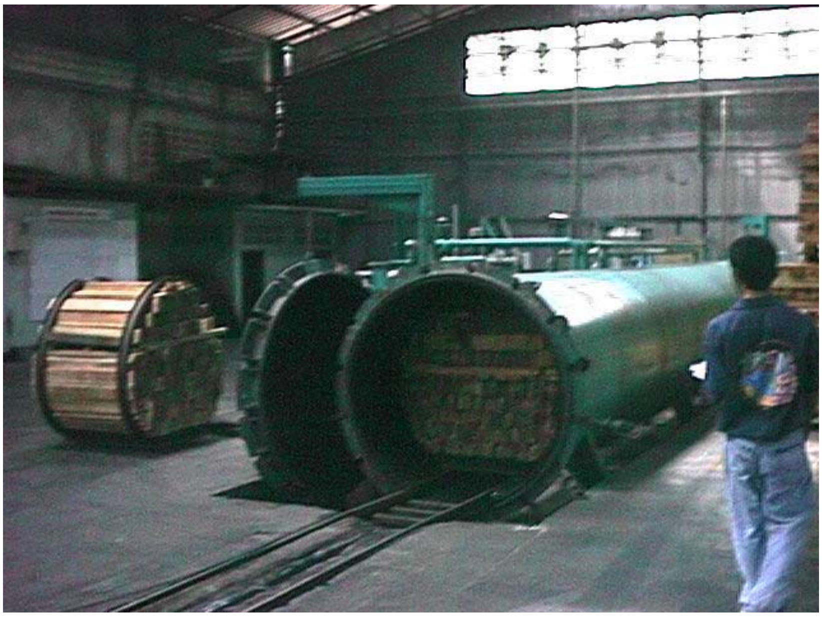


Figure 2.7: Treatment of lumber with boron salt to prevent insect attacks.

Figure 2.8: Treated lumbers are stacked and prepared for drying.

Figure 2.9: Stacks of lumber are placed in the drying kilns and dried at 80-100°C.

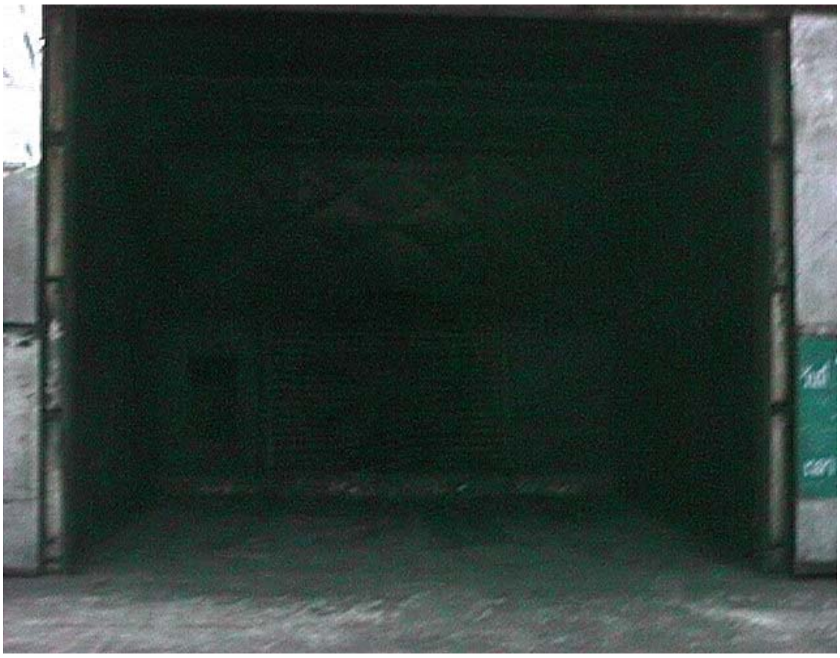


Figure 2.10: Drying takes about 7-16 days depending on the thickness of the lumber.

Figure 2.11: A typical boiler: steam or vapor mist is regularly injected into the chamber to reduce moisture stress.

2.5.2 Specialized Drying Techniques

• **Dehumidification Drying –** The majority of the water is condensed on the coils of dehumidifier and removed as liquid during the drying process, rather then being vented to the outside atmosphere. Dehumidification kilns have several advantages: (1) a boiler may not be required, except for relieving stresses during conditioning and for warm-ups of the kiln; (2) they are more energy efficient; (3) they offer good control in drying refractory (difficult-to-dry) species that require a low initial dry-bulb temperature as well as high relative humidity; and (4) a low cost kiln structure is adequate for some applications. Despite the advantages, there are several disadvantages with this type of dryer. They are as followed: (1) dehumidification kilns operate primarily on electrical energy, which in some regions may be more expensive that gas, oil, or wood residue; (2) the maximum temperatures are limited to about 71°C and in some units to only about 49°C; and (3) there may be concern over chemicals in the condensate. Finally, it is very important to properly size the compressor, because if the compressor is too small, there is a risk of stain, increased warp, and checking. If it is too larger, the humidity in the kiln can cycle excessively, possibly resulting in a lack of heat.

• **Solar Drying –** The advantage of solar kilns is the free and often abundant energy available. However, there is a substantial cost to collect free energy. This free energy is also low-intensity which often limits the kiln temperature to about 54°C, unless expensive solar collectors are installed. Another advantage to solar kilns is the fact that small inexpensive dryers can be built, which is ideal for small-scale operations.

• **Vacuum Drying –** Prior to the 1970s, vacuum drying was considered uneconomical. Since then, the economics of vacuum drying have become more favorable, especially for drying thick, refractory, high-value species. The most attractive advantage of vacuum drying is the lowered boiling temperature of water in a partial vacuum which 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. The main difference between the several types of vacuum kilns is the way in which heat is transferred to the lumber. Air is effectively eliminated as the heating medium during the vacuum period, and without heat the diffusion of moisture through wood is extremely low.

• **Microwave Drying** – Microwaves have also been used to heat the wood structure while the pressure is reduced to evaporate the water. However, this must be very carefully controlled if the phase change inside the wood is not to be destructive. In general, only exotic woods in the form of veneers are commercially dried using microwaves.

- **Superheated Steam Drying –** Superheated steam can also be used as the drying medium. "Superheated" steam may be produced by dropping the pressure at the end of the steaming operation or by the vapor-recompression of low quality steam coming out of another process. Because of the reduced opportunity for tannins to oxidize, the color of the wood is maintained through steam drying.

2.6 Past Works using Superheated Steam Drying

Douglas (1994) used steam to dry paper. He found that for paper made from mechanicals pulps, drying in superheated steam produced better bonded sheet. The added strength was accompanied by a lower scattering coefficient and improved surface properties. Moreover, the drying rate achieved using superheated steam was found to be about twice as high as that achieved with air.

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

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.

Furthermore, Li, Seyed-Yagoobi, Moreira, and Yamsaengsung (1999) found that superheated steam produced a faster drying rate for tortilla chips at elevated temperatures compared to air-drying. For the food material, steam-drying did not cause severe oxidation and burned regions like the air did. Hence, it may be possible for superheated steam at intermediate to high temperature (140-180°C) to not cause much discoloration of the lumber.

In wood drying, Taylor (1985) found that superheated steam drying under atmospheric conditions (118ºC) required less drying time than using high temperature drying for Southern Pine. However, the resulting mechanical properties were not presented.

Moreover, in Germany, Welling and Riehl (2000) studied the effect of steaming robinia or Black Locust (*Robinia psuedoacacia*), which is a medium dense hardwood. The investigator found that using superheated steam vacuum drying (SSV) conditions with temperature ranging from mild (60 – 75ºC) to severe (80 – 90ºC) can result in drying time between 5 and 2 days. This is a 70- 75% reduction in drying time; however, this drying technique resulted in unwanted green/yellow color and in effective conditioning technique has not been developed. Moreover, the researcher found that using high pressure steam treatment temperatures ranging from 100 – 140ºC (maximum vessel pressure of 13 bar) can produce the desired brown colors while also reducing casehardening defects as a final conditioning stage of drying.

Oil and other heat transfer fluids can also be used to convey heat into the wood. If the heating is the followed by pressure reduction, water will vaporize as it leaves the wood and can be easily separated from the heat transfer fluid, thus allowing the fluid to be recycled. All of the processes listed have been tried and operated. Several are the basis of patents while others are in commercial use.

Most recently, Yamsaengsung and Buaphud (2006) studied the drying of rubberwood using superheated steam. The researcher constructed an elliptical vessel 1.2 m long and 0.5 m in diameter drying kiln and injected it with superheated steam to test the effect of superheated steam on the drying of rubberwood. Pieces of boards with dimensions 1 m long x 1 in. thick x 3 in. wide were impinged with alternating cycles of superheated steam and hot air at ratios of 6:1, 4:1, and 1:6 hours until the moisture content was less than 15% dry basis. For the optimum condition, the following schedule was carried out: (1) saturated steam at 100°C was used during the first 4 hours of drying to prevent the wood surface from drying too quickly which minimized the moisture gradient between the center and wood surface, (2) superheated steam at 105°C and 110°C was used in alternating cycle with hot air (80°C) during the main drying stages to rapidly remove the free water and majority of the bound water inside the wood, and (3) hot air was used continuously during the final stages of drying to reduce the relative humidity inside the chamber making it possible for the removal of the residual bound water. This process successfully reduced the drying time to less than 2 days without causing any defects which compared favorably to the conventional hot air drying process of 7 – 8 days. Moreover, results of the mechanical properties for the optimum condition showed that the shear-parallel-to-grain was 13.46 MPa and the compression strength parallel-to-grain was 37.73 MPa, both of which were higher than the literature values. Thus, using superheated steam in conjunction with hot air presents a substantial saving in operating time and energy consumption compared to the conventional method while retaining the desired mechanical properties of the wood.

2.7 Research Objectives

1. Design and construct a 12 m^3 (420 ft^3) drying kiln chamber that can be injected with hot air and superheated steam.
2. Determine the rate of drying for a small batch of rubberwood.
3. Determine the optimum drying schedule for the batch process.
4. Determine the effect of drying process on the structural changes of the wood. This includes measuring strengths, toughness, and color after the drying process.
5. Propose a feasible drying process that utilized superheated steam for the drying industry of Thailand.

2.8 Methodology of Research

1. Carry out additional literature review regarding plant size operation, such as control, loading, and unloading.
2. Design the most efficient heating coil arrangements and heat transfer method.
3. Design a 12 m^3 or a 420 ft^3 drying kiln (3 m x 2 m x 2 m) that can be injected with hot air and superheated steam.
4. Perform batch drying experiments using combinations of superheated steam (110ºC at 1 atm) and hot air (90ºC).
5. Determine the optimum drying condition that results in physically acceptable pieces of wood.
6. Measure the mechanical properties, such as the tensile, compressive, and flexural strength of the resultant timber.
7. Determine the optimum drying rate that does not reduce the strength or appearance of the rubberwood.
8. Estimate the energy costs and conduct an economic analysis and make recommendations to the industry for possible implementations.
9. Complete a full report containing results and discussions.

CHAPTER III

DESIGN, CONSTRUCTION, AND OPERATION OF THE SUPERHEATED STEAM DRYING KILN

3.1 Parameters for Determining the Design

1. The Drying System – the capacity of the drying kiln should be able to hold a stack of rubberwood boards approximately 1 m wide x 1 m long x 1.2 m tall. The walls of the chamber should be able to withstand high temperatures of up to 200ºC and pressure up to 2 bars. Moreover, the walls should be insulated to prevent excessive heat loss and the chamber cover should be tightly sealed to prevent any leakages. Thus, the size of the drying kiln was approximated to be at least 2 m wide x 3 m long x 2 m tall.

2. Source of Steam – due to the high cost of boiler construction, the boiler located in the Department of Chemical Engineering, PSU, was used. Unfortunately, since the drying kiln has to be built outside the building, a steam line was constructed to carry the steam from the boiler to the drying kiln.

3. Source of Air – a high pressure blower was installed next to the heater to blow hot air into the drying kiln.

4. Production of Superheated Steam – an electrical heater should be used to superheat the steam up to 180ºC. The heater should be located near the drying kiln in order to minimize heat loss. This heater was also used to heat up the air from the high pressure blower.

5. Impingement of Superheated Steam – perforated steam pipes should be used to distribute the superheated steam onto the woods. Previous design called by impinging nozzle; however, due to excess pressure drop, standing columns of impinging perforated pipes were used.

6. Instrumentations – digital controllers should be installed to control the superheated steam temperature. Thermocouples connected to temperature switches must be inserted inside chamber for temperature measurements. The pressure gauge, temperature gauge, relief valve, reducing valve, and safety valve should be included. A vent located at the upper top of the chamber was designed to for automatic control open/close system depending on the moisture content. However, the automatic control was not set up properly and the vent had to be manually opened and closed.

7. Moisture Content Determination – wood samples were drawn from various locations within the stack for moisture content measurement. Since the wood were stacked 30 levels high with 10 boards per level, 3 samples each were drawn from levels 5, 10 and 15.

8. Temperature Measurements – ports were drilled to allow the insertion of wired thermocouples for various temperature measurements (e.g. surface of board, center of board, and drying kiln temperature. In addition, these holes must be plugged effectively to minimize condensation on the wires to travel back to the control box which could short-circuit the electrical components in the box.

9. Steam Condensate – a steam trap must be installed to remove condensation within the drying kiln.

10. Safety Precautions – there are many safety hazards associated with this operation. Firstly, all pipes, heating devices, with the drying kiln must be insulated due to their high temperatures. Next, the pressure inside the chamber must also be monitored, and safety valves and relief valves must also be installed to prevent excessive pressure buildup. Moreover, the thickness of the drying vessel must be able to withstand the pressure inside the chamber. Additionally, due to the number of electrical devices that are involved in the experiment, grounding is essential.

In addition to temperature and pressure, the dangers relating to the boiler are extremely important. The water level inside the boiler must be closely checked to prevent excessive pressure buildup inside the boiler which consequently could lead to pipe ruptures or damages of the drying vessel. The water pump must also work properly to ensure flow of water into the boiler. Furthermore, the gas tanks used to provide fuel for heating the boiler must be refilled or replaced intermittently to prevent pressure drop within the boiler, which consequently leads to reduced temperatures in the drying kiln. Finally, even though numerous safety measures will be implemented in this experiment, the most important safety precaution is the training of the operator. The researcher must be competent, alert, and well-trained for the operation of the boiler and the superheated steam drying kiln.

3.2 Design and Construction of the Drying System

Figure 3.1 presents a schematic diagram of the superheated steam drying system and the rubber board arrangement. The actual drying kiln was constructed by Patumwan Associate Co., Ltd. The drying kiln was made of SS400 steel plates 4 mm thick painted for rust protection. The size of the chamber was 2.4 m x 2.4 m x 2.4 mm tall (13.8 m^3 or 488 ft^3 in volume) with curved ceiling. A 6 kW heat exchanger was placed next to the drying kiln where a steam pipeline was linked to the boiler. Additional power lines were jumped from the faculty main line to add the needed voltage for the blowing fan and the heater. Details of the actual drying kiln can are shown in Figures 3.2 through 3.10.

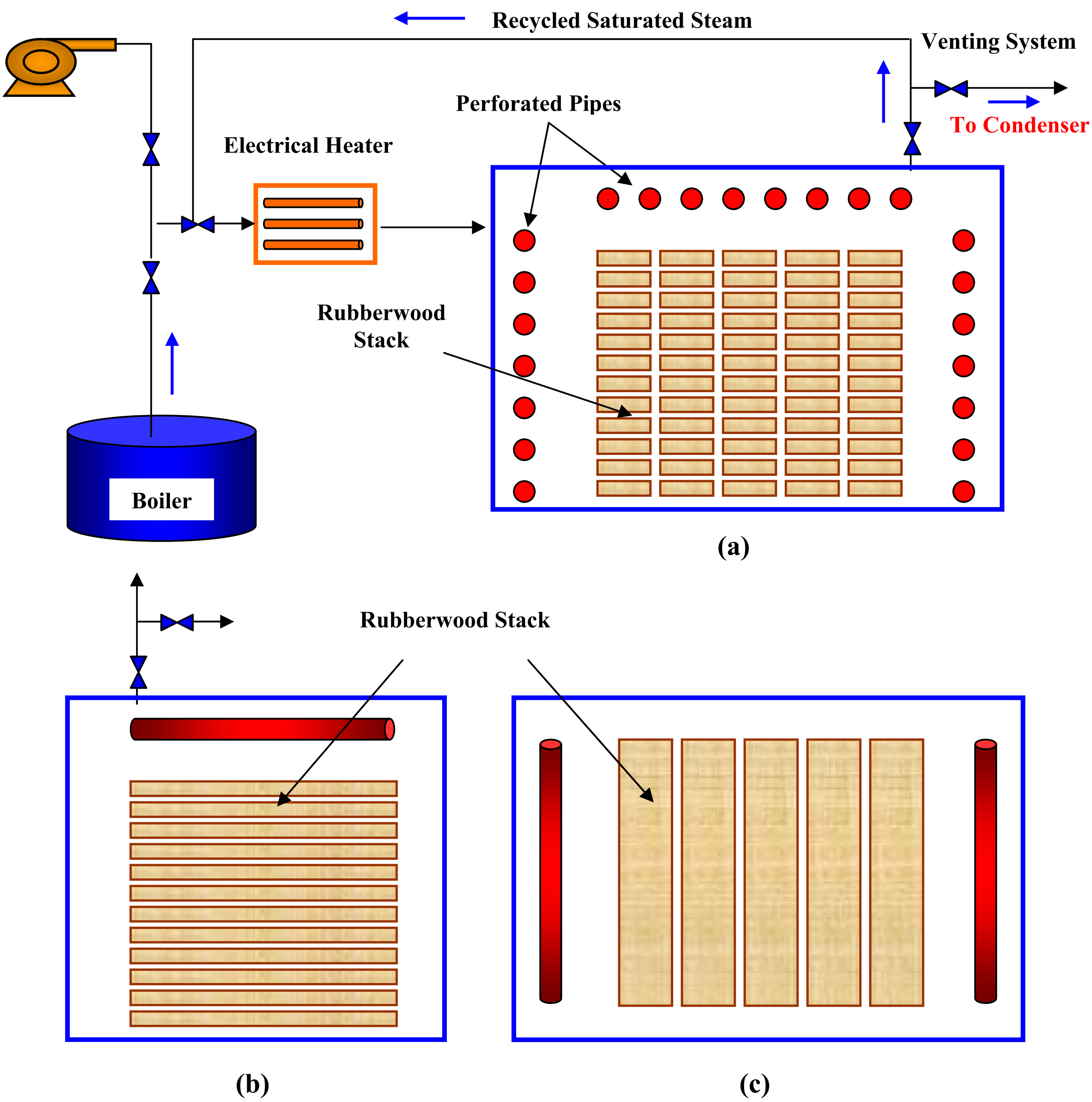


Figure 3.1: Schematic of the pilot scale drying kiln. (a) Front View, (b) Side view, and (c) Top View.

Figure 3.2: The 2.4 m x 2.4 m x 2.4 m drying kiln.

Figure 3.3: The drying kiln located just outside the Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University. The picture shows a steam pipe running from the boiler inside the building.

Figure 3.4: A vent located at the top of the drying kiln for removing moisture. To the right is the insertion point for thermocouples.

Figure 3.4: A super heater located next to the piping entrance into the chamber.

Figure 3.6: A steam trap and a water drain at the bottom of the drying kiln.

Figure 3.7: Routing of the steam pipe from inside the Department of Chemical Engineering.

Figure 3.8: High pressure blower for injection air passed the superheater into the drying kiln.

Figure 3.9: The temperature switch, the power switch, and the heat exchanger temperature controller are located in the control box.

3.3 Operation of the Drying System

Operation of the drying kiln requires much attention and care. The steps in operating the equipment are listed as followed:

1. Clean the steam pipe by first opening the bypass valve and closing the global valve that leads to the drying kiln.
2. Turn on the boiler carefully to allow steam to clean out any residuals within the pipe. Make sure to check gas level and water level.

Figure 3.10: Boiler provided by the Department of Chemical Engineering, PSU.

3. Arrange the pieces of chemically treated rubberwood board in a stack. Close and lock the chamber door. (See Figure 3.11)
4. Thermocouples are placed at the bottom, middle, and top row of the stack for measurement of temperature distribution. (See Figures 3.12)
5. Close vent and turn on steam. Allow steam to flow through electrical heater and set the appropriate temperature. Usually, the temperature set point will be slightly higher that the exiting steam from the heater and much higher than the actual temperature inside the chamber due to heat loss and the humidity inside the chamber.
6. Open the vent to allow release of steam as drying proceeds. Alternate cycle with hot air according to drying table.
7. Take temperature readings from the thermocouples at intermittent intervals.
8. Remove boards at selected time interval for weight measurement to determine the moisture content.
9. Once the desired moisture content has been reached, end the drying operation.

Figure 3.11: Wood is clamped and placed inside the chamber. (This operation was done in the latter stages of the research).

(a)

(b)

(c)

Figure 3.12: Thermocouples placed at (a) top stack, (b) middle stack, and (c) bottom stack.

CHAPTER IV
EXPERIMENTAL PROCEDURES

4.1 Sample Preparations

Rubberwood boards with dimensions 1 m long x 3 in. wide x 1 in. thick were taken from Rutthapoom Parawood in Songkhla Province, Thailand. The boards were treated with chemical preservatives to prevent insect infestation and chosen for the experiments according to the following grade.

- Grade A - had no defects and were used to test physical and mechanical properties.
- Grade C - had little defects and were used to determine drying rates.

The initial moisture content (IMC) of freshly chemically treated boards was approximately 85-95% dry basis (d.b.) and the initial weight was from 2.8 – 3.6 kg.

4.2 Methods

4.2.1 Drying Rate

Samples were dried using combinations of hot air and superheated steam. These conditions taken from Yamsaengsung and Buaphud (2006) are shown in Table 4.1. The moisture content was measured at each interval to determine the drying rate and observations were made as to the physical properties of the wood, i.e. warping and cracking. If severe cracking occurs, then the drying operation may be terminated to reconsider a new drying cycle. Moreover, if after 41 hours, the moisture content of all the rubberwood boards did go below 15% d.b., a new drying schedule must also be developed.

To determine the initial moisture content of the wood, a small piece of wood was but from the board and dried at 60°C in an oven for 24 hours (modified from AOAC, 1990).

Table 4.1 Preliminary drying schedule.

Period	Description
0 – 7th hour	Start of by drying with steam at 100ºC for 4 hours followed by steam at 105ºC for 3 hours.
8 – 14th hour	Dry with superheated steam at 105ºC for 6 hours followed by hot air at 90ºC for 1 hour.
15 – 21st hour	Dry with superheated steam at 110ºC for 6 hours followed by hot air at 90ºC for 1 hour.
22 – 26th hour	Dry with superheated steam at 110ºC for 4 hours followed by hot air at 90ºC for 1 hour.
27 – 31st hour	Dry with superheated steam at 110ºC for 4 hours followed by hot air at 90ºC for 1 hour.
32 – 35th hour	Dry with superheated steam at 110ºC for 1 hour followed by hot air at 80ºC for 3 hours.
36 – 41st hour	Dry with superheated steam at 110ºC for 1 hour followed by hot air at 80ºC for 5 hours.

4.2.2 Temperature Profile

Thermocouples were placed at the center wood boards in the top, middle, and bottom level of the wood stack to measure the temperature distribution along the stack. Thermocouples were also placed at the edges of the stack to measure the temperature distribution. Temperature readings were taken using a digital reader.

4.2.3 Prong Test

The prong test was conducted as the preliminary evaluation of the development of stress inside the wood. The prong test is used by industry as part of its quality control program to assess the degree of casehardening in lumber (Fuller, 1995). Currently, commercial kiln operators are advised to follow procedures set forth in kiln manuals, which includes using a prong test. The prong test indicates only whether a stress gradient of a form that causes prong deformation exists, not the stresses within the whole board. A half-inch thick cross section of the wood was taken and cut into U-shape. If the ends of the U bend toward each other (casehardening) or away from each other (reverse casehardening), the wood was deemed unacceptable due to excessive stress buildup. Figure 4.1 shows an illustration of the prong test, while Figure 4.2 depicts wood pieces that had excessive stress buildup during the drying process.

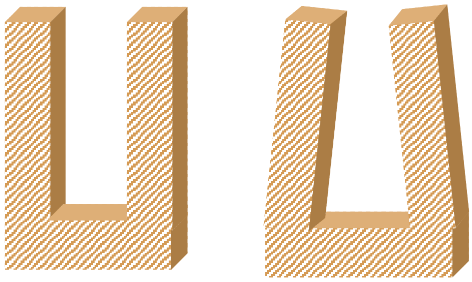


Figure 4.1: Prong test showing (a) acceptable piece of board and (b) unacceptable piece of board with excessive stress buildup.

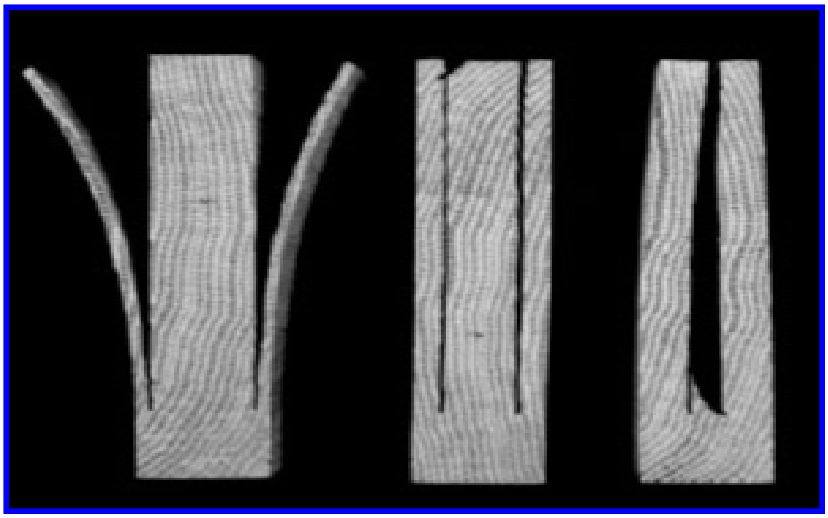


Figure 4.2: Pieces of wood showing the result of excessive stress buildup during drying.

4.2.4 Optimization of the Drying Conditions

After the preliminary drying cycle was studied, the acceptability of the product was tested using the prong test. If results were unsatisfactory, the drying operation must be adjusted accordingly. For example, if cracking surface checks or cracking occurs after the 20 hours of drying, then the temperature of the steam or hot air may be too high, or the internal stress must have developed as the drying may have been too rapid. In this case, the temperature of the steam may be lowered or the hot air period may be reduced to minimize the internal stress. Furthermore, if cracking occurs toward the end of the drying cycle, then saturated steam or superheated steam at 105°C may be used to condition to the wood boards and equilibrate the moisture gradient between the center of the wood and the surface. Finally, in order to remover the final interstitial bound water within the wood, the drying environment must be maintained at the lower humidity with hot air as the drying media. Boards obtained from these conditions were tested using the prong test to evaluate its acceptability.

4.2.5 Physical Properties Measurement

After the optimum condition was obtained, 300 pieces of wood were dried in a full stack. These woods were then sent for physical testing at Walailak University. The properties measurements included hardness, compression, shear and bending (See Table 4.2). Also, prior to testing, the boards must be cut into appropriate dimensions according to the Standards. See Appendix A for details. Figure 4.3 shows the oven for determining the moisture content of the product samples during the testing process and Figure 4.4 depicts the Lloyd Universal Testing Machine.

Table 4.2 Standard used for testing of the physical and mechanical properties using the Lloyd Universal Testing Machine at Walailak University.

Property	Standard Tests for Wood
1. Shearing Stress Parallel to Grain	BS 373 and ISO 3346
2. Compressive Stress	BS 373, ASTM 143 and ISO 3787
• Parallel to Grain	
• Perpendicular to Grain	
3. Hardness	ISO 3350
4. Strength and Stiffness in Static Bending	BS 373

Souce: Kyokong and Duangpet (2000)

Figure 4.3: Oven used for determining the moisture content of the wood samples during the physical and mechanical properties measurements.