Final Report

Microwave Heating and Impinging Hot-air for Rubberwood Drying

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Abstract

Many methods of wood drying have been tried over the years including microwave heating and impinging hot-air. In this research, drying experiment was divided into two main parts. Firstly, a potential continuous microwave heating method, and an impinging hot-air drying method have been employed to characterize efficacy of the two alternatives in rubberwood drying. The drying experiment consisted of two parts with a hot-air heating where temperature and jet flow velocity were kept at 60-80°C and 10 m/s, respectively, and a microwave heating with a maximum power input of 200W. The drying design for the 1 in. thick 46 in. long rubberwood samples with varying widths (1, 2, 3 and 4 in.) is as follows: (1) hot-air drying of 2 in. width samples at temperature of 60-80°C to evaluate the dried rubberwood properties so that the most appropriate temperature with optimum drying time with least defects could be selected to further determine the effects on different width sizes employing the same hot air drying technique, and (2) drying of the rubberwood with varying widths employing the 200W microwave. Results revealed that drying times in both methods were significantly reduced compared to those reported in conventional hot air drying process. Moreover, the natural color quality of the dried wood was superior, with modulus property, strength and hardness higher than published values. It is thus positive to assert that both methods are practicable for rubberwood drying. Secondly, an effect of combined microwave heating and impinging hot-air on rubberwood drying was investigated. A maximum microwave power level of 200W at a frequency of 2.45 GHz and hot air at 70°C was applied on the 1 in. thick 46 in. long rubberwood samples with varying widths (1, 2, 3 and 4 in.). Three replications were carried out for each test. After constant weight, the drying wood quality in physical properties was evaluated regarding occurrence of drying defects such as cup, bow and spring, colors, casehardening. The mechanical properties were also tested including bending test, compression test according to the ASTM standard D143, BS373 and ISO3787, shear strength parallel to grain according to the BS373 and ISO3346 and hardness according to the BS373 and ISO3350, respectively. In all cases, the drying time is reduced significantly to less than 8-15 h in various wood widths from initial moisture content ranges of 73%-49% to 15% of moisture level. Good quality in physical and mechanical properties of dried rubberwood were also obtained. Applying the microwave and hot air drying show that it is possible to develop a drying process for rubberwood using microwave-hot air in investigating further in this area. Finally, the experimental results obtained at pilot scale plant show the potential of hot air, microwave and combination are high energy efficiency as well as improvements in mechanical properties of rubberwood with the benefits of potential time savings to industry.

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Chapter 1

Introduction

1.1 Background and rationale

Rubber trees are cultivated in more than 30 countries in Asia, Africa and Latin America which rubber plantations around the world presently cover some 56.25 million Rais (9 million Hectares), with almost 95 percent in Asia and more than 75 percent in the three largest producer countries Indonesia, Thailand and Malaysia. In the South of Thailand, rubberwood holds the highest value accounting for nearly 90 percent of all lumber used in the furniture industry. The main use of rubberwood has been in furniture manufacturing because consumers can recognize rubberwood by its density and tight grain. Moreover the rubberwood is sometimes compared to teak, another close grained tropical wood, and some people prefer rubberwood to teak since teak is not always a sustainable choice. After that, rubberwood industry is increasingly important as it replaces more expensive wood from natural forest.

Manufacturing process in rubberwood factory is described in Figure 1-1. Rubberwood which after a 25-30 year period, latex is no longer produced by the trees, is cut down and delivered to the factory no later than 3 days after felling to reduce the chance of impurities such as fungi and insects being introduced. After milling of the wood is finished, under high pressure, it is impregnated by borax-based chemical solution and allowed to dry before their use. The drying of rubberwood is one approach used to add value to sawn products from the primary wood processing industries. Generally, the heat by steam must be supplied in lumber-drying kiln as almost all rubberwood destined for the market will pass through a strength grading procedure to determine the physical and mechanical properties before delivery to a customer.

Drying of wood is one of the most important industrial processes in wood manufacturing. In basic terms a lumber-drying kiln is simply a large convection oven where heated air draws moisture from the wood venting it into the atmosphere. An equalization period is then used to allow all of the lumber in the kiln to reach uniform moisture content. The most common method of drying is to extract moisture in the form of water vapour. To do this, heat must be supplied to the wood to provide the latent heat of vaporisation. There are several ways of conveying heat to the wood and removing the evaporated moisture. Nearly all the world's timber is, in fact, dried in air. This can be carried out at ordinary atmospheric temperatures (air drying), or in a kiln at controlled temperatures raised artificially above atmospheric temperature but not usually above 100 degrees Celsius, the boiling point of water. Air drying and kiln drying are fundamentally the same process because, with both, air is the medium which conveys heat to the wood and carries away the evaporated moisture. Operating temperatures in conventional kilns were low by today's standards typically 60 to 70^{o}C (80^{o}C maximum). The drying time depends on the thickness of the lumber and initial moisture content, which might take 8 to 12 days. Using geothermal energy, the cost is estimated 10.00 baht/ft^{3}. The final moisture content varies from 6 to 16% depending on the application. Drying influences the natural properties of rubberwood in three ways, namely through the direct effect of moisture loss, the internal drying stresses and strains. Almost all mechanical properties of wood can be improved by carefully controlling these factors [1].

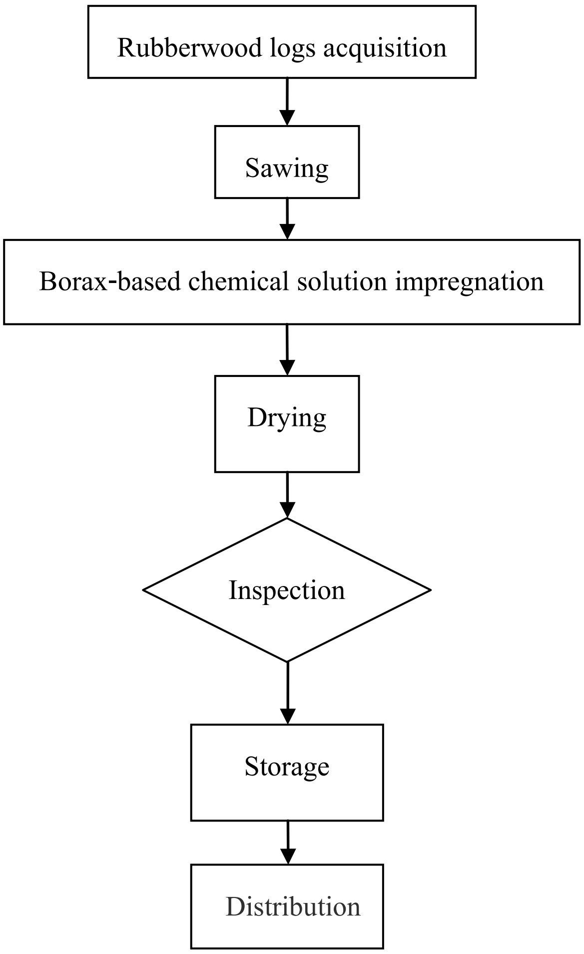


Figure 1-1. Manufacturing process in rubberwood factory

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. In addition to timber drying by the steam heat, a variety of methods such as hot air or a new approach of microwave that has not been used in the rubber industry. The use of microwave energy to dry wood is not very common, but it could be advantageous due to the possibility of heating and drying wood much faster than conventional methods and with preserved quality [2]. Microwave energy can be used to heat dielectric materials. Wood is a dielectric material in which all charges are bound rather strongly to constituent molecules. If the wood is exposed to an electric field, which the microwave creates, the electrostatic charges in the wood begin to oscillate. These oscillations give rise to heating due to friction heat from the oscillating charges. Using microwave power, it takes less than five hours to dry green wood to moisture content (MC) of about 7%. However, this depends on the kind of wood and the thickness and length of the products [3]. Furthermore, the quick energy absorption by water molecules causes rapid evaporation of water (resulting in higher drying rates of the wood), creating interior wood burns [4]. Applying microwave energy to drying is a good approach to some of the problems associated with conventional hot air drying methods. A major disadvantage associated with hot air drying is that it takes long time even at high temperature, which results in degradation of the dried product quality. As combined microwave-hot air drying could greatly reduce the drying time of many plant materials, without damaging the quality attributes of the finished products. Combination heating, which involves heating food with microwaves in combination with hot air, is one of the most significant methods used to achieve uniform temperatures in the food [5-6]. The idea was to combine internal volumetric heating of microwaves with the rapid surface heating of hot air. During the initial period, hot air dominates over microwave heating near the surface, with microwave heating being more significant in the interior (as shown in Figure 1-2).

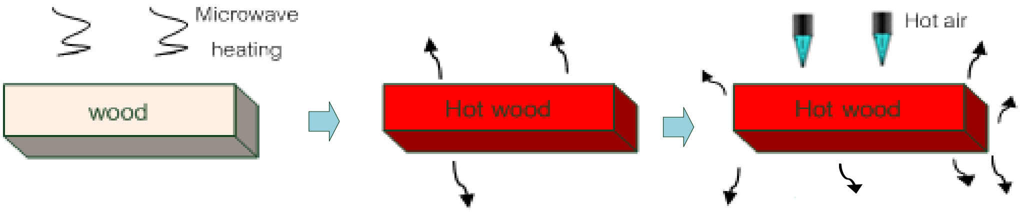


Figure 1-2. Model of rubberwood drying associated with using microwaves and hot-air

Hot air is a good complement to microwave heating as it has different spatial and time variation of heating rates. At later times, the roles switch with microwaves becoming more dominant on the surface while hot air takes a more significant role in heating the interior of the wood. These findings should help the rubberwood, process and equipment designer achieve the balance between speed and uniformity of heating in a more precise manner. Drying time is expected to be shortened by high-temperature drying which wood drying will not occur through the cracks or burn. Since fresh rubberwood contains medium-high content, a rapid heating of microwave can easily cause rubberwood damage. A method of drying rubberwood by combining microwave heating with circulated heated air kiln drying, water in lumber evaporates from the surfaces of rubberwood during hot air drying. This allows water to escape more quickly from the rubberwood. With possible improvements on rubberwood quality attributes and drying process efficiency, microwave exhibits a great potential to be used for rubberwood drying.

There are a few studies on hot air assisted microwave heating, but there is no study on the drying of rubberwood. The objective of this study is to explore the possibility of using the combined microwave-hot air drying method for the minimum rubberwood drying. In addition, the sensitivity of the structure to stresses set up in drying limits the drying rate; rapid drying causes defects such as surface and internal checks, collapse, splits, and warp. Especially, color is one of the most important appearance attribute of rubberwood, since it influences consumer acceptability. The development of combined microwave-hot air drying system to produce high quality dried rubberwood in relatively short time could make significant contribution to the wood industry. In order to optimize the drying process, drying temperature, relative humidity and air velocity of the kiln should be monitored and adjusted according to the designed optimum path. Furthermore, it is possible to develop, characterize and evaluate a drying process for rubberwood using microwave-hot air combination while the physical and mechanical properties of the dried rubberwood were studied. Outcome of this research could be helpful in investigating further in this area.

1.2 The Scope of study

1. Drying wood with a microwave heating, selection of 2.45 GHz is recommended as the operating frequency.
2. Temperature and speed is the variable of hot air drying.
3. Measuring rate of dry weight method by load cell online.
4. Rubberwood moisture level of 15 percent after drying by microwave and hot air heating.
5. Method for testing mechanical properties of rubberwood by Universal testing machine.
    - Compression Stress Perpendicular according to Grain standard ASTM standard D143.
    - Compression Stress Parallel to Grain according to standard BS 373 and ISO 3787.
    - Strength and Stiffness in Static Bending according to standard BS 373.
    - Shear Strength Parallel to Grain according to standard BS 373 and ISO 3346.
    - Hardness according to standard ISO 3350.
6. Physical properties of rubberwood failed quality.

- Cup is a form of distortion whereby there is a deviation from flatness across the width of the board.
- Bow is deviation of the face from being in a straight line along the length of a board.
- Twist is spiral distortion of a board.
- Spring is deviation of the edge from being in a straight line along the length of a board.
- Characteristic of rubberwood char is dark brown or black.

1.3 Objectives

1. Feasibility study on rubberwood drying by microwave heating and impinging hot-air.
2. Find the optimal velocity and temperature of hot air, including the power of microwave that obtainable in drying rate, physical and mechanical of rubberwood after drying.

1.4 Results and benefits of research

1. To develop rubberwood drying technique by microwave techniques and impinging hot-air.
2. To find the appropriate temperature conditions associated with the power of the microwave and temperature of the hot air for rubberwood drying.
3. To compare the quality of rubberwood drying by microwave techniques and impinging hot-air with conventional drying.

Chapter 2

Literature Review

2.1 Rubberwood

Rubberwood is taken from *Hevea brasilliensis* M*uell.*Arg., also called the rubber tree or Para rubber tree. The rubber trees are cultivated for their natural latex sap, but they also yield a high quality wood with a tight grain which can be used in a wide range of applications. In fact, rubberwood is one of the more durable lumbers used in the manufacturing of today's home furnishings. In addition to being beautiful, rubberwood is also an ecologically sustainable timber, making it popular with people who are concerned about the health of the world's forests. After the economic life of the rubber tree, which is generally 26-30 years, the latex yields become extremely low and the planters then fell the rubber trees and plant new ones (as shown in Figure 2-1). When the rubber trees is fell down and sawn into thick or thin sections (such as rafters, purlins and boards), they are usually allowed to dry before they are used.

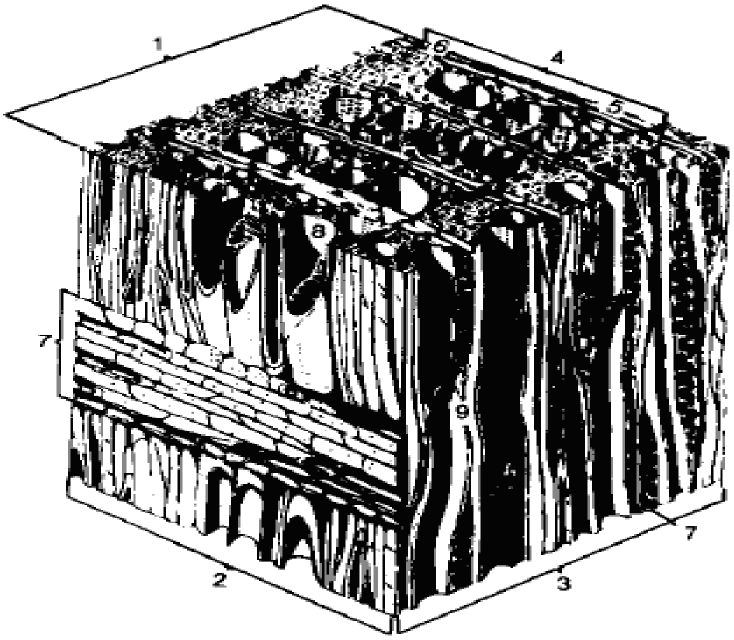
Figure 2-1. Features of common rubber tree

(Source: http://www.peace.mahidol.ac.th/nreport.php)

2.1.1 Physical properties

Rubberwood is a light hardwood. The wood is whitish yellow or pale cream when freshly cut and seasons to light straw or light brown. It is a moderately hard and "light to moderately heavy" timber with density ranging from 435 to 626 kg/m^3 at 12% moisture content. It is a diffuse porous wood with medium texture and straight grain. Sapwood and heartwood are not distinct. Occurrence of tension wood seen as white lustrous zones when freshly cut is a characteristic feature of rubberwood.

Moist wood is essentially a heterogeneous mixture of solid, liquid and gaseous materials. At the macro-structural scale, wood can be described in terms of early wood and later wood, longitudinal tracheids, rays, which run from the pith to the cambium, resin channels and vessels. Some of these elements are illustrated in Figure 2-2.



1. Cross-sectional face, 2. Radial face, 3. Tangential face, 4. Growth ring,
5. Early wood, 6. Latewood, 7. Wood ray, 8. Vessel, 9. Sieve plate

Figure 2-2. Wood structure of a hardwood [7]

The appearance of growth rings, associated with the deposition of early and late wood, is due to changes in the structure of wood produced through the growing season. Cells produced at the beginning of the growing season are commonly larger, and so this early wood appears less dense than the late wood produced towards the end of the season. Although all trees produce concentric layers of wood, not all trees produce visible growth rings, neither are all growth rings necessarily annual. In some trees seasonal changes in wood structure may be so slight that growth rings are not evident. Under conditions of severe drought an annual growth ring may not be produced. On the other hand, under continuously favorable conditions, such as in the tropics, several growth rings may be produced in a single year.

At the micro-structural level, wood can be described in terms of longitudinal tracheids, pit pairs, which connect between tracheids, primary cell walls and secondary cell walls. At the molecular level, wood must be described in terms of polymers, free and bound water, extractives and air. The polymers of wood can be classified into three major types: cellulose, hemi-cellulose, and lignin. The proportion of these three polymers varies between species.

- Cellulose is the most important single compound in wood. It provides wood's strength. Cellulose is a product of photosynthesis. In photosynthesis, glucose and other sugars are manufactured from water and carbon dioxide. The glucose is chemically changed to glucose anhydride by the removal of one molecule of water from each glucose unit. These glucose anhydride units then polymerize into long chain cellulose molecules that contain from 5,000-10,000 glucose units.
- Hemi-celluloses are a group of compounds similar to cellulose, but with a lower molecular weight. The number of repeating end-to-end molecules in hemi-cellulose is only about 150 compared to the 5,000-10,000 of cellulose.
- Lignin is a class of complex, high molecular weight polymers whose exact structure varies. It is an amorphous polymer that acts as a binding agent to hold cells together. Lignin also occurs within cell walls to impart rigidity.

2.1.2 Mechanical properties

The mechanical properties determine the ultimate capacity of the wood to bear the forces in bending, tension, compression, shear etc. in the three directions or planes. The following Table 2-1 gives the properties under bending, compression, shear strength and hardness as compared to teak wood.

Table 2-1. Physical and mechanical properties of rubberwood comparing with teak [8]

Properties	Rubberwood (MC 15%)	Teak (MC 12%)
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 Strength	11 N/mm^2	11 N/mm^2
Hardness	4350 N	4500 N

2.2 The importance of wood drying for the timber industry

Timber is used to produce a variety of products, including sawn and dressed poles, sawn and dressed planks, veneers, laminated products, particleboard, fiberboard, paper and cardboard. Wood drying is the first and perhaps most important process in downstream manufacturing. Wood, in its natural state, always contains a large amount of water. The presence of water influences the properties of wood to such an extent that for many purposes the moisture must be removed before the wood can be used to manufacture anything. The main reasons for drying timber include:

- Legislation - To meet legislation relating to the use of structural timber in buildings.
- Ease of handling - Dried timber is lighter than green timber, therefore making it cheaper to transport.
- Higher strength - Drying increases the strength of most species of timber.
- Increased durability - Drying reduces decay susceptibility and insect attack.
- Better finishing properties - Dried timber can be sanded, painted, stained and polished.
- Gluing - Glues do not adhere to green timber very well.
- Treatment - Drying helps the diffusion of timber preservatives into the wood structure.
- Color - Drying can change the color of various timbers.

2.3 Wood-water relationships

2.3.1 Moisture content of wood

All wood in growing trees contains a considerable quantity of water, commonly called sap. Although sap contains some materials in solution, from the drying standpoint sap can be considered plain water. Most of this water should be removed to obtain satisfactory service for most uses of wood. All wood loses or gains moisture in an attempt to reach a state of balance or equilibrium with the conditions of the surrounding air. This state of balance depends on the relative humidity and temperature of the surrounding air. Therefore, some knowledge of wood-moisture relations is helpful in understanding what happens to wood during drying, storage, fabrication, and use. The amount of moisture in wood is termed the moisture content. It can be expressed as a percentage of either dry or wet weight. For most purposes, the moisture content of lumber is based on dry weight, but the moisture content of wood fuel is usually based on wet weight. Moisture content on dry and wet basis is defined as follows: On dry basis,

$$\text{MC}(\%) = \frac{(\text{wet weight} - \text{oven dry weight})}{\text{oven dry weight}} \times 100\% \qquad (2.1)$$

In oven drying, all the water is evaporated from a wood section by heating. Knowing the wood weight before and after oven drying allows calculation of moisture content. The amount of water in green or wet wood varies greatly, depending mainly on species. The moisture content of some species may be as low as 30 percent, whereas that of others may be as high as 200 percent. Large variations may occur not only between species but also within the same species and even in the same tree.

2.3.2 Fibre saturation point

After felling and especially after conversion, green timber will start to lose moisture from any freshly exposed surfaces. The free water is lost before the bound water. This reduces the weight of the wood but does not affect its dimensions. The point at which the free water has been removed and the bound water remains is called the fibre saturation point. The moisture content of the timber when the fibre saturation point has been reached is usually between 25% to 30%. Timber that is dried to moisture contents below this level will exhibit some degree of shrinkage as the cell walls lose moisture.

2.3.3 Equilibrium moisture content

Wood loses or gains moisture until the amount it contains is in balance with that in the surrounding atmosphere. The amount of moisture at this point of balance 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 60.5°C (141°F) and 65 percent relative humidity, it will eventually either gain or lose moisture until it reaches approximately 10 percent moisture content.

2.3.4 Shrinkage and swelling

Initially, as wood dries, free water is lost from the tracheids and between cell spaces. This continues until the timber reaches "fibre saturation" at about 30 % moisture content, depending on the species. As drying continues, bound water is removed from the cell structure. Drying to fibre saturation results in very little change in the basic structure of timber. However when bound water is removed, shrinkage occurs. Shrinkage is not uniform in all dimensions. Shrinkage along the wood grain is only slight, while both radial and tangential shrinkage are much greater. Ray cells in the wood structure reduce radial shrinkage compared with tangential shrinkage. Therefore, back-sawn timber shrinks along the tangential plane; while quarter-sawn timber remains relatively stable. The effect of shrinkage on various cuts of timber is illustrated in Figure 2-4.

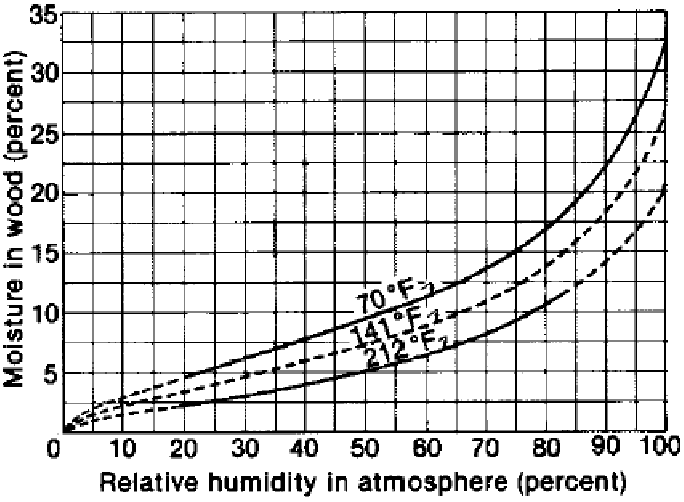


Figure 2-3. Relation of the equilibrium moisture content of wood to the relative humidity of the surrounding atmosphere at three temperatures [7]

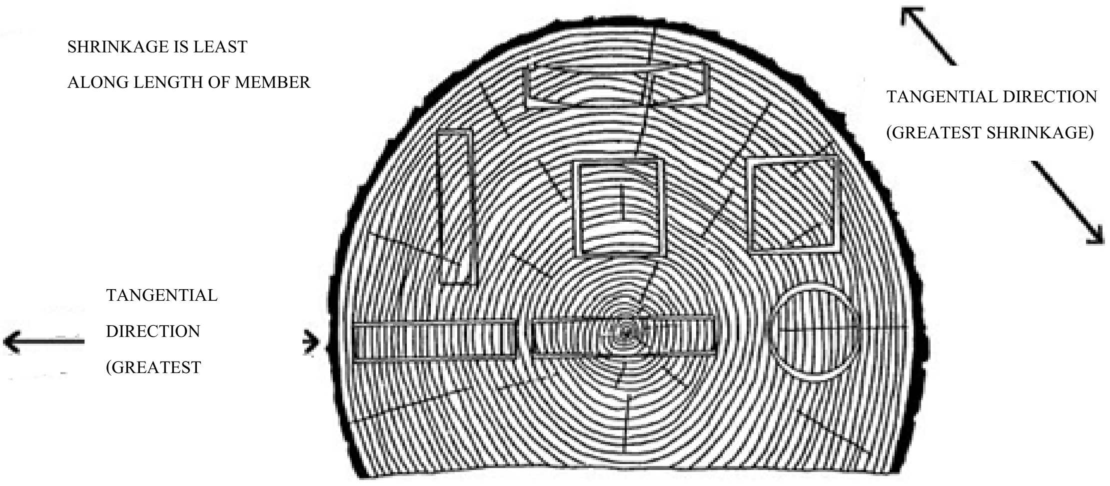


Figure 2-4. Relative shrinkage of wood members due to drying [9]

The following general assumptions regarding wood shrinkage should be remembered:

- Shrinkage only occurs below 30 % moisture content (fibre saturation point).
- Shrinkage along the grain is negligible in most cases.
- Shrinkage across the width of a flat sawn board (the tangential direction) can be twice as much as shrinkage across a quarter-sawn board (the radial direction).
- Shrinkage associated with different sections cut from a log.

2.4 How wood dries

Wood will seek an EMC in relation to the relative humidity (RH) and temperature of its surroundings. That is, as wood is dried below its fiber saturation point, the amount of moisture leaving the wood will be determined by the relative humidity of the atmosphere surrounding the wood. For wood to air dry, the moisture content of the air must be less than that of the wood.

Lumber drying is usually accomplished by evaporating the moisture from the surface of the wood. Wood dries "from the outside in"; that is, the surface of the wood must be drier than the interior if moisture is to be removed. Moisture will move from an area of higher moisture content to an area of lower moisture content within the wood. When the surface moisture evaporates from the sides or ends, moisture moves from the interior toward these locations. This process continues until the wood reaches its EMC. At this point the moisture content is equal throughout the piece of wood. Thicker lumber exposed to the same drying conditions will take longer to reach its EMC than thinner lumber.

Wood dries along the grain up to 15 times faster than across the grain. Therefore, a board will dry at a faster rate from its ends. However, because a board is usually many times longer than it is thick, most of the moisture loss occurs across the grain and out the surfaces of the piece. In other words, the moisture travels across the grain at a slower rate, but it has to cross a much shorter distance and, except near the ends of the board, it dries more through the surfaces. The rate at which lumber dries is controlled both by the rate of evaporation from the surface and by the rate of movement of the water within the piece. As long as the moisture can move from the interior to the surface at a fast enough rate to keep the surface moist, the drying rate will be increased if the surface evaporation rate is increased. This can be accomplished by:

- Increasing the air across the surface of the wood. As long as the RH is low enough, the air will continue to dry all exposed surfaces of the wood.
- Increasing the temperature of the air surrounding the wood. Warmer air holds more moisture; by increasing the temperature, the moisture-carrying ability of the air is increased.
- Reducing the RH of the air. Water evaporates faster into the drier air.

2.5 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).

2.5.1 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. 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.

2.5.2 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 vapour, 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 vapour from the surface of the wood.

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 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.

2.5.3 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.

2.5.4 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 fibre 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 maximise the moisture gradient without damaging the timber.

2.5.5 Supply of heat

A supply of heat is required to dry timber. In kiln drying, sensible heat is needed to raise the temperature of the wood and the water it contains to the required drying temperature, and latent heat is needed to evaporate the water. Energy is a major element in the running costs of conventional kilns which vent warm, moist air to the outside and therefore recover none of the drying energy input. As the relative cost of energy rises, efficient heat utilization has become a more significant factor and much attention has been given to techniques which might reduce expenditure on energy. These range from simple upgrading of kiln insulation to the development of heat pump kilns.

2.6 Drying defects

In the drying process, timber containing tension wood tends to have abnormally high longitudinal shrinkage and may cause distortion in the form of bow, cup, spring or twist, especially in relatively thin boards and small dimension stock. Dried boards containing tension wood may suffer further distortion like splitting and resawing or machining because of stresses set up during drying. Collapse during seasoning may also be due to tension wood. This is especially liable to occur where the tension wood is in well-defined bands. Unlike collapse in normal wood, it is not remediable by any form of conditioning treatment. However, in the case of rubberwood, the incidence of collapse is rarely reported. Strength properties information pertaining to the strength properties of tension wood seems to be rather limited and is not always consistent. Generally, tension wood is weaker in most strength properties than normal wood, the differences are usually not large enough to constitute a hazard if the material containing tension wood is used in the usual specifications for construction purposes. Basing on the above, the use of rubberwood containing tension wood may cause serious degrade and reduction in quality of wood, depending on the intensity of its occurrence and the purpose for which the wood is used. Its effects can be minimized by careful selection and manufacturing, starting with detection either in the log or at an early stage in processing. In breaking down logs, tension wood should be included, if possible, in short and thick pieces, where it is less liable to warp, and not in sizes where shape and stability in the finished article are important.

The five major types of warp are cup, bow, crook, twist, and diamonding (Figure 2-5). Cup is a distortion of a board in which there is a deviation flatwise from a straight line across the width of a board. It begins to appear fairly early in drying and becomes progressively worse as drying continues. Cup is caused by greater shrinkage parallel to than across the growth rings. In general, the greater the difference between tangential and radial shrinkage, the greater the degree of cup. Thinner boards cup less than thicker ones. Because tangential shrinkage is greater than radial shrinkage, flatsawn boards cup toward the face that was closest to the bark. A flatsawn board cut near the bark tends to cup less than a similar board cut near the pith because the growth ring curvature is less near the bark. Similarly, flatsawn boards from small-diameter trees are more likely to cup than those from large-diameter trees. Due quartersawn boards do not cup. Cup can cause excessive losses of lumber in machining. The pressure of planer rollers often splits cupped boards. Cup can be reduced by avoiding overdrying. Good stacking is the best way to minimize cup.

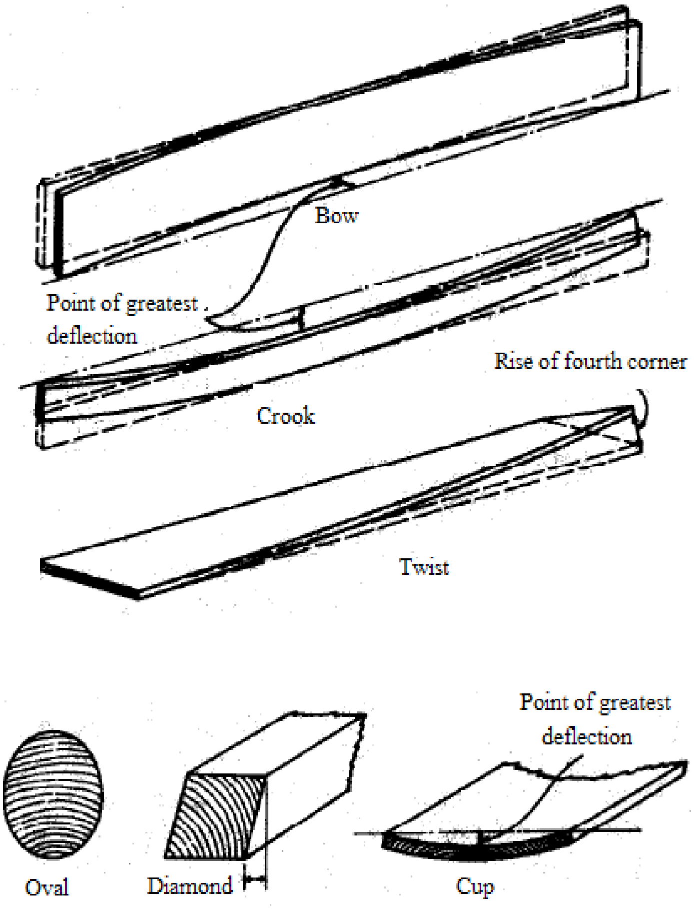


Figure 2-5.Various types of warp that develops in boards during drying [7]

- Bow is a deviation flatwise from a straight line drawn from end to end of a board. It is associated with londescribed gitudinal shrinkage in juvenile wood near the pith of a tree, compression or tension wood that occurs in leaning trees, and crossgrain. The cause is the difference in longitudinal shrinkage on opposite faces of a board. Assuming that there are no major forms of grain distortion on board faces, bow will not occur if the longitudinal shrinkage is the same on opposite faces.

- Crook is similar to bow except that the deviation is edgewise rather than flatwise. While good stacking practices also help reduce crook, they are not as effective against this type of warp as they are against cup and bow.
- Twist is the turning of the four corners of any face of a board so that they are no longer in the same plane. It occurs in wood containing spiral, wavy, diagonal, distorted, or interlocked grain. Lumber containing these grain characteristics can sometimes be dried reasonably flat by wing proper stacking procedures. Twist, bow, and crook have definite allowable limits in the grading rules for softwood dimension lumber, so it is desirable to minimize these defects.
- Diamonding is a form of warp found in squares or thick lumber. In a square, the cross section assumes a diamond shape during drying. Diamonding is caused by the difference between radial and tangential shrinkage in squares in which the growth rings run diagonally from corner to corner. It can be controlled somewhat by sawing patterns and by air drying or predrying before kiln drying.

2.7 Methods of wood drying

Wood is generally dried by either air drying or kiln drying or by a combination of both methods in Table 2-2. Each drying methods mentioned has advantages but in many cases the advantages are outweighed by the disadvantages. In this section, each method will be discussed in terms of its advantages, disadvantages, and practicality for drying lumber. They are as follows:

2.7.1 Predrying

Predrying is used to remove most of the free water from lumber before it is placed in a kiln for final drying. In a predryer, lumber is stacked in a building where heat and humidity are controlled. The temperature is usually kept around 35°C (or 90-100°F). The lumber is dried to 20-30% moisture content, then placed in a kiln for final drying.

2.7.2 Conventional kiln

A conventional kiln uses heat provided by either steam or hot water coils or a furnace to heat the kiln chamber and remove water from the wood. The water removed from the wood is turned into water vapor by evaporation, then exhausted from the kiln with the heated air. This process takes a great deal of heat and requires constant heating of air, so these systems are not as energy efficient as dehumidification kilns. To remove one pound of water from the lumber, a conventional kiln has to draw in about 400 cubic feet (or 12 cubic meters) of air, heat the air, then exhaust it with the evaporated water. Between heating these large quantities of air and heating the water to evaporate it, conventional kilns have a very high heat requirement. They can provide a very good quality of lumber if a good method of kiln control is provided, but their energy consumption is much higher than that of a dehumidification kiln.

Table 2-2. Advantages, disadvantages and limitations of kiln drying and air drying

Kiln drying	**Air drying**
- Rate of drying can be controlled by varying heat and relative humidity. Controlling drying rates minimizes drying defects in lumber.	- Rate of drying is subject to the weather.
- Lumber can be dried to 8% MC, or less, for use in interior applications.	- It is not possible to dry lumber to less than about 15%MC, without further drying in a heated building.
- Staining of lumber can be controlled by using heat and air flow to rapidly dry the surface of boards.	- Warm, humid conditions with little air movement can promote some types of stain.
- Drying time is normally less than one month for common northeast species.	- Drying can take several months under ideal conditions.
- Lumber must be trucked to and from the kiln.	- Lumber can be dried on-site, in any area which receives good air-flow.
- There is an out-of pocket cost associated with kiln drying.	- Air drying can be a low cost alternative.

2.7.3 Dehumidification kiln

A dehumidification kiln uses a heat pump system to remove the water from lumber. One primary advantage of this type of system is that it recycles heat continuously instead of venting away heated air, as a conventional kiln does. So it is more energy efficient and its operating cost is usually lower. This is true even though a dehumidification kiln uses electric energy to run the fans, the blower that draws the air over the dehumidification coil, and the refrigeration compressor; while a conventional system burns less expensive fuel such as gas or wood. The reason a dehumidification system costs less to run even though a conventional system burns cheaper fuel lies in the dehumidification system’s ability to conserve energy by recycling heat. With the heat being constantly recycled, the amount of electricity demanded by the system is small, so it comes out ahead of a conventional system that may use cheaper fuel, but needs a lot more of that fuel to do the same job.

In a dehumidification kiln, heated air (usually starting at a heat of about 27°C, or 80°F) is circulated over the lumber with separate circulating fans, evaporating the water contained in the wood. The hot, moist air then passes over a cold refrigeration coil where air is cooled to about 15°C (60°F). At the cooling coil, the evaporated water in the air condenses into liquid form and flows down the drain as a stream of cool water instead of as a cloud of steam carried by heated air, as in a conventional kiln.

When the air is cooled at the cold coil, the heat removed from the air is immediately used by the system to heat the air back up again. The energy efficiency of the heat return is such that each time this process occurs, the air leaves the dehumidifier at an even hotter temperature than when it entered. As the air temperature in the kiln rises, it can ultimately reach temperatures as high as 72°C (160°F). If the temperature becomes higher than desired, the operator can vent surplus heat to the outside.

Dehumidification kilns are very easy to operate and are very popular with beginning lumber dryers. They are also popular with experienced operators who want a system that requires minimum attention to get zero defect drying. Dehumidification is usually the least expensive system to install by a wide margin. Drying times are about the same as conventional kilns that operate at comparable temperatures.

2.7.4 Solar kiln

There are several types of solar kilns, but they all generally rely on some type of solar collector to provide the heat energy that evaporates the water in the lumber. Unlike solar heating for an office or home, in lumber drying it's not possible to reduce the heat requirement to the point where solar heating can be competitive. When you've got a certain amount of water to remove from a certain amount of wood, you need a certain amount of total heat to do it, and that heat requirement can't be changed.

Solar kilns are slow, and dependent upon the weather. In hot climates they can degrade lumber due to excessive drying. In colder climates they are unreliable and slow. Some solar kilns use electric-powered fans to circulate air through the lumber, but the cost of running these fans is high and because of the long drying times, you've got to run the fans for a long time, making solar drying quite expensive.

2.7.5 Vacuum kiln

When lumber is placed in a vacuum, the water evaporates quickly. Vacuum kilns take advantage of this fact to achieve drying times that are usually only a fraction of the time required for conventional or dehumidification kilns. A major drawback of vacuum kilns, however, is that the chambers are small, so the kilns cannot dry large quantities at any one time. It is also necessary to provide heat to the lumber continuously in a vacuum kiln. To do this, some systems use electric blankets in contact with each piece of lumber, while some use heat coils or microwaves. All of these systems are extremely expensive to run when compared to dehumidification or conventional kilns. Operating costs are usually three to four times higher than costs for dehumidification kilns. Initial or capital costs are also much higher. When compared on the basis of cost per thousand board feet of annual production, the costs for a vacuum system are much higher than dehumidification.

2.7.6 Radio frequency

Heating materials with electromagnetic radiation, called dielectric heating, can be done at a number of frequencies which are usually separated into the radio and microwave frequency ranges. The energy transfer to the material is caused by the oscillating electric field interacting with molecular diopoles and ionic species. Because water has a strong permanent dipole, it is heated very readily in an alternating electronic field. This is advantageous for selectively heating water in materials of uneven moisture such as veneer and for drying hygroscopic materials to low moisture contents.

The radio frequency range is usually considered to be between 1 and 100 MHz in the electromagnetic spectrum. In the forest products industry this type of energy has been used to set adhesives in wood joints and for drying paper. More recently veneer and lumber have been dried in radio frequency dryers. The simplest way to envision a radio frequency heater is to imagine the materials being heated between two plates which are attached to a frequency generator. The plates and the material to be dried are essentially a capacitor, the frequency of which must be tuned to match the generator. This can be done by adjusting the plate distance or by adjusting another inductor or capacitor in the circuit. Heating occurs because dipoles and ions oscillate and ions migrate through the body. This in effect, is a current flow and the associated resistance causes heating dependent on the loss factor, temperature, and moisture content of the material. The loss factor is a material property which describes the material's ability to be heated by the electric field. For thinner materials the other electrode arrangements may be advantageous but the heating principles are the same.

One of the main advantages of a radio frequency dryer is its ability to selectively heat water more than the surrounding material. This is important in drying a hygroscopic material such as wood to a low moisture content. At low moisture contents, heat transfer through the material from the surface becomes more difficult to accomplish. Radio frequency generates the necessary heat internally, eliminating a slow step in the drying process. Selectively heating water is also an advantage in an operation such as a veneer redryer or paper dryer where an uneven moisture profile may exist. For these applications radio frequency dryers have been shown to effectively level out uneven moisture distributions in the product [10].

The plant space required for a radio frequency dryer is less than for a hot air dryer, the weight is less so foundations are less costly, and no boiler is needed, a very important point if the boiler is already working at capacity or if no boiler is present. Depending on the specific application of this equipment, the operating and maintenance costs may be lower. The largest disadvantage is the installation cost, partly because of design considerations and partly because of the complexity of the equipment. As more radio frequency dryers come on line these costs may decrease.

Some work, such as that of James and Hamill [11], has been done to determine the dielectric properties of wood. Other work's have examined the effect of time, energy consumption, degrade, and moisture profiles on radio frequency drying. Miller [12] developed a radio frequency process in which dryer control is based on the air dry-bulb, air wet-bulb, and lumber surface temperature. A quarter of the time was required to dry 2 in. thick white spruce with radio frequency compared to conventional schedules, and degrade was minimal. He concludes that most wood can be dried in a radio frequency unit using available kiln schedules. If the species is prone to collapse, the schedule may need to be modified. Simpson [13] dried 24 in. lengths of 4/4 red oak in a 5 kw radio frequency dryer. Moisture profiles, power consumption, and degrade were considered. He concludes that drying from 80 to 25% moisture content in 15 minutes was fast, but that boards dried to a moisture content lower than this exhibited obvious degrade and that radio frequency drying has potential as a predrying process to be followed by drying at a lower temperature.

Radio frequency drying seems to have its greatest potential with a high value product, for example a hardwood species for furniture production. It also has potential as a redry system for veneer where selective heating of the wet spots is desirable. The available systems were compared to conventional drying.

2.7.7 Microwave

Microwave drying systems are the second generation of dielectric heating. In concept, microwave heaters operate in a manner similar to radio frequency dryers except they utilize a much higher frequency, in the range of 500 to 5000 MHz. The higher frequency allows a much higher rate of energy transfer to the material, however, as the frequency increases the depth of penetration into the material decreases. Rather than being between charged plates, microwaves are generated with a magnetron or a klystron. Wave guides are used to contain the microwave and deliver them to the material.

Like radio frequency, microwave dryers selectively heat water which makes them ideal for drying to even moisture profiles and to low moisture contents. The design of microwave dryers is somewhat complex, which contributes to their high initial cost. Dryer design considerations include wave reflection, distribution, penetration, attenuation, and power dissipation. The basic limitation to the microwave drying of nonconducting materials is cost. Generally, there must be some good reason to install this type of dryer.

Considerations are often based on space savings, product quality improvements, or increase plant throughput.

Like radio frequency dryers, a microwave system may have good potential in certain situations. No systems are designed to dry lumber on a commercial scale, but, veneer has been redried with microwave energy. Cost comparisons for this case were not made because no commercial systems have been developed for lumber.

2.8 Theory of microwave and impingement drying

2.8.1 Microwave propagation and dielectric heating

Microwaves are electromagnetic waves whose propagation characteristics can be described by Maxwell's equations.

$$\nabla \times E = \frac{-\partial B}{\partial t} \qquad (2.2)$$

$$\nabla \times \frac{B}{\mu} = J + \frac{\partial(\varepsilon E)}{\partial t} \qquad (2.3)$$

$$\nabla . (\varepsilon E) = \rho_f \qquad (2.4)$$

$$\nabla . B = 0 \qquad (2.5)$$

where E and B are the electric and magnetic fields, respectively, J is the conduction current, ρ_f is the free charge, μ is the magnetic permeability and ε is the electric permittivity of the medium. The interaction of the microwave field with the surrounding medium will depend on its dielectric properties. In a vacuum, $\varepsilon = \varepsilon_0 \approx 8.85 \times 10^{-12}$ F/m is a constant, and the microwaves will propagate with a velocity of $c \approx 3\times10^8$ m/s and no interaction and energy absorption will occur. However, when microwaves propagate into dielectric materials, the dipole will interact with the electric field component of the microwave, and thus wave propagation and its interaction with the materials can become very complicated.

Water is a good absorber of microwave energy due to its electronic configuration, the absorbed energy is dissipated as heat inside dielectric materials. When placed in an electric field, the dipole will be re-orientated with respect to the field. The positive end of the dipole will experience a torque in the negative field direction whilst the negative pole would align itself with the positive direction of the field. If the field is made to alternate the molecule will oscillate as it endeavours to line up with the instantaneous field direction. The amount of lag between the axis of the dipole and the field direction will determine the amount of energy lost to the field in the form of friction. The tangent of the angle between the dipole and the electric field is called the loss tangent and is a measure of the dipole's ability to absorb microwave energy. It is both frequency and temperature dependent. At 2.45 GHz, the frequency used in this research, and 25°C, the loss tangent of water is about 0.17 [14].

The loss tangent can be derived from a material's complex permittivity. Figure 2-6 shows the dependence of ε' and ε'' on the microwave frequency in liquid water at 25°C. The complex permittivity ε is given by Metaxas & Meredith as;

$$\varepsilon = \varepsilon' + i\varepsilon'' \qquad (2.6)$$

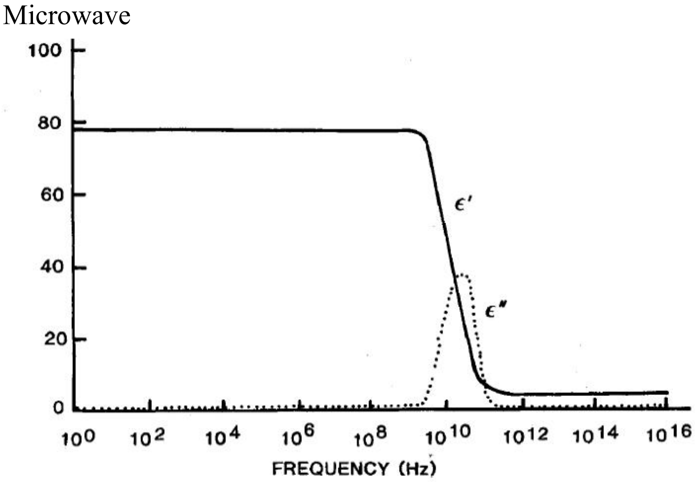


Figure 2-6. Dependence of ε' and ε'' on microwave frequency in liquid water at 25°C [15]

Knowledge of a material's dielectric properties enables the prediction of its ability to absorb energy when exposed to microwave radiation. Collisions between polar molecules occur during rotation under the influence of the alternating electric field component of the microwaves, generating friction and heat. The efficiency of energy absorption will depend on the microwave frequency. For liquid water at 25°C, the resonance of the energy absorption occurs at $f \approx 20$ GHz. The energy absorption, $P_{\text{abs.}}$ is expressed in equation 2.7.

$$P_{\text{abs.}} = 2\pi f \varepsilon' \varepsilon'' E^2 \qquad (2.7)$$

where E is the amplitude of the microwave electric field component.

2.8.2 Principle of impingement drying

An impingement dryer consists of a single gas jet or an array of such jets, impinging normally on a surface. Some characteristics of impingement drying include: rapid drying, popular for convection drying, and the large variety of nozzles available (multizones). Typically, the temperature and jet velocity in impingement drying may range from 100°C to 350°C and 10 to 100 m/s, respectively [16]. Figure 2-7 shows an example of a symmetrical exhaust air flow. There is a great variety of nozzles that can be used and selection of the nozzle geometry and multinozzle configuration have important relevance on the initial and operating costs and product quality.

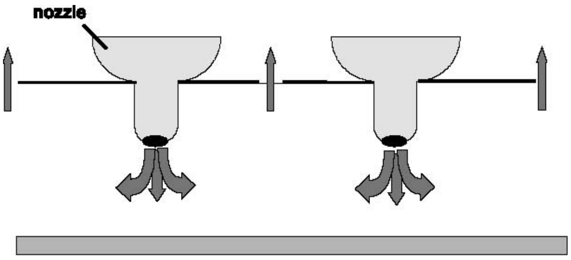


Figure 2-7. Symmetric arrangement for exhaust of spent jets [17]

As shown in Figure 2-8, air jets are usually discharged into a quiescent ambient from a round nozzle of diameter *D*. Typically, the jet is characterized by a uniform velocity profile at the nozzle exit. However, with increasing distance from the exit, momentum exchange between the jet and the ambient causes the free boundary of the jet to broaden and the potential core to contract. Downstream of the potential core, the velocity profile is not uniform over the entire jet cross-section and the maximum (center) velocity decreases with increasing distance from the nozzle exit.

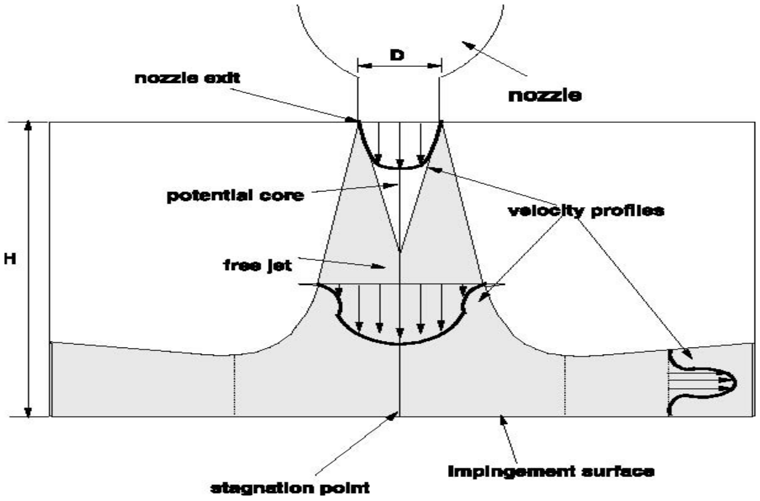


Figure 2-8. Surface impingement of a single round jet [17]

Heat transfer from the air exiting the impinging nozzle to the target is calculated by assuming that the air jet exits its nozzle with a uniform velocity (V_a), temperature (T_a), and species concentration $C_{A,e}$.

Thermal and compositional equilibrium with the ambient is assumed ($T_a=T_\infty$, $C_{A,a}=C_{A,\infty}$), while convection heat and/or mass transfer may occur at the impingement surface of uniform temperature ($T_s \neq T_a$, $C_{A,s} \neq C_{A,e}$). Newton's law of cooling and its mass transfer analog may then be expressed as:

$$q' = h(T_s - T_a) \qquad (2.8)$$

$$N_A' = h_m(C_{A,s} - C_{A,a}) \qquad (2.9)$$

Where q' is the heat flux and N_A' the mass flux. Conditions are assumed to be independent of the level of turbulence at the nozzle exit, and the surface is assumed to be stationary. Convection correlations for a variety of external flow conditions are available. The following correlation to calculate the average convective heat transfer coefficient, h, for a single round nozzle:

The air impinges at high velocity on the product surface removing the boundary layer of moisture and cold air thus greatly accelerating heat transfer and reducing process time. The air is continuously recirculated for removal of the moisture and reheating. A majority of laboratory studies have used contoured entry nozzles, even though this type of nozzle is impractical for industrial use. However, for studying the effects of impingement transport phenomena of other design variables, it provides uniform nozzle exit conditions with low nozzle exit turbulence.

2.9 Literature review

Microwave heating has found applications in the wood industry, including tempering of wood for further processing, microwave input and drying time. In those applications, microwave heating demonstrates significant advantages over conventional methods in reducing process time and improving wood quality.

Schiffman [18] tested potential problem of fluid evaporation during microwave drying. The rationale behind this is that microwave drying is more efficient when the timber is dried to certain moisture content and by initially drying the extremities, pathways through which steam can exit are created. However, the problem would appear to be slightly more complicated than this. The quality of the wood is also dependent on the temperature at which it is dried, since overheating will lead to charring, burning or other deleterious effects.

Barnes *et al.* [19] developed a continuous drying system for lumber which utilized microwave energy. A low level of degrade was obtained with drying times of 5 to 10 hours for ten foot two-by-eights. Hot air was used but they state that its only advantage was to prevent heat loss from the wood. They further state that a microwave drying system for lumber would most likely be advantageous when the wood has a low moisture content, is prone to degrade, or has a high inventory value.

Oloyede and Groombridge [20] studied the mechanical properties of Caribbean pine timber using several drying methods. The wood was dried in air at ambient temperature, in a conventional oven at two elevated temperatures and in a microwave oven at two different power settings. The wood specimens were then subjected to tensile loading in order to determine the mechanical properties of the dried timber samples. These revealed that microwave drying reduced the strength of the dried timber by as much as 60%.

Antti *et al.* [21] studied multivariate data analysis that material parameters such as fraction of heartwood and distance between annual rings have greater influence on mechanical properties than to the drying method and drying temperature for Scots pine. A drying temperature up to 110°C has no difference in MOE, MOR and tensile stress at 5% significance level between the two drying methods for Scots pine.

Hansson and Antti [22] studied microwave drying and conventional air-circulation drying, and the species tested for Norway spruce. The result shows that it is not possible to demonstrate any difference between the two drying methods with respect to the strength of the wood. The variables such as moisture content, number of annual rings and the density properties weight, width and thickness affect wood strength. The drying method, regardless of whether microwave drying or air-circulation drying, has no impact on the strength of the wood.

Du, Wang and Cai [23] studied the microwave drying process consisted of three distinct periods (warm-up period, evaporation period, and heating-up period) during which the temperature, moisture change, and drying efficiency could vary. Characteristics of temperature, moisture content, and unit energy consumption during microwave drying of wood strands (80% southern pine and 20% hardwood) were examined in this study and compared with the conventional drying process. The typical curve of temperature change during the microwave drying of strands indicates that there were normally three distinct periods: warm-up, water evaporation, and heating-up. Water evaporated faster during the early drying process when the MC was high. Water then evaporated at a decreasing rate when the MC was decreasing. During the heating-up period when the strand's MC was low, some of the microwave energy was used to heat up the strands. The temperature of strands would sometimes be so high that the strand surfaces would char.

The advantages of jet impingement heating over more traditional convection heating include faster cooking, higher efficiency and better water retention. Walker [24] showed that the impingement heated product had higher final moisture content and maintained a higher level of compressibility. A review of the energy efficiency of ovens has shown the jet impingement ovens to be 65% efficient while gas fired ovens have only 35% fuel efficiency [25]. Other studies have also looked at the efficiency of jet impingement systems [26] and measurements and modeling techniques for such ovens. Detailed measurements of flow [27] and heat transfer coefficient [28] in jet impingement heating have been reported. Thawing of frozen foods using jet impingement has also been modeled [29].

Heating combination, which involves heating food with microwaves in combination with hot air, is one of the most significant methods used to achieve uniform temperatures in the food [3, 6]. Microwave application has been reported to improve product quality such as better aroma, faster and better rehydration, considerable savings in energy and much shorter drying times compared with hot air drying alone [15].

Chapter 3

Experiment and Method

3.1 Wood samples

The wood samples used in all experiments were selected with uniform composition from furniture factory in Songkhla province. The general range of moisture content for green (undried) hardwood lumber can range between 45% and 150%. Samples of 1 in. (thickness) by 46 in. or 1.15 m (length) with width ranging from 1 to 4 in. were cut from a fresh log shortly then the rubberwood samples were impregnated with borax-based chemical solution to prevent boring insects and fungi before samples were dried (see Figure 3-1). Drying experiments were conducted by hot air drying, microwave heating and combined microwave hot air drying. For hot air drying, the temperature and flow rate of the air were kept at 60-80°C and 10 m/s, respectively while the maximum microwave power level of 200W was introduced. The weight of sample was measured by a load cell every 5 minutes for microwave and hot air drying experiments with three replications until the weight of the sample was reduced to the final constant moisture content.

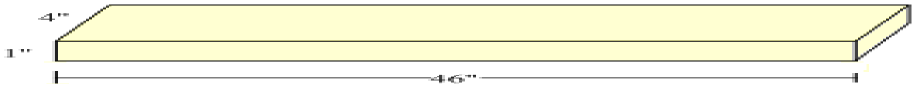


Figure 3-1. Sample dimensions of 1 in. thickness x 4 in. width x 46 in. length

At successive time all samples were weighed and moisture content was calculated. Moisture content (MC) is a measure, usually expressed as a percentage, of the weight of water in wood compared to the oven-dry weight of the same piece of wood as shown in Equation 2.1.

3.2 Drying apparatus

The experimental system consisted of two heat sources, one for the application of hot air and another for the generation and application of the microwaves. Details with two main components are as follows in Figure 3-2.

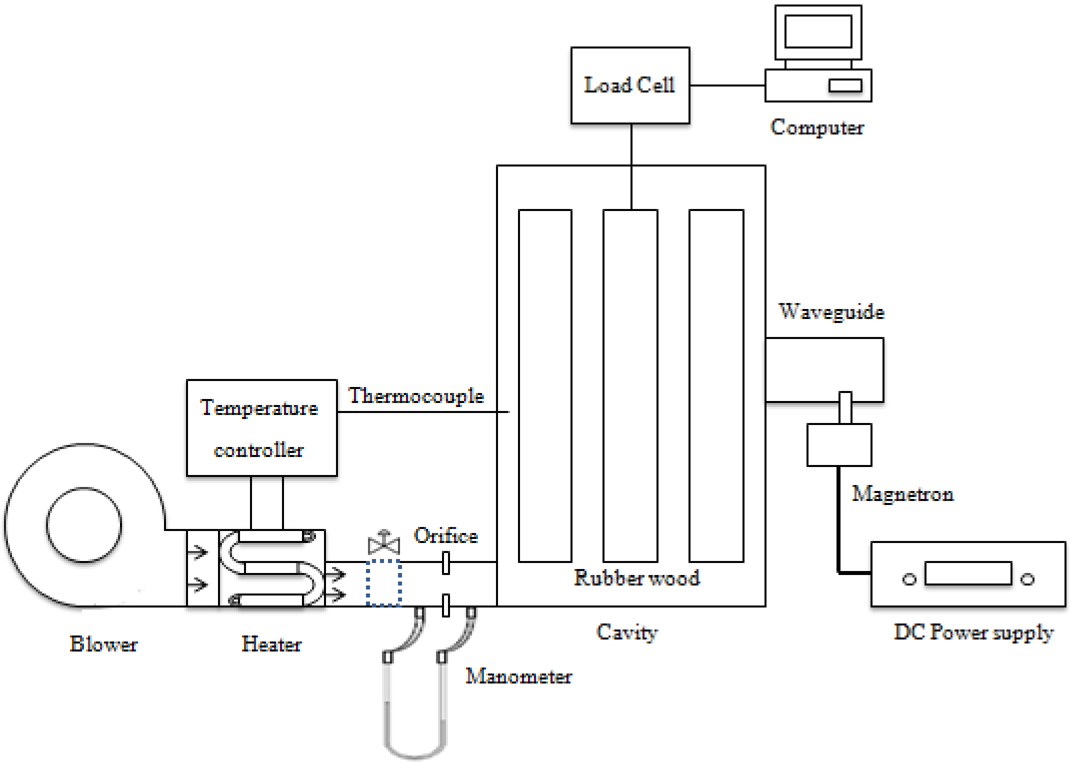
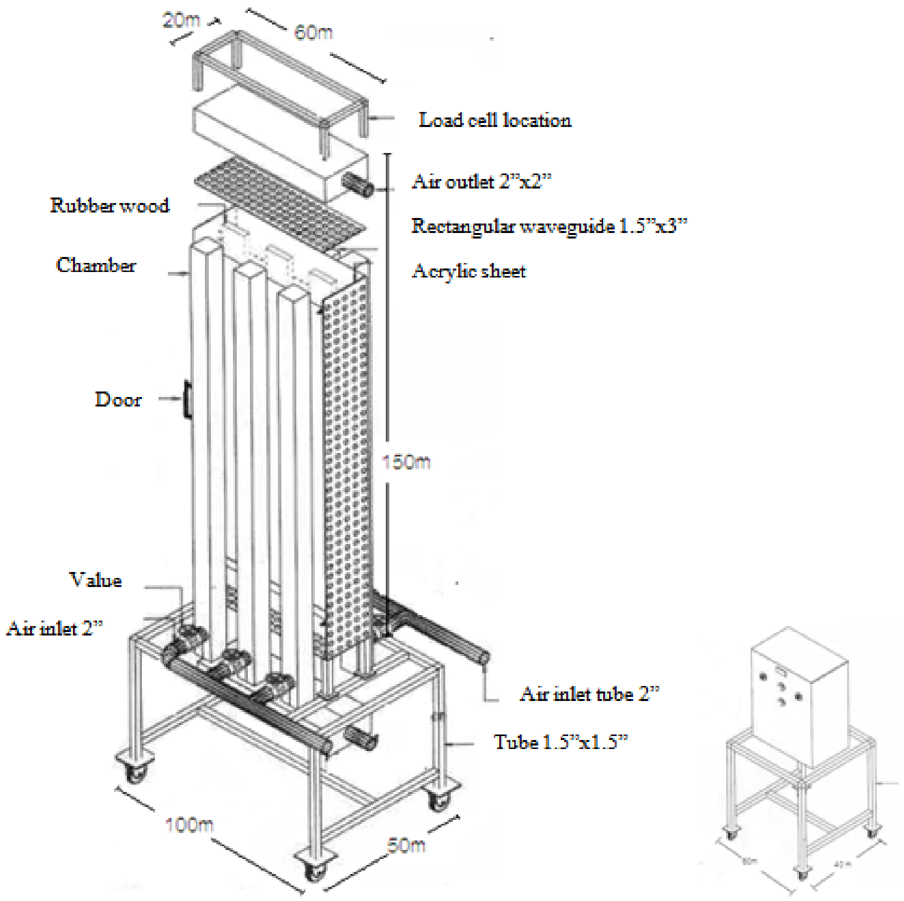


Figure 3-2. Schematic diagram of microwave-hot air dryer

3.2.1 Design and construction rubberwood drying

The structure of the microwave cavity is designed for standardized rubberwood sizes required for the furniture industry. In each experiment, 3 rubberwood sample pieces were dried. Each piece had a length of 1.15 m (46 in.) by width 2.5 to 10 cm by thickness of 1 in. and the space each piece of wood was about 5 cm. The inside of the cavity used has the dimensions 60 (W) x 20 (D) x 150 (H) cm^3. The modeling of the design and construction of rubberwood drying chamber are shown in Figure 3-3 and Figure 3-4. The main structure is comprised of stainless steel for high heat resistance and corrosion decay with exception of the top and bottom of the microwave cavity which are steel. The apparatus in the experiment had six chambers (1.5 x 1.5 in.) used as jet impingement zones, then heated air is pumped into the chambers through thirty-six circular orifices in each side of the cavity (distance of each orifices 4 cm). The front and back of the cavity is connected to a stainless steel hot air duct row. The duct has a diameter of 1 cm to provide a conduit for the hot air of up to 80°C. A heater which propels air at a velocity from 1.0 to 15.0 m/s directs air forward towards the surface of rubberwood. Two openings with an inner diameter of 5 cm were made on the bottom left side of the cavity to supply hot air to the chamber. Electrical heating devices, located on the bottom and two sides, control temperatures inside the cavity which are measured by thermocouple. Two outlet tubes with a 5 cm diameter were provided on the both upper and lower side of the cavity.



Side View

Microwave controller

Figure 3-3. Design of rubberwood drying chamber

For this study a 2.45 GHz frequency and two magnetrons directed in power microwave source is supposed to be connected to a closed cavity. Based on the study of Tubkiow T. and Vichakhun A, the factor of the mechanical properties of rubberwood drying by microwave heating was investigated [30]. The samples, 50 inch in length, 1 inch in height, and 1, 2, 3, and 4 inch in width, were dried by microwave heating at 100W, 150W, and 200W. Whereas the air was also ventilated at speed 2 m/s until the wood reach humidity level at approximately 12%. The result showed that at 200W gave the highest MOE and MOR whereas at 150W gave the highest compressive stress parallel to grain. As a result, the 200W output of power distribution in terms of energy into the cavity is chosen. The distribution is assisted by a rectangular waveguide made of aluminum having 1.5 in. inner diameter and 3 in. length was fitted to the inside back of the cavity for effective transmission of microwave fields into the chamber. Energy emission was microprocessor controlled from 10 to 200W at 10 W increments. The inside wall of the cavity, made of stainless steel mesh which is much smaller than the wavelength of microwave was placed over the opening to prevent microwave leakage. The outside wall of opposite the door cover the acrylic plastic sheet that can be seen within. As another side, The stopping of microwave device is installed to prevent collision wave while the door open. During the experiments, the center of rubberwood weights with string holder were measured by a load cell program for continuous recording of sample weight every 5 minutes which a 0.001 kg precision load cell with capacity of 5 kg was placed on the top of drying cavity.

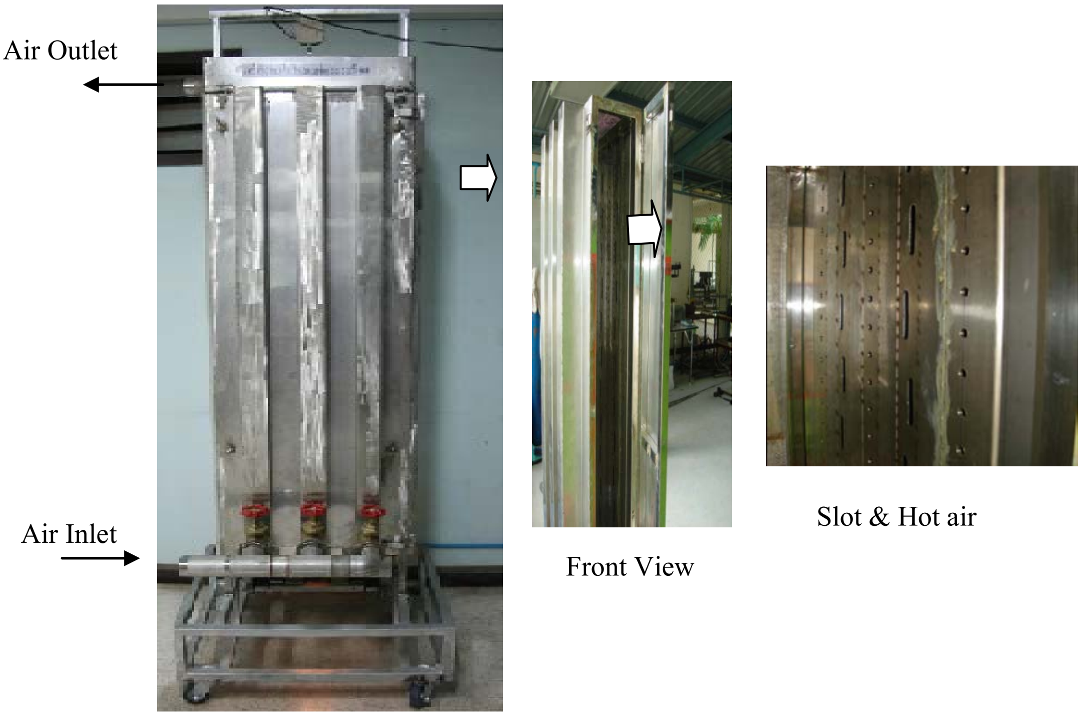


Figure 3-4. Construction of rubberwood drying chamber

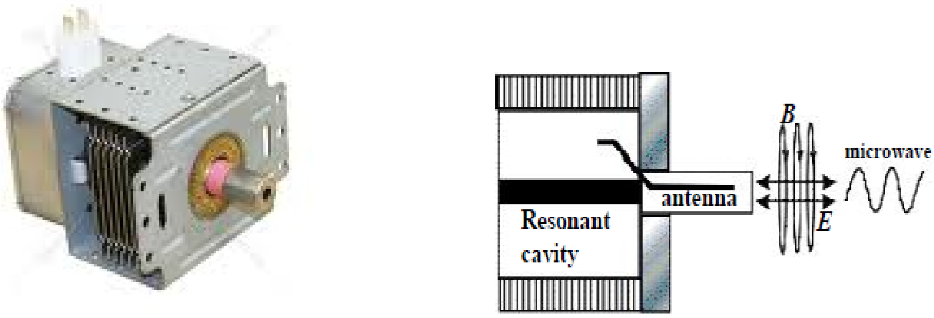
3.2.2 Microwave devices

The system includes a high-voltage DC power supply, magnetron, waveguide and cavity. While output power of the magnetron of the microwave oven was regulated by varying the anode current as described by [31]. A high voltage transformer was incorporated in the circuit to supply current to the anode of magnetron separately. Phase control was also placed on the primary side of the high voltage transformer to regulate the anode current, thus varying the output power of the magnetron from 0-200W. The output power of the magnetron was measured by the calorimetric method [32].

3.2.2.1 Magnetron

The magnetron is used as a microwave radiation source. To generate continuous and adjustable microwave power from 0-200W, the magnetron was biased by appropriate currents and voltages from the power supply. The details of each component in the magnetron are described below:

A commercial magnetron producing microwaves with a frequency of 2.45 GHz, found in a domestic microwave oven, is shown in Figure 3-5a. Figure 3-5b shows the magnetron resonant cavity where the microwave field is generated by motion of an electron cloud under electric and magnetic fields. The electrons are emitted from a hot filament, supplied by a 3 V and 11 A power supply. The electric field is produced between the cathode and anode by an external high-voltage power supply, and magnetic field is produced by two permanent magnets. The threshold voltage for radiation of microwave power is about 4,000 V. As the voltage is increased from 4,000 to 6,000 V, the microwave power increases from 0 to 200W. The microwave field in the resonant cavity is coupled to the antenna allowing propagation of microwave radiation [14].



(a) (b)

Figure 3-5. A commercial magnetron producing microwaves: (a) Picture of a commercial magnetron and (b) schematic diagram of a magnetron

3.2.2.2 Waveguide

For effective transmission of microwave power to the rubberwood, the waveguide and multimode cavity were designed carefully. The rectangular waveguide made of aluminum having 1.5 in. inner diameter and 3 in. length was fitted to the inside back of the cavity for effective transmission of microwave fields into the chamber. The rectangular waveguide, made of aluminum, is designed for a TE01 mode where TE is the transverse electric field mode as shown in Figure 3-6.

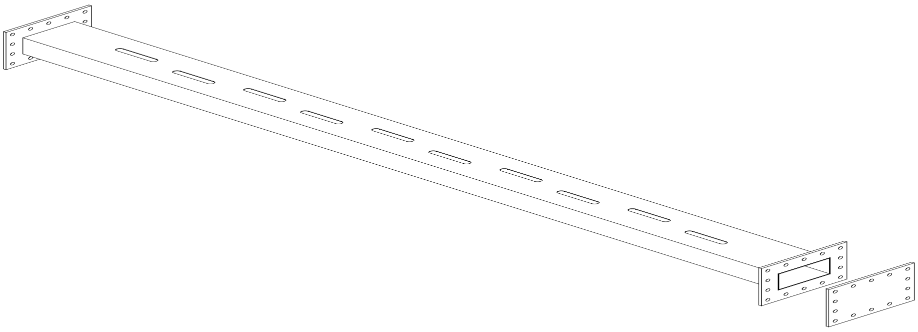


Figure 3-6. The rectangular waveguide for a TE01 mode

3.2.2.3 Cavity

The wall of the cavity is made of stainless steel mesh with dimension 2 mm which is much smaller than the wavelength of microwave. Since the impedance of the rubberwood will vary widely during drying, it is very difficult to acquire impedance matching by a single-mode excitation. The microwave field pattern inside the cavity is the superposition of all possible modes.

3.2.2.4 High-voltage power supply

The circuit and picture of the high-voltage power supply which produces continuous and adjustable voltage is shown in Figure 3-7.

(a) (b)

Figure 3-7. High-voltage power supply: (a) Schematic circuit of High-Voltage Power Supply and (b) picture of HV power supply [14].

The voltage can be varied from 4,000 V to 6,000 V by controlling two high-voltage transformers. A switching technique using a control unit and high-power MOSFETs is utilized to adjust the input voltage properly for the two transformers. The output of the lower transformer is fixed at 3,000 V, whereas the upper transformer produces an output voltage between 1,000 and 3,000 V [14]. The microwave power, $p_{\mu w}$ is calculated from the heat generated in the water, as it absorbs microwave power. $p_{\mu w}$ is calculated using Equation 3.1.

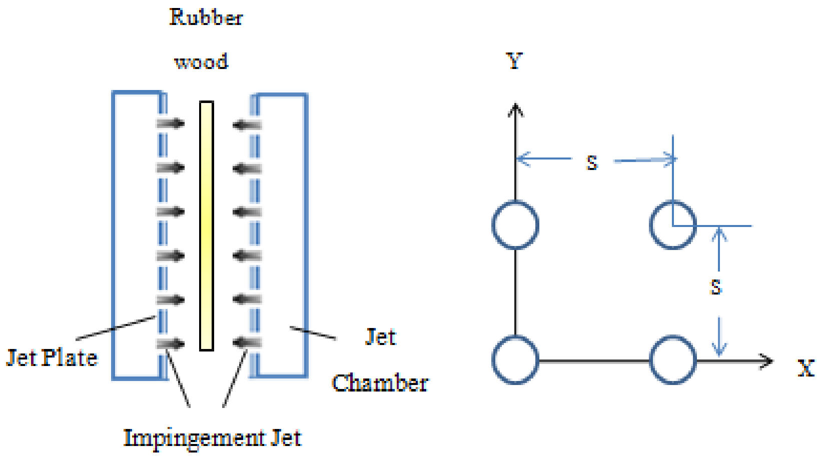
$$p_{\mu w} = \frac{4.19V\Delta T}{t} \qquad (3.1)$$

where t is time, V is the water volume, ΔT is the temperature difference of the water after absorbing microwave power for t seconds.

3.2.3 Hot air

The dual-hot air drying unit consisted of a blower, a valve, an electric heater, a temperature controller. An air blower of 2 HP with 3000 r.p.m. was connected a tube of dimension 1.5 in. x 1.5 in. and its shaft fitted heater to the front and back of three chamber to enable the impinging hot-air. In each experimental condition to control the flow and temperature of the jet for both sides equally (see Figure 3-8a). Electrical heaters of 3 kW were used to supply hot air which the temperature controller was able to control the digital temperature controller range of 1-100°C. A gate valve was also connected after the heater, to regulate the supply of hot air through inside a closed chamber. Temperature measurement can be done by thermocouple type K. For online weight measurement of samples, a load cell is integrated into the computer system.

In this experiment, orifice jet is used with diameter 10 mm and the distance between the jet is five times of the orifice jet diameter (see Figure 3-8b). Velocity in center of orifice jet by anemometer measurement ran at 10 m/s and parameter of temperature was taken 60-80°C (see in Table 3-1). Combined microwave and hot air construction is shown in Figure 3-9.



(a) (b)

Figure 3-8. Details of experimental condition: (a) Expression measurement of dried rubberwood (b) Showing arrangement of jet orifices

Table 3-1. Details of variables used in the experiment

Orifice diameter (D)	10 mm
Jet-to-Jet distance (S)	5D
Jet velocity (V)	10 m/s
Jet temperature (T_j)	60, 70 and 80°C

(a) (b) (c) (d)

Figure 3-9. Combined microwave and hot air construction: (a) Front, side and inner body with installing equipment (b) Power supply (c) Manometer (d) load cell program

3.3 Experimental procedure

Rubberwood drying experiments, divided into two main parts. The first part was described in chapter 4 entitled “drying characteristics of rubberwood by impinging hot-air and microwave heating and the second part was in chapter 5 entitled “a comparison of impinging hot-air and microwave heating on rubberwood drying”. An overview of all experimental conditions and testing is shown in Figure 3-10.

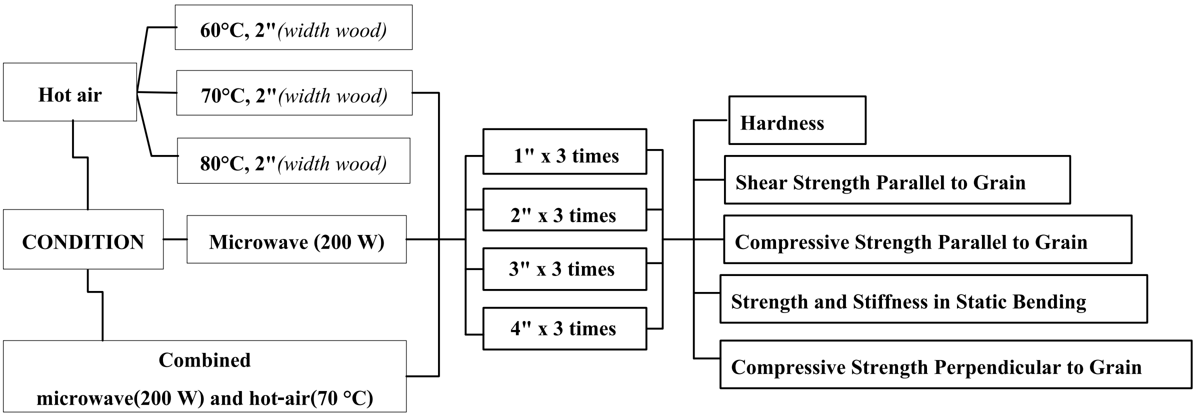


Figure 3-10. Procedure of rubberwood drying by hot air and microwave methods

3.4 Properties of rubberwood

3.4.1 Physical of wood properties

Defects in any one of these categories are caused by an interaction of wood properties with processing factors. Physical properties according to standard quality rubberwood can all be detected by visual inspection. The five major types of warp are cup, bow, crook, twist, and diamonding.

3.4.2 Color measurements

The color of the finished product is crucial to the acceptance in the market. In order to produce a high quality rubberwood, wood boards of naturally different shades and colors are required to be classified and grouped. Within each group, wood boards of comparable shade and color are form shade and color of the required dimensions. Surface color are used widely for the evaluation of rubberwood surface quality which high temperature drying process caused a darkening on the surfaces of rubberwood. A light color of the dried rubberwood is preferred, which is usually obtained through maintaining a low drying temperature. Currently, many manufacturers in Thailand still rely heavily on a manual classification process by an expert. In this paper, the outcome is used to classify an unknown color rubberwood board with a color group identification algorithm of factory (see Figure 3-11).

A-1 (Pass) A-2 (Pass) A-3 (Pass) B-1 (Fail) B-2(Fail)

Figure 3-11. Sample of rubberwood drying compared standard of color measurement: A-1 (white-cream), A-2 (white-yellow), A-3 (yellow-red), B-1 (dark red), B-2 (dark red-black)

3.4.3 Mechanical properties

Five methods were conducted for testing mechanical properties of rubberwood by Lloyd Universal Testing Machine (see in Table 3-2 and Figure 3-12). The mechanical properties tested were strength and stiffness in static bending, hardness, compression strength parallel to grain, compressive strength perpendicular to grain and shearing strength. All wood samples were dried to a moisture content of approximately 15%(d.b.) and three test samples were used for each of the tests that were performed in a temperature and humidity controlled testing laboratory at the Walailuk University (see Figure 3-13)

Table 3-2. Standard for testing mechanical properties of rubberwood

Properties	Standard tests for rubberwood
Compression stress - Perpendicular to grain - Parallel to grain	BS 373, ASTM D143 and ISO 3787
Strength and stiffness in static bending	BS 373
Shear strength parallel to grain	BS 373 and ISO 3346
Hardness	ISO 3350

Compression strength parallel to grain   Shearing strength   Compressive strength perpendicular to grain

Bending   Hardness

Figure 3-12. The samples of rubberwood for mechanical tests

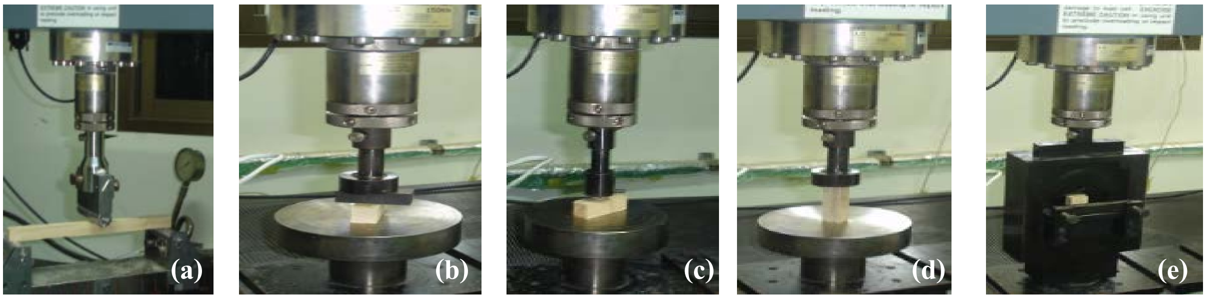


Figure 3-13. Testing mechanical properties of rubberwood by universal testing machine: (a) Strength and stiffness in static bending, (b) Compressive strength perpendicular to grain, (c) Hardness, (d) Compression strength parallel to grain and (e) Shearing strength

Chapter 4

Drying Characteristics of Rubberwood by Impinging Hot-air and Microwave Heating

4.1 Introduction

The wood from rubber tree has been used for a wide range of products. Rubberwood factory processes essentially include logs acquisition, sawing, borax-based chemical solution impregnation, drying, inspection, storage and distribution. Drying is a most important process to be carried out as it is one of the energy-intensive processes with desired targets in shorter drying times at appropriate drying temperature while rendering minimal quality deterioration. Practices by different factories vary in technical details. In an industrial-scale operation, the heat, mostly transferred by steam in a closed conduit, is supplied via conventional lumber-drying kiln, providing drying temperature in the range of 60-85°C. The required final moisture content of a product varies from 6 to 16% depending on its intended applications. Drying time depends on the wood thickness. This usually takes 8 to 12 days under conventional drying, which is rather time and energy consuming. Many researchers on wood drying have aimed over the years to reduce energy consumption and material losses via many methods, such as, accelerated conventional temperature drying [33], superheated steam [34], superheated steam vacuum drying [35], vacuum drying [36], microwave drying [20, 22, 37-40], microwave vacuum kiln drying [41] and combined microwave and convective drying [42]. Microwave energy application in particular has been investigated due to an advantage on rapidity over conventional methods. Woods investigated yielding successful desirable outcomes include: southern pine strands, softwood, Norway spruce, and Scots pine [22, 37-41]. Although heating by microwave is recognized as a rapid treatment, it is nonetheless characterized by a certain degree of non-uniformity in temperature distribution [43]. In addition, the use of microwave power depends on the kind of wood, as well as thickness and length of the products [3]. Moreover, the non-uniform airflow effect is particularly difficult to resolve in industrial wood drying kilns [44]. Airflow patterns have been investigated in conventional heat-and-vent timber kilns to determine appropriate design modifications that will promote more uniform flows and heating [45]. As for another successful alternative, jet impingement has been successfully and efficiently employed in drying or dehydration of moist substrates, like food slices or plates, among other applications [46]. All these benefits lead to the conclusion that it is of high potential that microwave and impinging hot-air drying are taken into account in the development of wood drying process. The main objective of this study hence is to explore and charaterize rubberwood drying using the two above method, physical and mechanical properties included. Outcome of the findings is anticipated to be a helpful step in any further investigations on the subject.

4.2 Materials and methods

All wood samples used in the experiments were of A-B grade and were obtained from *Woodwork* Advanced Co., Ltd. Songkhla province, Thailand. Rubberwood samples, 1 in. thick 46 in. long with width ranging from 1 to 4 in., were produced and impregnated with borax-based chemical solution prior to drying. The experimental system, shown in Figure 4-1, consists of two heat sources, one for the application of hot-air and the other for the generation of microwave. The laboratory-scale drying chamber cavity has been designed to fit general wood sizes in furniture industries, having an inside dimension, in inch, of 23.6 (width) x 7.9 (depth) x 59.1 (height). The dual hot-air drying unit with temperature controller consists of a blower, a 3 kW electric heater, and a valve. Each 2 HP 3000 rpm air blower is connected to a 1.5 in. dia. pipe with its shaft fitted with the electric heater. Temperature measurements were conducted employing a thermocouple type K. Hot air was blown through six 1.5 in. x 1.5 in. rectangular tubes placed at the front and the back of the three vertically fixed samples within the chamber. The orifice of free jet flow has a diameter of 0.4 in. with spacing between the jets of five times the orifice diameter, i.e. every 2 inch. A 0.001 kg precision load cell with a maximum capacity of 5 kg is integrated into the computer system for online weight measurement of the samples. The load cell, with a string holder for continuous weight recording of the sample, is placed on top of the drying chamber to record every 5 minutes the weight of the middle rubberwood sample. The other two samples were weighed before and after each experiment. Moisture content was calculated based on dry basis. As for the microwave, connected to the other side of the chamber which houses the three samples, the 2.45 GHz device has a maximum power of 200W. It is operated through a magnetron connected to a power supply. Energy is dissipated through 2 rectangular waveguides situated between the three samples.

The drying experiment thus consisted of two parts with a hot-air heating where temperature and jet flow velocity were kept at 60-80°C and 10 m/s, respectively, and a microwave heating with a maximum power input of 200W. The drying design for the 1 in. thick 46 in. long rubberwood samples with varying widths (1, 2, 3 and 4 in.) is as follows: (1) hot-air drying of 2 in. width samples at temperature of 60-80°C to evaluate the dried rubberwood properties so that the most appropriate temperature with optimum drying time with least defects could be selected to further determine the effects on different width sizes employing the same hot air drying technique, and (2) drying of the rubberwood with varying widths employing the 200W microwave.

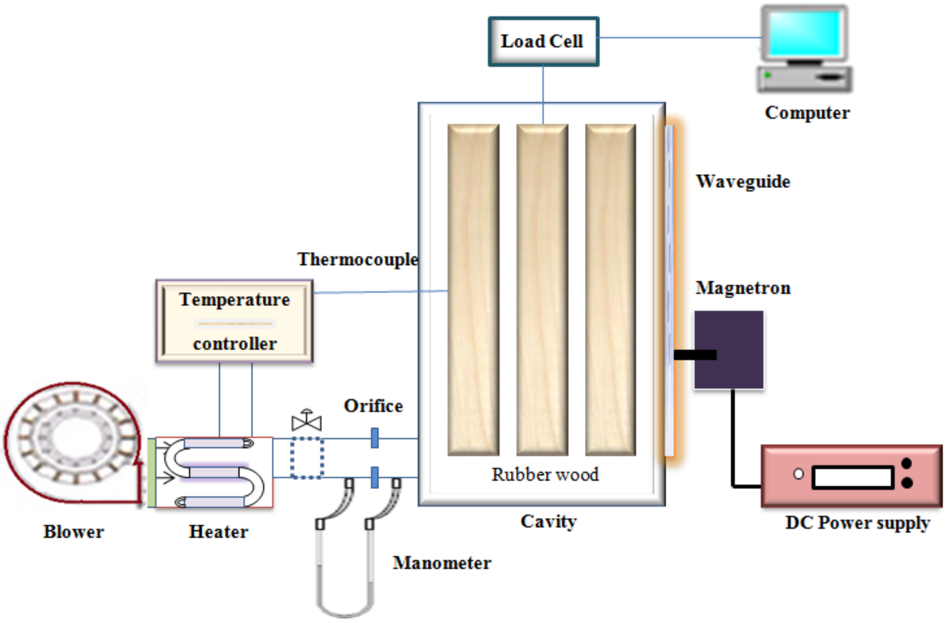


Figure 4-1. Schematic diagram of the hot air - microwave dryer

One the surface of each sample, three temperature measurements, one at the center and another two at two evenly-spaced positions along the length, were measured every 2 hours with the thermocouple. After the weight became almost constant, physical properties of the dried wood regarding occurrence of drying defects such as cup, bow spring and colors were evaluated. Moreover, the dried rubberwood was cut for case hardening to assess initial acceptability through prong test with U bend performance. In addition, mechanical properties on maximum stresses in compression parallel and perpendicular to grain according to ASTM D143, BS 373 and ISO 3787, and shear strength parallel to grain according to BS 373 and ISO 3346 were carried out. Additional measurements were made to evaluate the modulus of elasticity and the modulus of rupture in static bending according to BS 373, and hardness according to ISO 3350. All mechanical tests were performed in triplicates in a temperature and humidity controlled laboratory employing a Lloyd Universal Testing Machine.

4.3 Results and discussion

Drying rate: For hot air drying experiments within the 60-80°C temperature range, when the hot air temperature was maintained at 80°C reduction of moisture content from around 55% (d.b.) to 15% (d.b.) was achieved in approx. 7 hours, as depicted in Figure 4-2, albeit with excessive bending defects. With temperature maintained at 70°C and 60°C, the required final moisture content of 15% (d.b.) was reached in about 9 hours and 18 hours, respectively, without resulting in excessive defects. The operating temperature at 70°C was thus determined to be the most appropriate temperature of the hot air drying technique considering the lesser time of drying while maintaining the desirable physical properties of minimal defects on the dried wood product.

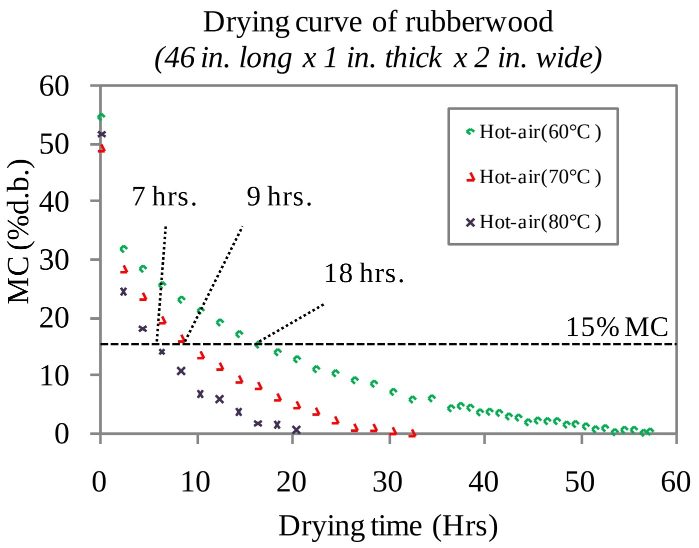


Figure 4-2. Drying curve of rubberwood by hot-air drying at 60, 70 and 80°C

The varying width size tests in subsequent experiments were conducted in triplicates under the chosen hot air drying temperature of 70°C and the results are shown in Figure 4-3. In this case, the average reduction of the initial moisture content value of 52% (d.b.) to less than 15% (d.b.) was reached after 6, 9, 10 and 10 hours. for the drying widths of 1, 2, 3 and 4 in., respectively. This implies that it is possible to dry 1 in. thick rubberwood of size larger than 2 in. wide together to attain similar dryness at same time and temperature. On the other hand, the average time required under the 200W microwave drying, as evidenced in Figure 4-4, from an average initial wood moisture content of 54% (d.b.) to 15%(d.b.) was 16, 20, 26 and 29 hours for the 1, 2, 3 and 4 in. width samples, respectively. Obviously, as the width of the rubberwood increased, the time required to achieve a certain moisture level increased. The surface temperature of all wood samples were around 40°C after 2 hours and increased to nearly 70°C then leveled off until the final moisture contents of the wood samples approached zero under continuous maximum magnetron power output. During drying, the warm-up periods for all samples were almost identical regardless of sample widths. An evaporation period ensued until their surface temperatures increased up to a common plateau. This is plausibly due to certain temperature dependent properties and surface evaporating effects on different rubberwood widths. The drying time-moisture content characteristics for our impinging hot-air drying at 70°C and our microwave drying at 200W had been further compared, respectively, with a drying behavior exhibited under superheated steam at 110°C on 3 in. wide rubberwood samples reported by Yamsaengsung and Buaphud [34] in Figure 4-3 and Figure 4-4. The results indicate that our impinging hot-air and microwave dryings are both faster to dry rubberwood than the superheated steam drying method.

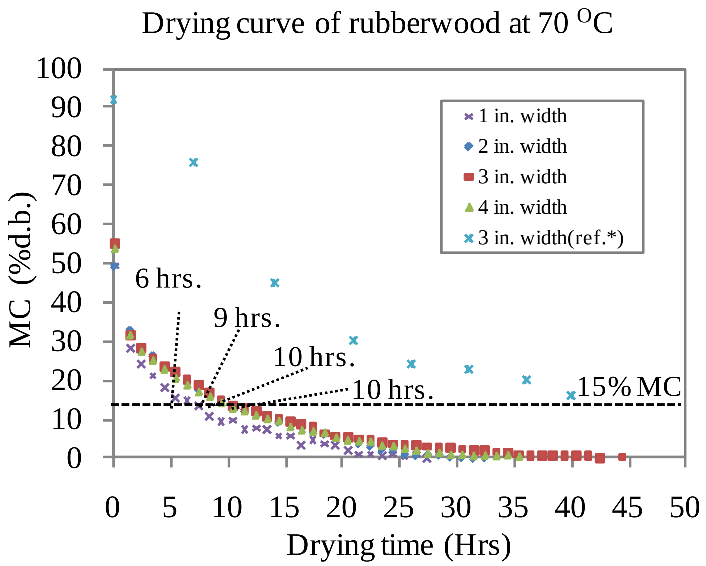


Figure 4-3. Drying curve of rubberwood with varying width size for hot-air at 70°C (*Ref. taken from Yamsaengsung R. and Buaphud K., 2006 [34]).

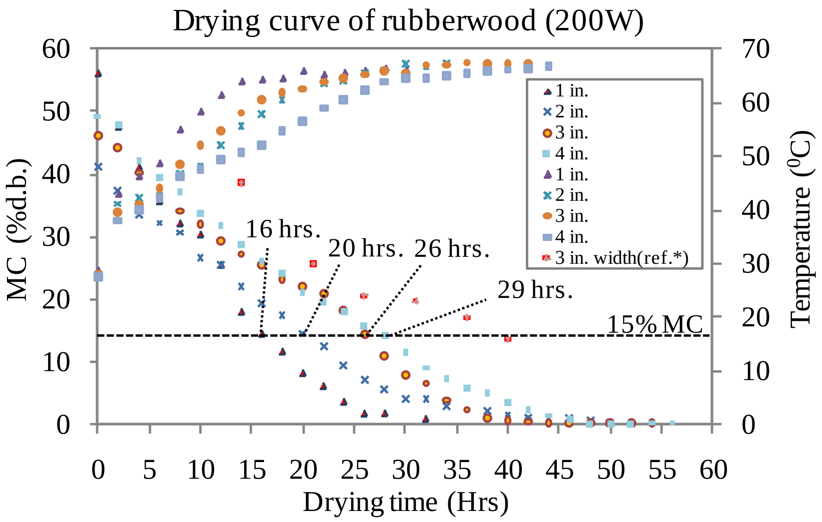


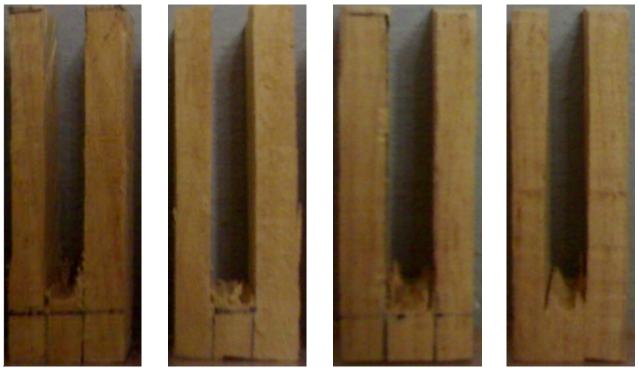
Figure 4-4. Drying curve and average temperature change of dried rubberwood with varying width size for microwave drying at 200W

(*Ref. taken from Yamsaengsung R. and Buaphud K., 2006 [34]).

Physical properties: After removal from the chamber cavity all samples were visually inspected. Of the 9 samples (3 samples in triplicates for each width size) on the 1 in. wide samples subjected to the hot-air (70°C) drying method, 3 pieces exhibited bow-and-spring defect; of the 9 samples on the 2 in. samples 2 pieces exhibited bow defect; of the 9 samples on the 3 in. samples 1 pieces exhibited spring defect; of the 9 samples on the 4 in. samples not one piece exhibited any kind of defects. For the microwave drying (200W), 4 out of 9 pieces of the 1 in. wide samples were rejected with bow-and-spring defect; 4 out of 9 of the 2 in. with bow defect; 1 out of 9 of the 3 in. with crack defect; and for the 4 in., 1 out of 9 with spring defect plus 1 with bow-and-spring defect. The ends of the 2 in. wide dried rubberwood remained relatively flat after being subjected to impinging hot-air at 70^{o}C, as can be visualized in Figure 4-5a. In contrast, hot-air at 80^{o}C had an effect, shown in Figure 4-5b, in increasing the curvatures at their ends. The color after drying by either hot-air or microwave exhibited minimal changes from the originals. The overall color appearance on all dried rubberwood surface retained its white-cream (A-1) characteristics, which is the most preferred appearance category. Moreover, results of both drying methods from prong tests revealed no bends to slight bends in the prongs, as depicted in Figure 4-6, indicating no residual stresses from drying.

(a) (b)

Figure 4-5. Physical property resulted: (a) After drying with impinging hot-air at 70^{o}C, (b) After drying with impinging hot-air at 80^{o}C



(a) (b) (c) (d)

Figure 4-6. Prong test of the dried rubberwood from different width size of the sample: (a) 1 in. (b) 2 in. (c) 3 in. (d) 4 in.

Mechanical properties: Results from mechanical property tests for the hot-air and the microwave dryings are shown in Figure 4-7, together with reference values reported by Yamsaengsung and Buaphud [34] and by Killman and Hong [8]. The ability of wood to resist loads depends on a number of factors, including the type, direction, and duration of loading; ambient conditions of moisture content and temperature; and the presence or absence of defects such as knots and splits [47].

Wood stiffness is generally more significant than wood strength for mechanical performance [48]. In the measure of wood stiffness, the average modulus of elasticity (MOE) value (Figure 4-7a) of the 1 in. width wood samples subjected to hot-air drying was found to be higher than those of other sizes and the references values [8, 34]. Values for the 2 in. and the 3 in. wood samples under hot-air drying, however, were found to be lower compared with those subjected to microwave drying, while for the 4 in. similar MOE values from both drying methods were obtained. In Figure 4-7b, values of the modulus of rupture (MOR), which is a measure of material breaking strength, for the 1 in., 3 in. and the 4 in. obtained under hot-air drying were found to be rather similar to that of the corresponding same sizes under microwave drying, while for the 2 in. the average of those from hot-air drying was slight lower than those from microwave drying. MOR and MOE averages for each width size from both drying methods were observed to be higher than the referencing values except for MOR of the 2 in. (97.4 MPa) and 3 in. (102.84 MPa) under hot-air drying, which were slightly lower than that of the reference value from Yamsaengsung and Buaphud (107.06 MPa), and might be because of variation of wood. Modulus of rupture reflects the maximum load-carrying capacity in bending and is proportional to the maximum moment borne by the specimen. It is also a well-known common accepted strength criterion though it is not a true stress because the formula by which it is calculated is valid only within the elastic range [47]. Nevertheless such comparison of rubberwood data ought to be helpful in furniture design.

For shear strength parallel to grain test, with shear failure typically occurring on both sides of the middle support, the shearing strength values found were mostly higher when subjected to microwave drying than those found under hot-air drying (Figure 4-7c). The average shear strengths in both drying methods were observed to be higher than both reference values for any width sizes. Because wood is highly orthotropic, it is very difficult to get it to fail in shear perpendicular to the grain [47] and hence no tests had been carried out in this research. Furthermore, it had been reported that effect of temperature has no significance on the mean MOR, MOE, and on the shear strength, of lumber after drying under high temperature [49].

For compression strength tests of the rubberwood, these were performed with load applied parallel to, and perpendicular to the grain. The compressive strength parallel to grain values (Figure 4-7d) for those subjected to microwave drying were observed to increase with increasing width size. The 1 in. width sample in hot-air drying is the only group that exhibited slightly higher value compared with the group subjected to microwave drying. As for the mean compressive strength perpendicular to grain, Figure 4-7e showed that the 1 in. width group after microwave drying yielded the highest average value, whereas the results of the 2 in. group after hot-air drying yielded the lowest. Compressive strength parallel to the grain is usually much greater than that perpendicular to the grain. Approx. 90% of the wood cells are aligned vertically (known as grain) and the remaining percentage is present in bands (known as rays). This means that there is a different distribution of cells on the 3 principal axes; this is the main reason for the anisotropy present in timber. Compressive strength of wood perpendicular to the grain is simply a matter of the resistance offered by the wood elements to being crushed or flattened. Therefore, the strength of wood under forces perpendicular to the grain is relatively small [50]. Finally, the mean hardness (Figure 4-7f) showed a slight trend to decrease in microwave drying from 1 in. to 4 in. width but were higher than those of same sizes under hot-air drying. The values of hardness found were all higher than that reported by Yamsaengsung and Buaphud [34] as well as Killman and Hong [8], indicating and confirming that rubberwood is sufficiently hard for various furnishing applications.

Results of different width size rubberwood derived from the conducted experiments and tests reveal that all wood sizes after subjected to either drying method, be it hot air or microwave, had higher, and hence better, mechanical properties than reference values; that rubberwood with 1 in. width size yielded the highest MOE by hot-air drying method; that compressive strength perpendicular to grain of the 1 in. by microwave drying and the 3 in. by hot air drying were among the highest; that the 4 in. width rubberwood by microwave drying gave the highest MOR, highest parallel-to-grain shear strength, and highest parallel-to-grain compressive strength; and that hardness by microwave drying was highest.

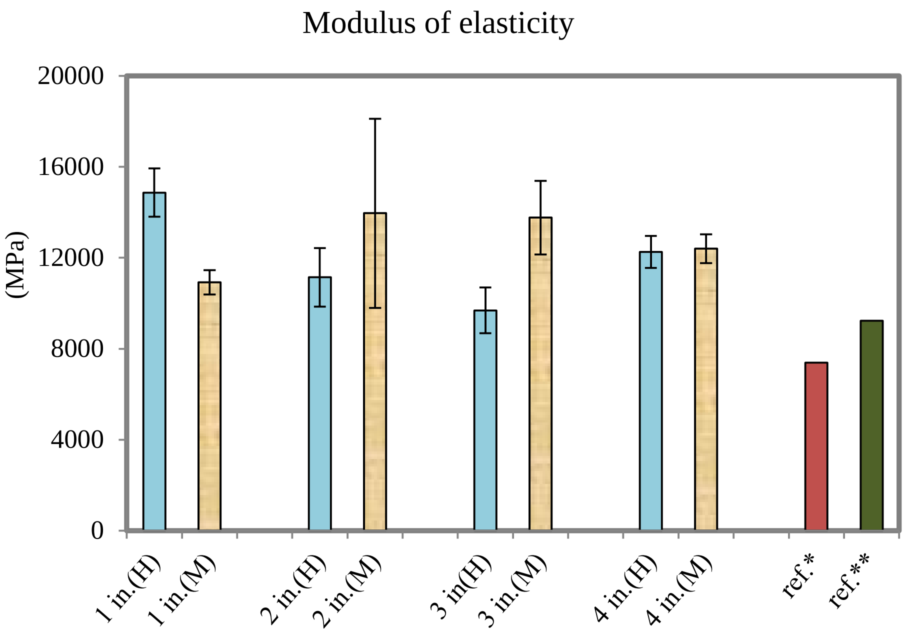
Energy consumption: The energy consumption of hot-air was generated by blower and heater whereas the energy requirement of microwave was consumed by the power delivered to water load. The specific energy consumption (SEC) of wood drying is defined as the energy per unit weight loss of drying process. The SEC values of both techniques were tabulated in Table 4-1. It is obviously found that the SEC values for those subjected to microwave drying were observed to have the higher values than that of hot air, resulting in higher energy requirement for drying process. Also, the SEC values for those subjected to microwave drying or hot air were found to decrease with increasing width size.

Table 4-1. Energy consumption of hot air drying and microwave heating.

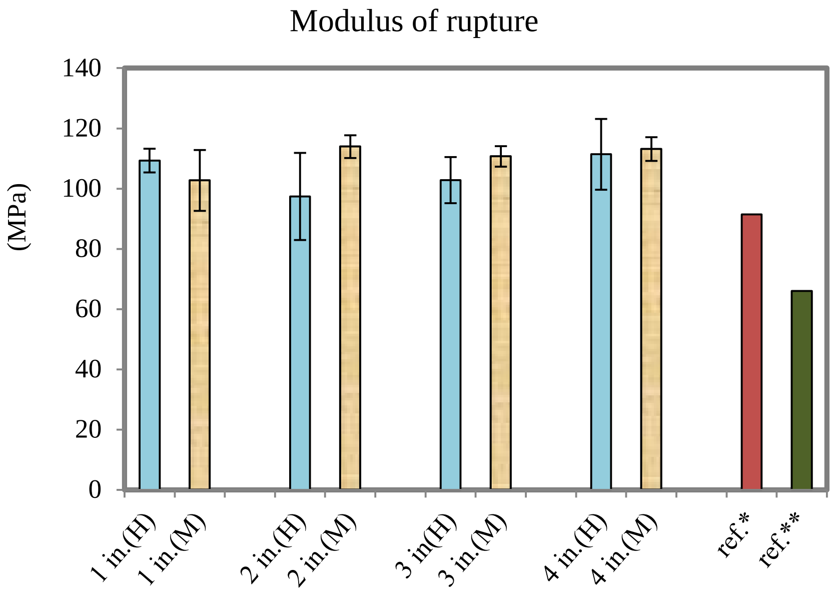
Heat source	Condition	Width sizes (in.)	Drying time (hrs)	Energy (kWh)	SEC (MJ/Kg)
Hot air	60°C	2	18	0.92	6.11
	80°C	2	7	0.36	2.55
	70°C	1	6	0.32	4.14
		2	9	0.45	3.19
		3	10	0.51	2.38
		4	10	0.53	2.10
Microwave	200W	1	16	4.1	43.03
		2	20	5	28.04
		3	26	6.4	23.02
		4	29	7.25	19.94

4.4 Conclusions

After reaching constant weight, the time required for impinging hot-air drying from an initial wood moisture content range of 54%-52% down to 15 percent moisture content is 10 hours, which is much less than the 29 hours needed for microwave drying under same constraints. The time required to achieve a certain moisture level of rubberwood for both drying methods increases with increasing width size, with hot air method yielding a plateau much sooner. For hot air drying the optimal temperature for drying is 70°C. For microwave drying, the average initial surface temperature of the wood after 2 hours is 40°C and subsequently increases to approx. 60-70°C at the center and at the two ends of the wood surface. The average moisture reduction time by hot air drying was 6 and 9 hours for drying widths of 1 and 2 in. whereas 10 hours were spent for drying widths of both 3 and 4 in., implying that it is possible to dry rubberwood of size larger than 2 in. wide together to attain similar dryness at same time and temperature. However, this is not applicable under microwave drying since the time required differs widely; from 16, 20, 26 to 29 hours for the 4 corresponding increasing sizes. In addition, the energy consumption of drying process by microwave heating was found much higher than that of hot air. More importantly, both experimental results obtained - though at pilot scale – indicate great potentials of the 2 processes by drastic reduction of drying times, while giving not much sign of residual stresses, retaining natural color of the wood, as well as improving certain mechanical properties of the dried products.


Modulus of elasticity
(MPa)
20000
16000
12000
8000
4000
0
1 in.(H)
1 in.(M)
2 in.(H)
2 in.(M)
3 in(H)
3 in.(M)
4 in.(H)
4 in.(M)
ref.*
ref.**

(a)


Modulus of rupture
(MPa)
140
120
100
80
60
40
20
0
1 in.(H)
1 in.(M)
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2 in.(M)
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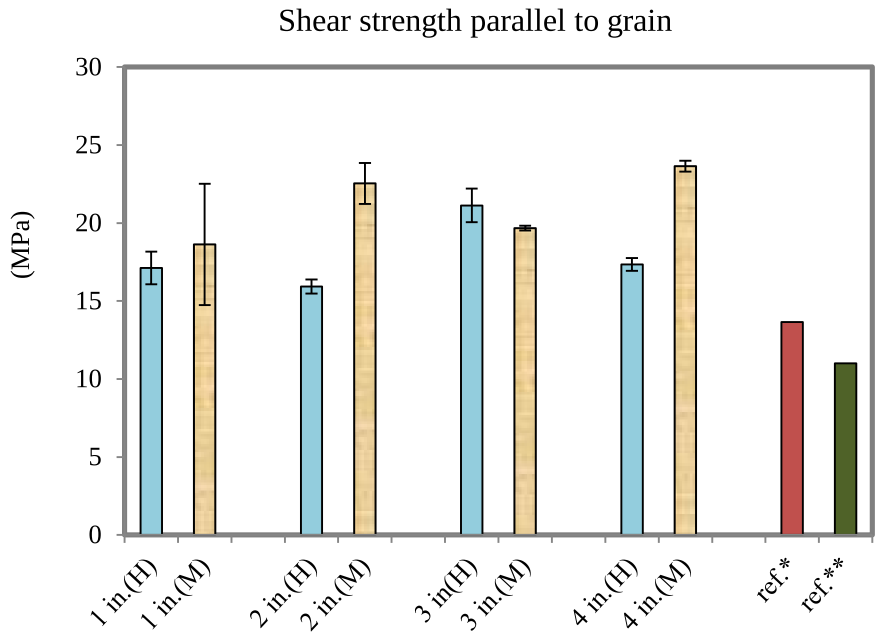
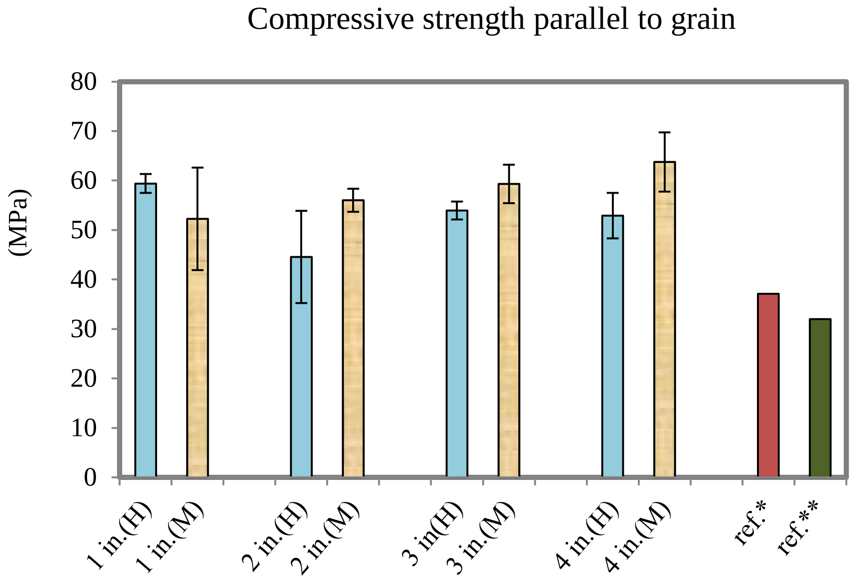
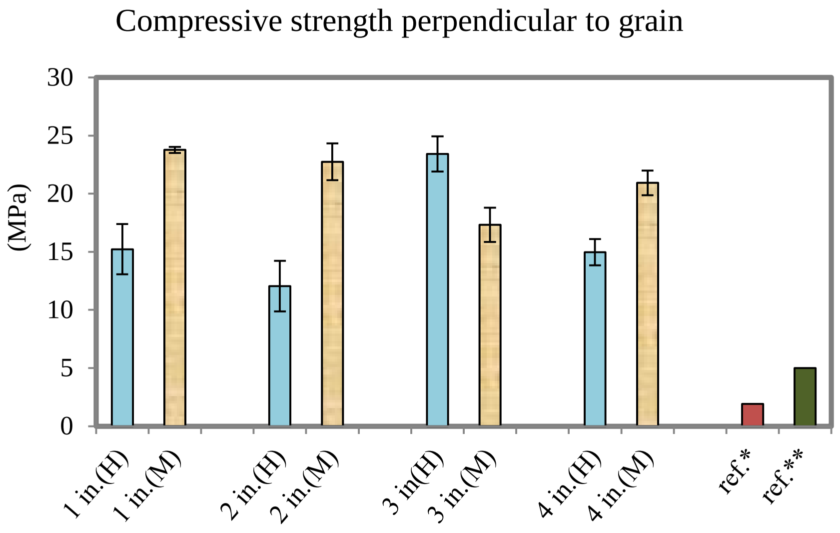
(b)


Shear strength parallel to grain
(MPa)
30
25
20
15
10
5
0
1 in.(H)
1 in.(M)
2 in.(H)
2 in.(M)
3 in(H)
3 in.(M)
4 in.(H)
4 in.(M)
ref.*
ref.**

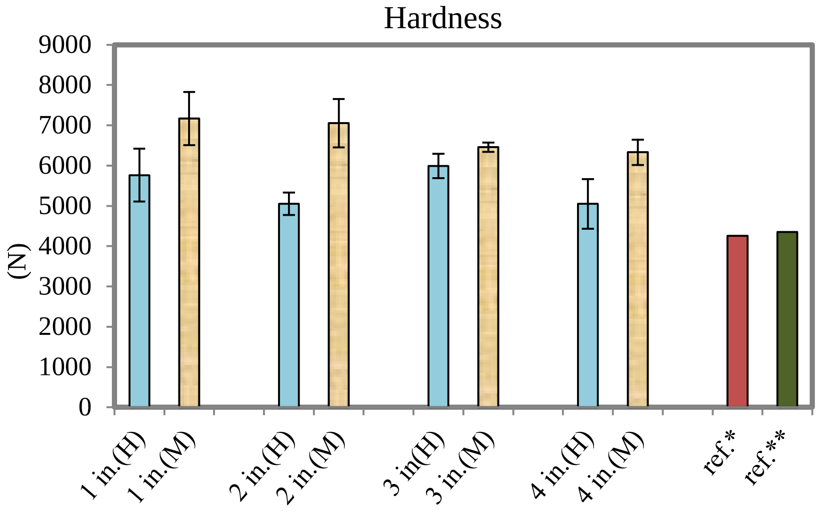
(c)


Compressive strength parallel to grain
(MPa)
80
70
60
50
40
30
20
10
0
1 in.(H)
1 in.(M)
2 in.(H)
2 in.(M)
3 in(H)
3 in.(M)
4 in.(H)
4 in.(M)
ref.*
ref.**

(d)



(e)



(f)

Figure 4-7. Average mechanical property result of various width sample tested under microwave (M) and hot-air (H) drying, together with reference values

(*Ref. taken from Yamsaengsung R. and Buaphud K., 2006 [34]; **Ref. taken from Killman W. and Hong L.T., 2000 [8]).

Chapter 5

Effect of Combined Microwave Heating and Impinging Hot-air on Rubberwood Drying

5.1 Introduction

Rubber trees are wood material used and exported instead of natural forest for wood processing industries in the South of Thailand. Before delivery to a customer, drying of rubberwood is the most important process because of time consuming and high cost. The common used method in rubberwood industry is to heat the lumber by steam in lumber-drying kiln [33]. Rubberwood is usually arranged in stacks and dried in a 400–600 m^3 chambers at temperatures of 80–100^oC and the drying time varies from 7 to 16 days depending on the thickness of the lumber and initial moisture content (about 0.85–0.95 db for freshly chemically treated wood) [34]. Because of reasonable cost, drying time is expected to be shortened by high-temperature drying but a higher drying rate is not always desirable because higher drying rates develop greater stresses that may cause the timber to crack or distort [51]. Microwave drying is one of the most significant methods due to the possibility of heating and drying materials much faster than conventional methods that the temperature is the higher at the surface and the lower in the interior of lumber. There are many successful of drying woods by applying microwave energy including southern pine strands, softwood, Norway spruce and Scots pine [22, 23, 38-41]. However, a major drawback with microwave heating is the inherent non-uniformity of the electromagnetic field within microwave cavity [52] and one more is that too rapid mass transport by microwave power may cause quality damage [53]. In recent years, microwave in combination heating with hot air is one of the most interesting methods used to achieve uniform temperatures [6]. A 22–30% increase in uniformity has been observed for combination microwave and jet impingement heating over microwave-only heating [54]. The plant materials investigated using mirowave assisted hot-air include apple, laurel berry, corn, grapes and carrots [32, 55-59]. Although, microwave technology assisted hot air has found wide application in many materials, but there is no study on the drying of rubberwood with significant contribution to the wood industry. Therefore, the objective of research was to examine the feasibility of combination of microwave heating and hot air in helping to attain increased uniformity of heating and to determine properties of the obtained wood compared with conventional drying in an experimental kiln.

5.2 Materials and methods

The rubberwood of 1 in. (thickness) by 46 in. (length) with width ranging from 1 to 4 in. were obtained from Wood Work Factory in Songkhla province, Thailand. The construction of the microwave-hot air dryer is shown in Figure 5-1, with detailed information in two main components as follows Table 5-1. During the experiments, a 0.001 kg precision load cell with capacity of 5 kg. on the top of drying cavity is integrated into the computer system in online measurement of the center rubberwood weights with string holder for continuous recording every 5 minutes.

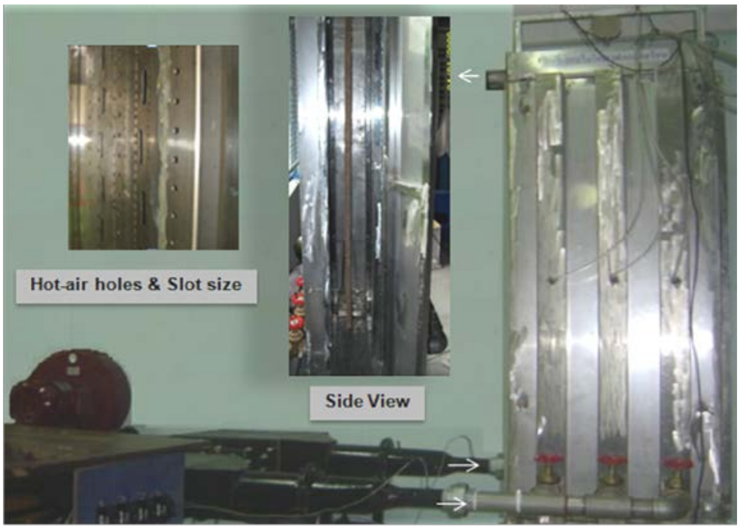


Figure 5-1. Construction of rubberwood dryer

Table 5-1: Components of microwave-hot air dryer

Cavity size:	23.6(W) x 7.9(D) x 59.1(H) $in.^3$
Hot-air: Orifice diameter (D)	 0.4 in.
Jet-to-jet distance (S)	5D
Jet velocity (Vj) Jet Temperature (Tj) Blower An electrical heater	10 m/s $70^{o}C$ 2 HP with 3000 r.p.m. 3 kW
Microwave:	200W at 2.45 GHz

Experiments were conducted in two parts; (1) comparisons of hot air, microwave and combined microwave-hot air heating and (2) effect of different rubberwood width on combined microwave-hot air heating. For the first part, the size of rubberwood with 46 in. length x 2 in. width x 1 in. thick was selected to evaluate the drying time and defects of each technique. The second part was carried out using only combination technique with different width sizes (1, 2, 3 and 4 in.) by 46 in. length by 1 in. thick. Three replications were done for each test. After constant weight, the drying wood quality in physical properties was evaluated regarding occurrence of drying defects such as cup, bow and spring, colors, casehardening. The mechanical properties were also tested including bending test, compression test according to the ASTM standard D143, BS373 and ISO3787, shear strength parallel to grain according to the BS373 and ISO3346 and hardness according to the BS373 and ISO3350, respectively. All specimens were conditioned to the ambient room environment over several weeks in the Wood Mechanics Laboratory, Walailak University, Thailand.

5.3 Results and discussion

Comparisons of hot air, microwave and combined microwave-hot air heating: Hot air at 70°C, a microwave power level of 200W at a frequency of 2.45GHz with maximum working temperature of 70°C and combined microwave (200W)-hot air (70°C) heating are the setting values of each experiment. The results shown in Figure 5-2, indicate that the trend of combined microwave-hot air heating are faster in drying rubberwood than hot air only and microwave only drying technique. All samples showed minimal color change and no defects. The time required for combination heating from initial moisture content ranges of 70%(d.b) to 15%(d.b) of moisture level is 15 hours, which is less than the 21 hours needed for microwave heating or the 26 hours needed for hot air only.

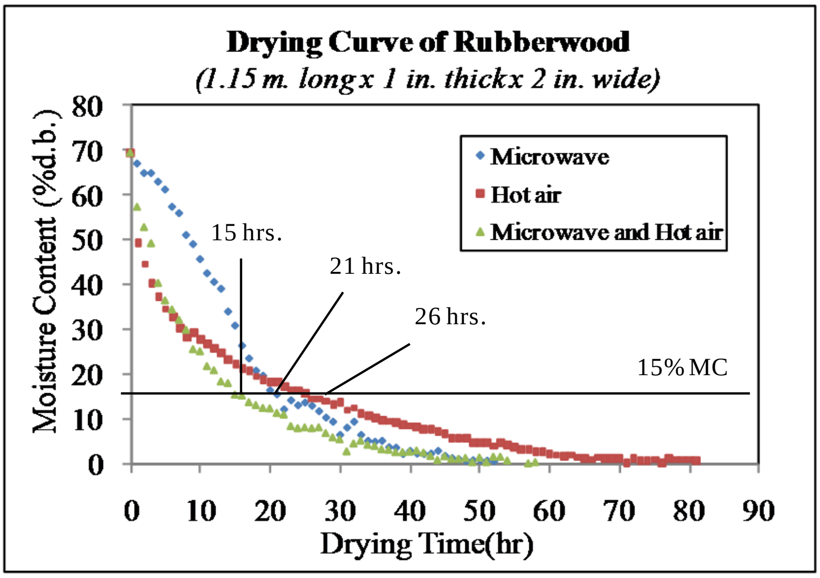
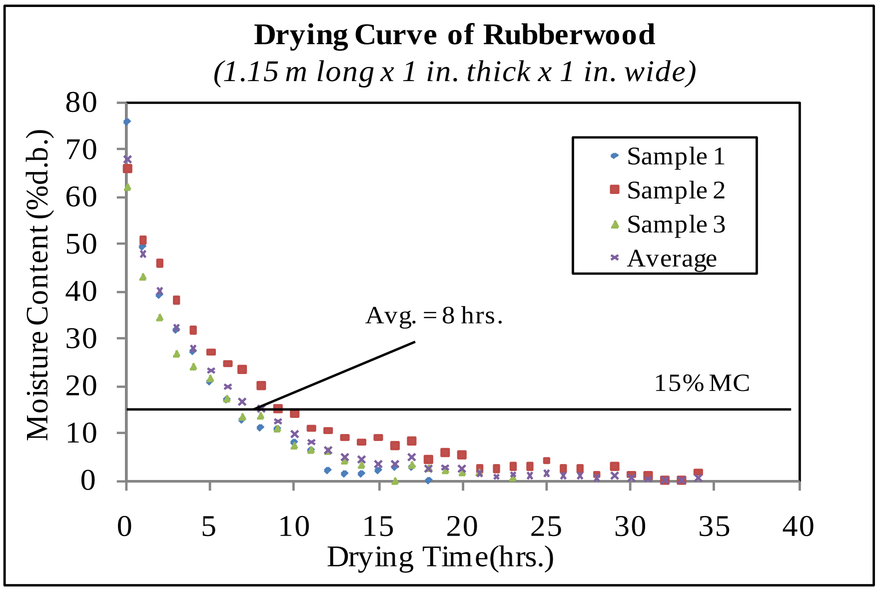


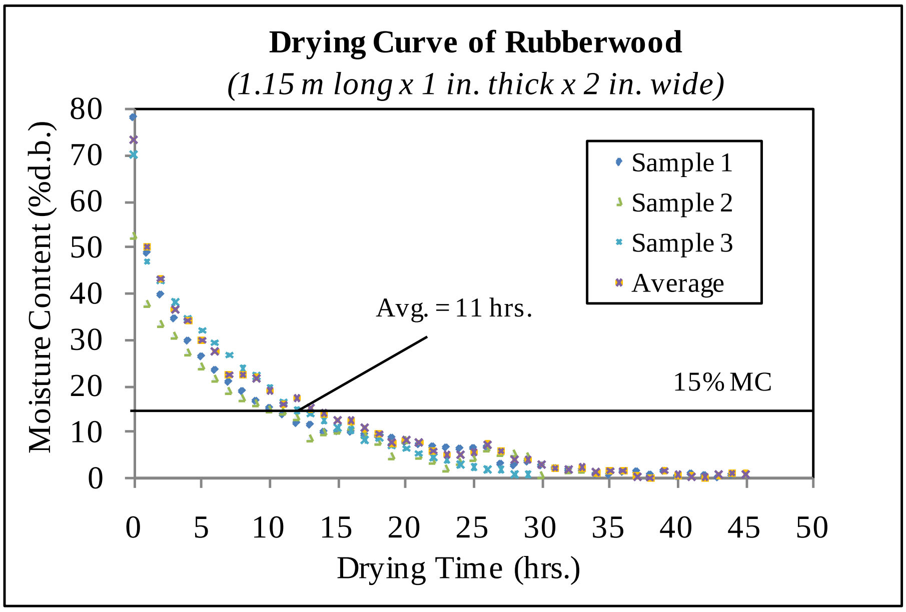
Figure 5-2. Rubberwood drying time of three methods

The experimental results could help to identify some of the potential problems. For hot air drying, the moisture content gradient decreased very fast in earliest stage and then decreases in the falling rate period with long drying times. As microwave drying method is slower in drying rate period of rubberwood than hot air only and combined microwave-hot air drying because the air in the microwave oven was saturated around rubberwood, preventing effective evaporation of moisture from the rubberwood. Meanwhile, the vapour pressure in the rubberwood is higher than that of the environment, the rubberwood starts to lose moisture, but at a slow rate. Considered the drying times in three drying methods, it is possible to dry rubberwood much faster in processing times with combined heating in acceptable physical properties.

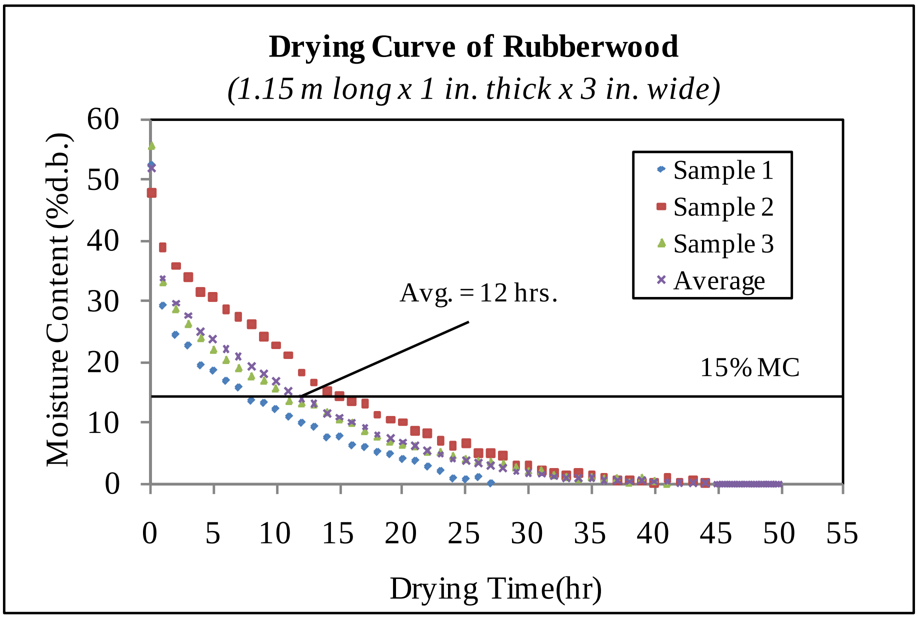
Second Experiment: The moisture content versus time curves for combined microwave (200W)-hot air (70°C) of rubberwood drying as influenced by different width sizes (1, 2, 3 and 4 in.) by 46 in. length by 1 in. thick are shown in Figure 5-3. As a result, the average time spent for combination heating from initial moisture content ranges of 73%-49%(d.b) to 15%(d.b) of moisture level was 8, 11, 12 and 12 hours for width 1 in., 2 in., 3 in. and 4 in. samples, respectively. The positive interaction between microwave and hot air treatments on rubberwood is possibly due to a direct heat generation inside the rubberwood, coupled with the convective heat transfer at the rubberwood surface by hot air. This coupling effect for microwave and hot air significantly shortened the drying time without excessive degradation. In addition, sample sizes used in combined microwave (200W)–hot air (70°C) heating similar reduction rate, it is possible to dry rubberwood in the variables as moisture content and the various width size under similar conditions.



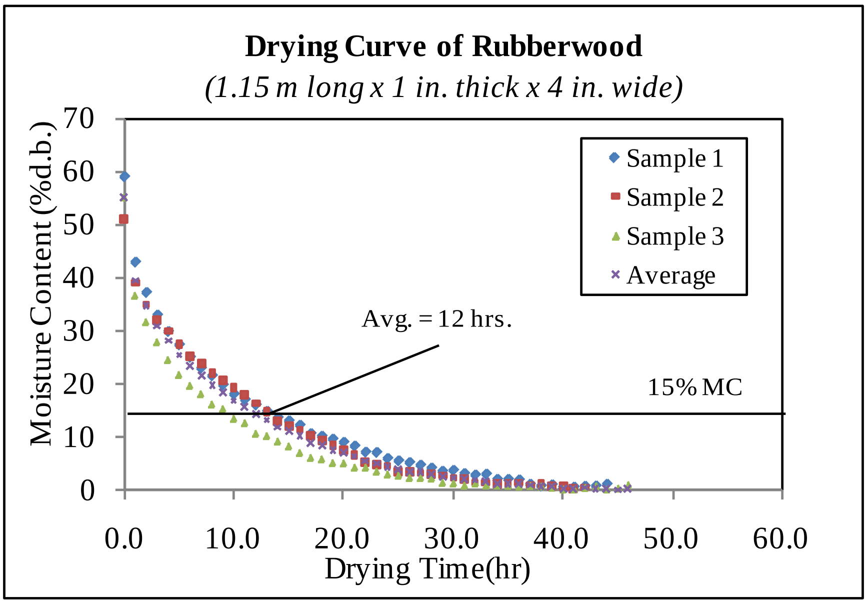
(a)


Drying Curve of Rubberwood
(1.15 m long x 1 in. thick x 2 in. wide)
Moisture Content (%d.b.)
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
Drying Time (hrs.)
Sample 1
Sample 2
Sample 3
Average
Avg. = 11 hrs.
15% MC

(b)


Drying Curve of Rubberwood
(1.15 m long x 1 in. thick x 3 in. wide)
Moisture Content (%d.b.)
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
55
Drying Time(hr)
Sample 1
Sample 2
Sample 3
Average
Avg. = 12 hrs.
15% MC

(c)

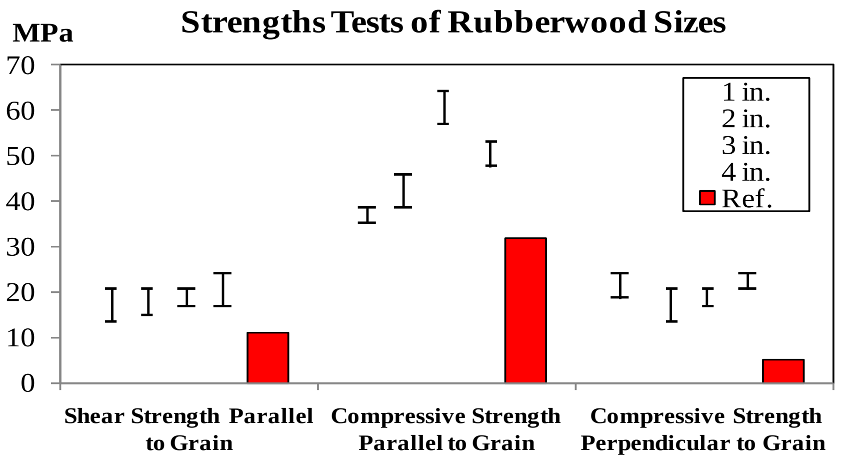


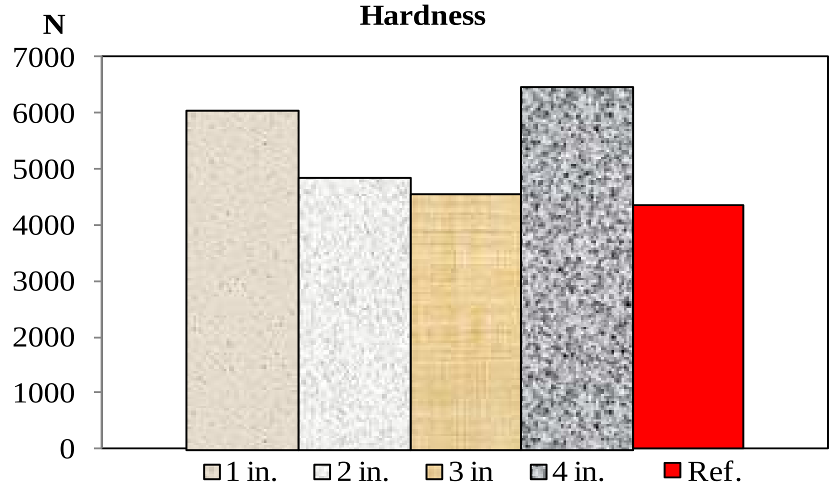
(d)

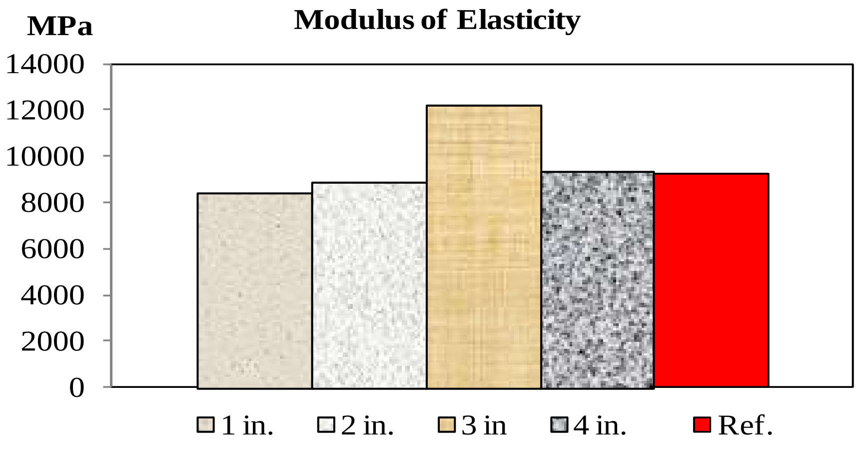
□ Figure 5-3. Drying curves of rubberwood in different width size using combination method

□

In the case of applying microwave-hot air drying methods has been found a critical form of warp, 22% by bow and spring in 1 in. width, 33% by bow and spring in 2 in. width, 22% by bow in 3 in. width and 11% by bow in 4 in. width wood samples will be rejected. Total color of rubberwood changed after high temperature drying is a natural surface compared to fresh wood. Typical prongs test was slight bend which the internal residual stress was relieved by combined microwave-hot air methods. The values of six strength compared with reference values obtained from W. Killman and L.T. Hong [8] in Figure 5-4 are concentrated in the ranges of 16.9-23.9 MPa for shearing strength parallel to grain, 4291.1-6701.6 N for hardness, 73.3-110.2MPa for MOR, 7059.5-12856.7 MPa for MOE, 27.2-14.3MPa for compressive strength perpendicular to grain and 60.6-35.7MPa for compression strength parallel to grain. All mechanical properties of rubberwood was extremely higher average value than the reference value except the MOE of rubberwood with width 1 and 2 in., were values of 8442.7±1383.21 MPa and 8915.92 ±368.84 MPa, respectively only slightly higher than that of the reference value (9240 MPa) due to an increase in variation. However, rubberwood with 3 in. width size has the highest compression strength parallel to grain, MOE and MOR and rubberwood with 4 in. width has a maximum shear strength in parallel-to-grain, compressive strength perpendicular to grain and hardness.


Strengths Tests of Rubberwood Sizes
MPa
70
60
50
40
30
20
10
0
1 in.
2 in.
3 in.
4 in.
Ref.
Shear Strength Parallel to Grain
Compressive Strength Parallel to Grain
Compressive Strength Perpendicular to Grain


Hardness
N
7000
6000
5000
4000
3000
2000
1000
0
1 in.
2 in.
3 in
4 in.
Ref.


Modulus of Elasticity
MPa
14000
12000
10000
8000
6000
4000
2000
0
1 in.
2 in.
3 in
4 in.
Ref.

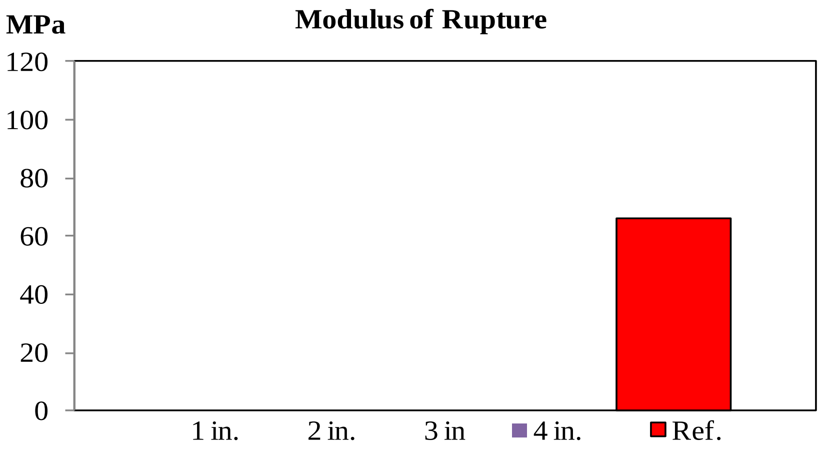


Figure 5-4. The mechanical properties of rubberwood using combination method

Energy consumption: The energy consumption of microwave was consumed by the power delivered to water load. The specific energy consumption (SEC) of wood drying is defined as the energy per unit weight loss of drying process. Table 5-2 shows the SEC values of rubberwood subjected to a combination of microwave and hot air. It was observed that the SEC values found to decrease with increasing width size of rubberwood. However, value for the 1 in. wood sample was found to be significantly higher compared with other width sizes while for the 2 in. and 3 in. have the similar SEC values. Even though the smallest width size has the fastest drying time but found to have the highest energy consumption. Therefore the SEC value would be an important factor in consideration of factory use.

Table 5-2. Energy consumption by combination method according to various width sizes.

Heat source	Width sizes (in.)	Drying time (hrs)	Energy (kWh)	SEC (MJ/Kg)
Microwave (200W) and Hot air (70°C)	1	8	2.42	29.04
	2	11	3.25	16.94
	3	12	3.6	16.82
	4	12	3.71	13.09

5.4 Conclusions

In all cases, the drying time is reduced significantly to less than 8-15 hours in various wood widths from initial moisture content ranges of 73%-49%(d.b) to 15%(d.b) of moisture level. Good quality in physical and mechanical properties of dried rubberwood was also obtained. The SEC values for those subjected to a combination of microwave heating and hot air were found to decrease with increasing width size. Applying the microwave and hot air drying show that it is possible to develop a drying process for rubberwood using microwave-hot air in investigating further in this area.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The study of rubberwood drying was divided into two parts. The first part was carried out by using a microwave heating (200W) and hot air drying (60, 70, 80^{o}C) whereas a combination of microwave (200W) and hot air (70^{o}C) was used in the second part. The rubberwood of 1 in. (thickness) by 1.15 m (length) with width ranging from 1 to 4 in. drying was selected as vehicle studies for each experiment. For the first part, the applications of potential continuous microwave heating and impinging hot-air were used to compare the efficacy of two alternative methods in rubberwood drying. The parameters are rubberwood sizes vary width from 1 to 4 in. and impinging hot-air 60-80°C with maximum microwave power level of 200W. The results of different methods showed that the drying time is reduced significantly from 168 h. to less than 6-30 h., and the quality of the dried rubberwoods in natural color is improved as compared with conventionally method. The mechanical results of compressive strength parallel to the grain of wood is from 69.76 to 35.24 MPa, the shearing strength parallel to the grain is from 23.99 to 15.47 MPa, the compressive strength perpendicular to grain is from 24.93 to 9.86 MPa, the modulus of rupture is from 123.13 to 82.96 MPa, the modulus of elasticity in static bending is from 18121 to 8680.4 MPa, and the hardness of wood is from 7826.33 to 4435.34 N. All mechanical properties of rubber wood by two different modes of heating was extremely higher average value than the reference value. In addition, the energy consumption of drying process by microwave heating was found much higher than that of hot air. It was concluded in a study that rubber wood after drying present excellent performance for use as structural resistance element of foundations. For the second part, applying microwave heating and impinging hot-air to increase the higher drying rates of rubberwood drying based on acceptable quality was studied. A maximum microwave power level of 200W at a frequency of 2.45GHz with maximum working temperature of 70°C, only hotair (70°C) and combined microwave (200W) - hotair (70°C) were choosed to evaluate the effect of rubberwood drying by different width sizes (1, 2, 3 and 4 in.) by 46 in. length by 1 in. thick. In all cases, the drying time is reduced significantly from 168 h to less than 8-15 h in various wood widths and resulted in saving to an extent of about 91% of drying time from initial moisture content ranges of 73%-49% to 15% percent of moisture level. Drying stresses from prong test no found during drying and total color of rubberwood changed after high temperature drying is a natural surface when compared to fresh wood. The values of six strength compared to the reference values are concentrated in the ranges of 16.9-23.9 (11.0)MPa for shearing strength parallel to grain, 4291.1-6701.6 (4350)N for hardness, 73.3-110.2 (66.0)MPa for MOR, 7059.5-12856.7 (9240.0) MPa for MOE, 27.2-14.3 (5.0)MPa for compressive strength perpendicular to grain and 60.6-35.7 (32.0)MPa for compression strength parallel to grain. These results show that it is possible to develop a drying process for rubberwood using microwave-hot air in investigating further in this area.

6.2 Recommendations

The results would retain some of the advantages of rapid drying without resulting in excessive defects. The effect of microwave is slow drying curve and may be possible to replace hours of microwave by impinging hot-air and then microwave could be used in drying to final moisture content levels. It might necessary to increase the power of microwave which is limited in this work up to 200W to achieve the shorter time require. To improve the quality of drying rubberwood by hot air and combined microwave-hot air drying methods, more information is needed on different rubberwood thickness, ranging of temperature and moisture content during microwave drying comparing to the conventional drying process. The testing enables the scale-up and development of innovative hot air and microwave process technology that highlight the implications of these findings on the design of structural kiln and systems using large volume of lumber without excessive degradation during drying.

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APPENDIX A

Summary of the warp characteristics and mechanical properties values of dried rubberwood by microwave and hot air

Table A-1. Summary of the warp characteristics after drying

	Hot-air				**Microwave**			
Defects	**1 in.**	**2 in.**	**3 in.**	**4 in.**	**1 in.**	**2 in.**	**3 in.**	**4 in.**
Bow	-	2	-	-	-	4	-	-
Spring	-	-	1	-	-	-	-	1
Crack	-	-	-	-	-	-	1	-
Bow and Spring	3	-	-	-	4	-	-	1
Total	3 (33%)	2 (22%)	1 (11%)	-	4 (44%)	4 (44%)	1 (11%)	2 (22%)
% Pass	67%	78%	89%	100%	56%	56%	89%	78%

Table A-2. Mechanical properties values of dried rubberwood by hot air

	Hot air					
	1 in.	**2 in.**	**3 in.**	**4 in.**	**Ref.***	**Ref.****
Shear strength parallel to grain (MPa)	17.13±1.05	15.92±0.45	21.13±1.08	17.35±0.42	13.66	11.0
Compressive strength (MPa)						
- Parallel to grain	59.41±1.90	44.56±9.32	53.97±1.81	52.9±4.59	37.1	32.0
- Perpendicular to grain	15.22±2.16	12.05±2.19	23.42±1.51	14.97±1.13	1.93	5.0
Static bending (MPa)						
- MOR***	109.27±3.92	97.4±14.44	102.84±7.62	111.39±11.74	91.4	66.0
- MOE****	14867.9±1060.6	11145.9±1289	9690.1±1009.7	12264.1±702.7	7388	9240.0
Hardness (N)	5763±657.97	5050±278.25	5991±301.05	5052±616.66	4259	4350.0

* Yamsaengsung R. and Buaphud K. [34] ** Killmann, W. and Hong, L.T. [8]

*** Modulus of rupture(MOR) **** Modulus of elasticity (MOE)

Table A-3. Mechanical properties values of dried rubberwood by microwave

	Microwave					
	1 in.	**2 in.**	**3 in.**	**4 in.**	**Ref.***	**Ref.****
Shear strength parallel to grain (MPa)	18.63±3.88	22.54±1.31	19.67±0.15	23.64±0.35	13.66	11.0
Compressive strength (MPa)						
- Parallel to Grain	52.26±10.39	56.02±2.31	59.32±3.91	63.77±5.99	37.1	32.0
- Perpendicular to grain	23.77±0.26	22.74±1.59	17.32±1.47	20.93±1.07	1.93	5.0
Static bending (MPa)						
- MOR***	102.72±10.07	113.96±3.76	110.71±3.4	113.13±3.89	91.4	66.0
- MOE****	10919.5±533.9	13962 ±4159	13767.1±1619.67	12400.2±633.8	7388	9240.0
Hardness (N)	7166.13±660.2	7051.82±602.6	6455.6±118.18	6330.6±311.98	4259	4350.0

* Yamsaengsung R. and Buaphud K. [34] ** Killmann, W. and Hong, L.T. [8]

*** Modulus of rupture(MOR)   **** Modulus of elasticity (MOE)

APPENDIX B

Summary of the warp characteristics and mechanical properties values of dried rubberwood by combined microwave and hot air

Table B-1. Summary of the warp characteristics of dried rubberwood by combined microwave and hot air

Physical properties	**1 in.** (9 PCS.)	**2 in.** (9 PCS.)	**3 in.** (9 PCS.)	**4 in.** (9 PCS.)
Bow	-	1	2	1
Spring	-	1	-	-
Crack	-	-	-	-
Bow and Spring	2	1		
Total	2 (22%)	3(33%)	2 (22%)	1 (11%)
% Pass	78%	67%	78%	89%

Table B-2. Mechanical properties values of dried rubberwood by combined microwave and hot air

	Microwave + Hot-air				
	1 in.	**2 in.**	**3 in.**	**4 in.**	**Ref.***
Shear strength parallel to grain (MPa)	17.29±0.42	18.47±1.38	18.39±2.16	22.28±1.64	11
Compressive strength (MPa)					
- Parallel to grain	37.34±1.64	42.73±2.68	59.83±0.75	50.24±2.68	32
- Perpendicular to grain	21.21±2.40	16.15±1.88	18.96±0.52	23.05±4.17	5
Static bending (MPa)					
- MOR**	75.81±2.56	84.45±1.28	104.83±5.33	97.93±9.03	66
- MOE***	8442.7±1383.21	8915.92±368.84	12215.07±641.6	9361.39±1151.9	9240
Hardness (N)	6065±283.62	4872±686.30	4578±286.90	6489±212.55	4350

** Killmann, W. and Hong, L.T. [8] ** Modulus of rupture(MOR) *** Modulus of elasticity (MOE)