STUDIES OF CONVECTIVE DRYING USING NUMERICAL ANALYSIS ON LOCAL HARDWOOD

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LIST OF SYMBOLS

A	Surface area [m^2]
A_n	Cross section area at flow direction [m^2]
C	Constant
C_p	Specific heat capacity [J/kgK]
C_{on}	concentration of vapour
D	Coefficient of diffusion [m^2/s]
D_{eff}	Effective coefficient of diffusion [m^2/s]
E	Effective permeability [m^3_{water}/m]
G	Specific gravity of wood
H_{latent}	Latent Heat of vapourization [J/kg]
h	Heat transfer coefficient [W/m^2K]
j	Flux of moisture movement [kg/m^2s]
K	Specific permeability [m^2]
$K_{g.30}$	gas permeability at 30% moisture content
k	Thermal conductivity [W/mK]
Le	Lewis number
l	Length [m]
ℓ	Length of one element in airflow direction [m]

ℓ_2	Length of one element normal to airflow direction [m]
M	Moisture content [kg_w/kg_s]
m	mass [kg]
$\dot{M}$	Rate of mass change [kg/m^2s]
Nu	Nusselt number
n	molar
P	pressure [Pa]
P_{vs}	Vapour saturation pressure [Pa]
Pr	Prandt number
p	partial pressure [Pa]
Q	power [W]
R	universal gas constant [J/kgK]
R_{mol}	molar gas constant(kcal/kmol•K),
Re	Reynold number
Rh	relative humidity of air [%]
S	saturation
T	Temperature [K or °C]
t	Time [s]
V	Volume [m^3]
V_a	Porosity of wood
V_d	Porosity at 30% moisture content
x	Direction normal to air flow
Y	humidity of air
z	Direction parallel to air flow
ρ	Density [kg/m^3]
μ	Viscosity [Pa.s]
v	Velocity of air [m/s]

Subscript

c	capillary action
cond	conduction

conv	convection
eff	effective
evap	evaporation
fsp	fiber saturation point
g	gas
i, j	node number
ℓ	liquid
m	moisture
max	maximum
min	minimum
s	solid wood
v	vapour
w	water
wb	bound water
wf	free water
wv or vf	water in vapour form
x	x-direction
z	z-direction

Superscript

s	saturation
a	air

LIST OF ABBREVIATIONS

BAR	bypass air ratio
RAR	recirculated air ratio
COP	coefficient of performance
SMER	specific moisture extraction rate (kg/kWh)
HPD	heat pump drying
EMC	equilibrium moisture content

MC	moisture content
FSP	fiber saturation point
RAM	random access memory

KAJIAN PENGERINGAN PEROLAKAN MENGGUNAKAN ANALISIS BERANGKA KE ATAS KAYU KERAS TEMPATAN

ABSTRAK

Pengering kayu adalah salah satu proses yang menggunakan tenaga yang banyak dalam industri pembalakan. Walaubagaimanapun, proses ini amatlah penting kerana proses ini boleh meningkatkan sifat mekanik kayu dan juga menghindari kayu daripada serangan serangga perosak dan serangan fungi. Kayu keras merupakan salah satu eksport utama negara Malaysia dan salah satu daripada kayu keras yang amat popular ialah Meranti Merah. Kajian ini adalah membincangkan analisa berangka terhadap pengeringan kayu dengan menggunakan kaedah unsur terhingga dan pengesahan secara eksperimen terhadap keputusan teori dengan mengunakan pengering haba.

Kaedah unsur terhingga yang digunakan adalah dalam satu dimensi dan menggunakan kaedah baki pemberat Galerkin dalam penyelesaian. Dalam model matematik ini, angin pengering diselesaikan dahulu untuk mendapatkan keadaan permukaan kayu, diikuti dengan penyelesaian persamaan pemindahan haba dan jirim dalam kayu. . Kajian parametric kemudian dijalankan dengan mengunakan model mathematik ini dalam mengkaji impak suhu angin, kebasahan udara relatif, halaju angin, ketebalan kayu dan kebasahan permulaan kayu terhadap proses pengeringan.

Untuk mengesahkan kesahihan model ini, satu pengering bersumber pemanas elektrik serta bersumber pam haba telah direka dan dibangunkan. Haba disalurkan ke dalam pam haba inin dengan mengunakan pemanas dan pam haba

berkuasa satu kuasa kuda, yang menggunakan bahan penyejuk R-22. Ekperimen telah dijalankan dengan alat ini dan didapati kepincangan keputusan teori dan keputusan eksperimen adalah dalam lingkungan 3% hingga 6%. Ini menunjukkan keputusan ramalan adalah bersetuju dengan keputusan eksperimen. Walaubagaimanapun, kajian yang dijalankan dalam tesis ini hanya mempergunakan pemanas elektrik sahaja.

STUDIES OF CONVECTIVE DRYING USING NUMERICAL ANALYSIS ON LOCAL HARDWOOD

ABSTRACT

In wood industry, drying of wood is the most energy extensive process that incurs a lot of cost and time. This process however is one of the most important, which enhances the mechanical properties and protects the wood against insect and fungal attack. Hardwood is one of Malaysia most important commodity export and present work is focused on Dark Red Meranti. This present work discussed the numerical analysis of wood drying by convective air using Finite Element Method and experimental investigation by using heater dryer.

The finite element model is a time stepping 1 dimension model and solved using Galerkin's weighted residual method. In this model, air flow is solved initially in its flow direction to obtain surface condition of wood piece, which then be used to solve the heat and mass transfer equation inside the wood piece. Parametric study was then conducted using the mathematical model to study the impact of air temperature, relative humidity, air velocity, wood thickness and initial moisture content of wood piece on drying.

To verify the mathematical model, an electrical heater cum heat pump-assisted dryer was design and developed. Heat provided into the dryer by heaters and a one horsepower heat pump, which its refrigerant is R-22. Experiments were conducted using this test rig and variation between theoretical data and experimental data is within 3% to 6%. This shows that there is good agreement between theoretical data and experimental data. However for studies presented here, only electrical heater was utilized.

CHAPTER 1

INTRODUCTION

1.0 Introduction

Manufactured product normally has to go through a series of finishing processes before it reaches consumers. Some of these processes involve drying as one of its important operation to get the desirable output. Looking around any shopping mall or grocery store, one may observe that many of the products has gone through drying; e.g. milk powder, textile, chinaware etc. Even purely mechanical manufacturing process may require drying of the product and it is possible that about 1 ½ - 2% of the total annual investment in new equipment in chemical process industries is devoted to the installation of drying equipment. (William-Gardner, 1971)

Drying is not only an energy intensive process but also a complex phenomenon, where energy is used to provide heat and mass transfer, in most cases, related to a porous medium (Chua *et al*, 2002). Various studies report national energy consumption for industrial drying operations ranging from 10-15% for USA, Canada, France, and UK to 20-25% for Denmark and Germany (Mujumdar *et al, 1987)*.

Drying of wood has been a major part of wood industry for many years. Freshly felled trees have relatively high moisture content and they have to be dried to a desirable level of moisture content, usually below 20% before they are usable and having commercial value. The reasons for drying of wood to this level of moisture content are:

a) The mechanical properties of wood, such as strength, hardness, electrical resistance, thermal insulation, are better for dried wood.
b) Dry wood are less prone to insect and fungal infestation, stain and decay
c) Reduction of weight, resulting in reduction of transportation cost
d) Suitability for various finishing processes, such as polishing and painting.
e) Shrinkage of dry wood are minimal, hence wood are more dimensional stable.

Although Malaysia is a tropical country, where solar energy for drying can be used throughout the year, energy consumed in drying process has become more and more important as consumer demands a better quality product and also to ensure local products reach the level of global competitiveness. Hence, research and development (R&D) in drying technologies is essential for greater efficiency as price of fossil fuel are on the rise and in danger of depletion in the near future. It is interesting to note that there is a correlation between the amount of water removed per unit energy consumed in industrial processing and the GDP (or standard of living) of a country (Mujumdar *et al*, 1987) Being one of the oldest production process in the world, which can be dated to ancient era, only in the past two decades that we saw some exponential rise in R&D in the inter and multi-disciplinary field of drying. (Mujumdar, 2002)

Natural convection is the process usually used to dry wood, as it is cost efficient. However, there is no control that can be exerted to the quality and drying time in this process, which leads to fluctuation in the production. Due to the increased demand in quantity and quality of wood in recent years, industries are starting to investigate the alternative to improve production and quality of their products. Hence, there is a need to study and understand the moisture movement from the core of wet wood to the surface and the mechanism of vapour removal from surface of wood.

1.1 Scope of the project

In this project, the scope of study is to focus into the mechanism of moisture movement of wood, which is modeled as wet porous solid. This complex mechanism will involve the use of heat and mass transfer theories and some biological theories of wood.

The focus of the research will be on the modeling of heat transfer and moisture movement of a piece of rectangular shaped wood, which undergoes forced convection drying by heated air and subsequent experimental verification. Some of the phenomena that were investigated in this study were the drying rate, moisture distribution and temperature distribution of wood. Parametric studies of these criteria due to the changes of temperature, velocity and relative humidity of drying medium are also carried out to have a better understanding of these phenomena.

The computer simulation of wood drying are based on finite element method and was done using MATLAB software. Wood species studied was Dark Red Meranti (*Shorea laevis*) which is a hardwood timber that known to dry very slowly but has a very valuable export market.

Experimental validation of the simulation was conducted by using electrical heater dryer. This test rig was design and developed as an electrical heater cum heat pump-assisted dryer. However in the studies present here, only electrical heaters were used for validation purposes.

1.2 Studies Objective

Objectives for this project are:

1) To investigate the drying mechanism of wood drying based on heat and mass transfer of wet porous solid using Finite Element Method
2) Design and development of a heat pump-assisted convective dryer to conduct drying experiment
3) Validation of the simulation model with experimental results
4) Study the influence of drying medium to the drying rate, temperature distribution and moisture distribution of wood.

CHAPTER 2

OVERVIEW OF WOOD DRYING

2.0 INTRODUCTION

The structure of wood is a large study on its own, which involves a lot of knowledge in botanic, biology and chemical building component of wood. Therefore, presented here are only the important aspects of wood structure science, which is a brief summary that would be useful in later stage of the studies.

Wood is a hygroscopic substance consisting of dead and living cells of trees. Wood is also a porous material, where its cavities are filled with either water (for freshly felled and living tree) or air. Commercial timbers are classified into softwood and hardwood. Softwoods are woods that derived from a botanic group called gymnosperms, which are commonly known as conifers or cone bearing plants (Desch *et al, 1981*). Hardwoods are derived form a sub-group called dicothyledon from the botanic group of agiosperms. Softwood has the characteristic of needle or awl shaped leaves and naked seed, whereas, hardwood has the characteristic of broad leaves and enclosed seed case. Majority of wood produced in Malaysia are from the group of hardwoods, as the tropical condition of Malaysia is more suitable for such tree to live.

As the research was carried out on Malaysian hardwood, the properties and characteristics of the wood as well as different drying methods practiced would be reviewed as a necessary prerequisite.

2.1 Properties of Wood

2.1.1 Macroscopic and Microstructure characteristics

Two types of wood characteristics are discussed; (i) macroscopic and (ii) microstructure characteristics.

Macroscopic characteristics are those features visible with naked eye or with magnificent lens. A cross section of wood consists of 3 distinguishable parts: pith, wood and bark. Pith is normally located at the center of the stem of a tree. It varies in sizes and colours, from black to whitish and its structure may be solid, porous chambered or hollow.

Trees grown in seasonal area consist of concentric layer of tissues, called growth ring, which comprises of wood produced by cambium in a single season (Desch *et al, 1981*). In tropical species, growth rings are not always distinct, especially in areas with fairly uniform rainfall.

The inner portion of the cross section of wood is usually darker in colour than the outer layer. This portion is called heartwood, whereas the peripheral portion is called sapwood. Sapwood is the growing and youngest cell of tree and function as sap conductor and wood storage of tree. Heartwood normally consist of older cells that no longer takes part in translocation and storage of food, but provides mechanical rigidity to the steam and support to the canopy. (Kollmann *et al, 1968*).

Under microscopic observation, wood composed of cells that connected together in various ways. Cells of softwood are mainly long and narrow tubes like with closed and pointed or blunt ends. Cells of hardwood consist mainly long and narrow with closed or pointed end but generally shorter in length compare to softwood cells. There are generally three types of cells; vessel members, fibers and parenchyma cells. (Tsoumis, 1991)

Vessels are a pipe-like structure of indeterminate length formed by individual vessel cells or element connected endwise, Vessels appear as solitary pores, or in multiple chains or cluster in a wood cross section. Size of vessels greatly varies within growth ring and between species, where the length of vessel elements average ranges from 0.2 to 0.5 mm and 20 to 400μm in diameter.

Parenchyma performs the function as storage tissues in wood. Parenchyma cells are typically prismatic in shape under microscope observation and have simple pits.

Fibers are long narrows cells with closed and mostly pointed ends. Fibers are only presented in hardwoods in bulks and it borne most of the loads of hardwood trees. Its length varies on the average of 1 to 2 mm and its diameter ranges from 0.01mm to 0.05 mm.

Tree cells consist of 2 walls, primary wall (original cell wall that form together with cell) and secondary wall (layers added after cell formation). At the primary wall, the area that unthickened during the formation of the inner layer is called pits. Pits serves as the means of communication between cells by allowing liquids pass through. There are mainly two types of pits – simple pit and bordered pit. Pits in hardwood are often bordered. The opening of pits is called pit aperture and the space between aperture and membrane is called pit cavity. Cavity of bordered pits is narrow and abrupt toward the cell lumen. For softwood, the center of pit membrane is thickened; this is called torus; but this feature does not exist in hardwood.

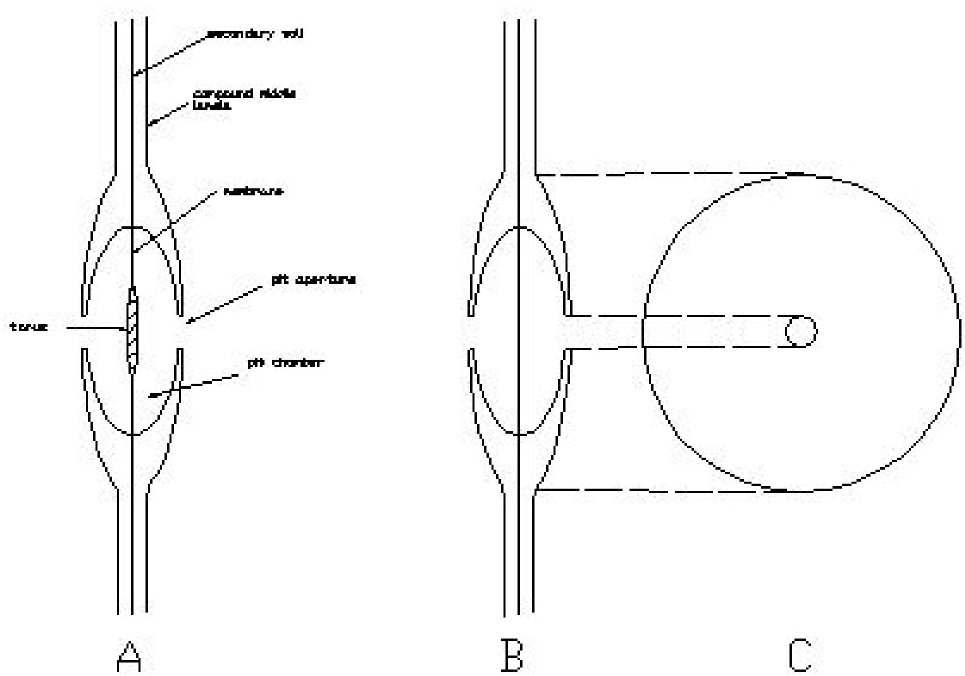

Figure 2.1: A) Bordered pit with torus, B) Bordered pit in hardwood, C) Radial view of a bordered pit (source: Tsoumis)

2.1.2 Water in wood

Living trees and freshly felled timber contain high amount of water, which may constitutes greater proportion by weight than the solid wood. The water in wood influences strength properties, stiffness, shrinkage, weight, hardness, abrasion, machineability, heat value, thermal conductivity, insect and fungi attack resistance and resistance of wood against decay. (Kollmann *et al*, 1968, Desch *et al*, 1981).

Water in wood present in two conditions

1. Bulk of water that contained in the cell cavities of wood, which is called “free” water. This water are free from intermolecular attraction of cells walls, however it is subjected to capillary force and therefore is not in the same thermodynamic state of ordinary liquid water in wide container. Furthermore, cell cavity water may also contain water-soluble materials, which reduce its thermodynamics state (Skaar. 1988).
2. Liquid water in cell walls, which is called “bound” water. Water held in wood is by the attraction of water molecules by the hydroxyls (-OH) of its chemical constituents, mainly cellulose. Bound water is contained in the void of cell walls of wood. (Tsoumis, 1991)

Water may also present in form of vapour contained in cell cavities. However, normally these vapour constitutes only a small amount of total weight and negligible at normal temperature and moisture content.

The amounts of water presented in wood are expressed by moisture content of a sample. Moisture presented in a converted wood varies appreciably in different circumstance, but the dry weight of wood substance in a given sample is constant (Desch *et al*, 1981). The moisture content of wood is generally expressed as percentage of weight of water present to the dry weight of the sample.

$$M = \frac{weight\ of\ sample - weight\ of\ oven\ dried\ of\ the\ sample}{weight\ of\ oven\ dried\ of\ the\ sample}$$

Living tree with fully saturated cell wall has moisture content of 30% or more. A green wood from a freshly felled tree is exposed to atmospheric condition and losses its moisture content to the surrounding until it reaches equilibrium with the ambient. This moisture content is called equilibrium moisture content, EMC and is approximately proportional to the ambient relative humidity. Exposure condition, exposure history or histeris, mechanical stress and temperature affect EMC. This factor has been extensively studied by some of the researchers (Skaar, 1988). Other factor includes wood species, proportion of cell-wall constitutes and extractives and between heartwood and sapwood.

One of the most important phenomena in wood drying is the fiber saturation point. A green wood contains both bound and unbound water. Drying will remove unbound water first because the weaker capillary force holds unbound water. Fiber saturation point is defined as the moisture content at which all unbound water has been removed from cell cavities while cell walls were fully saturated with bound water (Skaar, 1988). Many of the properties of wood change when reaches fiber saturation point or lower, such as:

(i) Mechanical properties of wood such as strength, hardness and toughness of wood increase.

(ii) Rapid increase of electric resistance of wood with loss of water

(iii) Shrinkage of wood occur only when moisture content are below fiber saturation point

(iv) Drying rate of wood decrease as moisture movement of bound water is slow compared to unbound water.

Siau (1984) has reported that fiber saturation point is dependent to temperature and can be expressed as following generalized equation for all wood:

$$M_{fsp} = 0.598 - 0.001T \qquad (2.1)$$

where M_{fsp} is moisture content at fiber saturation point and T is temperature in Kelvin

2.1.3 Mechanism of moisture movement

Moisture content in wood change constantly according to the ambient condition it subjected to. As discussed earlier, moisture may appear in 3 general forms, (a) free water in cell cavities, (b) hygroscopic bound water in void of cell walls and (c) vapour in cell cavities.

There are several types of passageways that moisture move through, such as cavities of the vessels, fibres and pit chamber, intercellular spaces and transitory cell wall passageways, depending on its driving force. In modeling of moisture movement in wood, it is assumed as a porous material with interconnected void space to allow movement of air and moisture, which depends on the density and porosity of wood. Porosity is the volume fraction of void space to solid in porous material. Another important physical properties of wood related to moisture movement is its permeability, which refers to the measurement of capability of solid substance to allow fluids to transports through a porous solid under influence of some driving force.

At above fiber saturation point, moisture moves as liquid free water thorough interconnected voids and over the solid using *capillary* action. This is due to the adhesion action of water particles and the cell walls; and cohesion between water particles. At the same elevation, capillary water is in equilibrium in saturated wood. Evaporation of moisture from wood surface creates a capillary pressure to pull free water from zones of wood beneath the surface. This mechanism can be described by Darcy's law where capillary pressure gradient is the driving force.

When moisture content of wood reaches below fiber saturation point, capillary action will be cease and moisture movement is driven by diffusion of bound water within cell walls. Diffusion is described as the random molecular motion of single molecules in response to concentration gradient. When a difference of moisture gradient occur in wood, a chemical potential will transport the moisture to redistribute itself throughout the wood until it reaches equilibrium or uniform chemical potential. An adaptation of Fickian's law is applied to the diffusion in wood, where difference of moisture content between surfaces to adjacent wood zone move the bound water (Whitaker, 1977). Moisture content gradient are assumed as the driving force and its diffusion coefficient is a function of temperature and moisture content. This mechanism, which has been described in detailed in Chapter 4, is slower than capillary action and generally applied to drying of hardwoods.

A small fraction of moisture in wood is vapour form and it it transported from high vapour pressure region to low vapour pressure region. Vapour movement is more significant when temperature approaching or exceeded boiling point of water, as more vapour is generated and contributed to additional of partial vapour pressure. Movement of water vapour is possible for both above and below fiber saturation point and in accordance to diffusion law where vapour partial pressure gradient is the driving force.

2.2 Methods of wood drying

Wood drying is a process that consumes a lot of energy and requires a lot of time. Mujumdar (1987) has reported that drying of wood world consumed as much as 70% of total energy required in wood processing. Drying of high-density hardwood such as balau may take as long as 3 months to complete. Workers around the world have used various methods of wood drying. Some of the more common methods of drying processes are presented here.

2.2.1. Air Drying

Air drying is the drying of the wood using the natural energy, which is by the power of wind and sun. The process involves simple stacking of the wood pieces systematically at open space and letting the sun and air to dry it. Stacking of wood is an essential key to air drying, hence the wood stacking and layout must be optimized according to the wood size and wood species. It is cost effective and it is the most popular form of wood drying in the world. The downside of this process is that the output of the drying is very dependent on the local climate. Air drying also causes significant wood defects such as fungal infection, insect infestation, discoloration and shrinkage.

2.2.2 Shed Drying

Shed drying are similar to air drying, the difference is that a permanent roof is constructed over the wood stacks, thus preventing wood from being wetted by rain. Some of the operators also install fans inside the shed to provide uniform airflow, thus accelerating the drying process. Compared to conventional air drying, this process is faster, but it increases the cost because of the need to construct roofs and electricity bill for fan usage.

2.2.3. Conventional kiln drying

A drying kiln is a room or chamber that provides an artificial environment, which optimizes the drying process. Woods are stacked in the same way as air drying, but sometimes, spring clamps or heavy weights are placed on the wood stack to prevent drying defect. Throughout the drying process, a sample of wood would be weighted to determine its moisture content. Inside a conventional kiln, a recirculation system is used to provide effective airflow. Heat is provided either directly, using energy provided by fossil fuel or wood waste; or indirectly, using electrical heating element or using heat from heated water or steam running through a heat exchanger. Using a combined control of steam sprayer and the power of heat source provides humidity control and temperature control. Kiln environment has to be changed according to the moisture content of the wood, which normally follows a recommended schedule.

2.2.4. Dehumification kiln drying

In dehumidifier kiln drying, the kiln is fully sealed and the moisture in air is extracted by using a dehumidifier without using extra heat source. A dehumidifier is a heat exchanger with surface temperature at dew point, hence water will condense on it and drained away. The advantage of this system is it requires less initial cost and lower energy requirement. However, compared to conventional kiln, drying is slower and it uses electricity as energy source, which is considered as high-grade energy source.

2.2.5. Vacuum Drying

Vacuum drying also requires a sealed kiln, and the air inside the kiln is evacuated to provide a very low air pressure. At this pressure, moisture can evaporate at much lower temperature, as the boiling point of water is lower. Dehumidifiers are used to extract moisture from circulating air, and sometimes, heat sources are provided to accelerate drying. This process is expensive and only used for woods that require special treatment in later stage.

2.2.6 Superheated steam drying

Superheated steam drying uses water vapour to dry wood. Usually, air pressure of the drying chamber lowered by evacuating air with low power vacuum pump, followed by steam being introduced into the drying chamber. At low pressure, steam would be in superheated phase at lower temperature, usually in the range of 50°C to 90°C. This method claimed to reduce defect in wood such as stresses, crack, warpage, stain and discolouration. Furthermore, compared to conventional dryer, some authors (Eluntondo *et al,* 2002, Kiiskinen *et al,* 2002 and Devahastin, 2000) claim that this method offers faster drying rates and no risk of fire or explosion. However, the initial cost of this method is higher and superheated steam dryers are usually smaller.

2.2.7 Radio frequency drying

In radio frequency drying or microwave drying, energy is transferred directly to water molecules throughout the wood so that heating becomes volumetric, resulting a higher interior temperature, and water would evaporate within the wood. This will increase the internal pressure of wood, thus this pressure gradient will push the unevaporated water to surface, speeding up the drying process. However, capital cost of radio frequency drying still represents a major obstacle and there are lack of fundamental knowledge on this method where most development were mainly obtained by “trial-and-error” approach. (Koumoutsakos *et al* , 2001, Datta *et al*, 2002)

2.2.8 Heat Pump Drying

One of the recent innovations of wood drying are using heat pump to supply heat to a drying chamber. Heat pump is essentially an air refrigerating system, but the heat rejected by the system is used instead. In a closed cycle heat pump, heat from drying chamber is recovered by evaporator, which is used again in condenser to heat air that is entering into the drying chamber. Researcher in this field has shown that by using a heat pump dryer, energy cost were reduced as heat is constantly recovered and not wasted (Prasertsan *et al*, 1998 and Hawlader *et al*, 2003) This system also act like a dehumidifier, thus moisture and any chemical evaporated from wood can be recovered and reprocessed if it is useful. However, this system uses high-grade electricity as the power source, hence involve an expensive proposition.

CHAPTER 3

LITERATURE SURVEY

3.0 Introduction

Literature survey are done on both (a) modeling of wood drying and (b) drying experiment by using heat pump dryer. Numerous works was done on both of these areas to be used as reference for this study.

3.1 Literature Survey on Modeling of Wood Drying

Drying of wood is a complex phenomenon that has led to numerous interest of researcher for a long time. Since the proposal of drying theory; based on continuum mechanics by Whitaker (1977) and Luikov's theory (1966), numerous models has been developed based on finite element method or finite differential method. Some of the recent works are presented here, which based on above theories and other's wood drying theories as well.

S. Pang *et al* (1995) had developed a mathematical model of drying of radiata pine (Pinus *radiata*) during high temperature drying (>100 °C). The authors used the receding evaporization plane model to predict the surface and centre temperature profile as a function of time for heartwood and sapwood. This model suggested that below the evaporation plane, water exist as unbound water and bound water, while at the layer above this plane, water exist as bound water and vapour. Hence, the evaporative plane of wood will slowly recede into the centre of the wood, and the moisture movements behave differently for these different layer.

This model is used to study the influence of periodically airflow reversal for convection kiln dryer. The predicted data and data from experiment done by authors' shows some discrepancies of temperature at the wood surface and the authors suggested this was due to error in temperature measurements during experiment. Airflow reversals give an evenly distributed temperature on wood, hence reducing the number of drying defect.

Nijdam *et al* (2000) also developed a one-dimensional model to study the moisture-transport mechanism between fiber saturation and irreducible saturation, and moisture flow within the thin layer of damaged cells at the sawn surface of a wood board. The model is used to predict the temperature and average moisture content profile for radiata pine during high temperature drying Due to the high temperature drying, the author suggested that pressure gradient play an important role in heat and mass transfer. Comparison of experimental and simulated data gave a good agreement and the authors concluded that liquid diffusion is small in comparison to capillary-driven liquid convection.

Drying of wood chips with air and with superheated steam were studies theoretically by Johansson *et al* (1997). The authors used a computer code call TOUGH (transport of unsaturated groundwater and heat) that was originally designed for geothermal processes and developed by Lawrence Berkeley Laboratory, to simulate the drying process for wood chips. The similarities of governing equation between wood drying and groundwater seeping permitted such application. It was found that drying with air offer greater drying rate than superheated steam at the same temperature due to the greater heat flux and less condensation of water on wood surface during drying with hot air.

A numerical code known as WoodID was developed and presented in a paper by Turner *et al* (1998). The code was used to analyse the impact of dielectric heating and the overall drying kinetics of a combined microwave and convective drying of hygroscopic porous material. The basis of the model is based on the important work of Whitaker (1977), in which the authors manipulate the drying process mathematically into water, air and energy balance equations. These equations were then discretized by using control volume technique proposed by Patankar (1980) and solved using finite different method. Based on the data from experiments conducted by authors, the numerical simulation shows adequate agreement for both convective drying and combined microwave and convective drying. Combined drying proved to reduce drying time and a steep increase of internal pressure of wood, thereby increasing the possibility of creating internal defect in wood, which has low gas permeability such as high density hardwood.

Martinovic *et al* (2001) presented a paper on development of numerical simulation on wood drying based on discretization using finite volume method. The authors had implemented the governing equation of energy, mass and momentum balance to a computer code, in which the momentum balance equation is useful to predict the stress generated during drying at high temperature. Similar to Turner *et al* (1998), these governing equation were discretized by using control volume technique proposed by Patankar (1980), however the differences are the solution algorithm of this paper was based on a 3 dimension control volume, which has a greater complexity. (Martinovic et al, 2001)

Lim *et al* (2004) proposed a new of drying model, derived from diffusion controlled drying period. The author stated that in most cases, the diffusion coefficient is assumed constant, but some research outcome had shown this assumption is not valid for the whole drying process. The authors derived a new function for diffusion coefficient, which assumed that diffusion coefficient has a linear function of the distance between drying boundary and material core. A drying experiment of rough rice was then carried out in a rapid bin dryer (Retsch type TG100) and it showed good agreement when compared with the theoretical result.

An unsteady state non-isothermal model for wood drying was proposed by Horacek (2003). The author suggested that most previous work was focused on three categories: a) diffusion modes, b) transport properties based models, c) model based on physiological properties and transport properties of wood. However, research on unsteady state non-isothermal was lacking, where heat and moisture transfer is considered as coupled process. A system of partial differential equation was proposed and solved using a software called FlexPDE. The author interpreted the wood drying process as a simultaneous heat and moisture transfer with every point within the wood are at thermodynamic equilibrium.

Khraisheh *et al* (1995) took a different approach in the modeling of drying curve of a combined microwave and air-drying. This model was achieved through empirical modeling of the drying process based on experimental result, which relied on data fitting. By deriving a multiple linear equation based on air flow rate, air temperature and microwave power output, the authors related these parameters to the drying curve equation. Then, by using Gauss elimination technique, a multiple regression program was done to produce a functional form relating the drying performance to its operational parameter.

Hunter (2001) had taken a new and informative way in deriving an analytical model for the process of drying of impermeable wood. The model arose out of the observation of the logarithmic relationship of moisture content and drying time. Instead of using the traditional drying models for wood that based on the analogy with Fick's Law for diffusion, this model takes the pressure of water vapour as the potential of moisture movement, while flows at sides of the board were also taken into consideration. The one-dimensional mode proposed by the author also incorporated the geometric factor and wet-bulb depression term into its governing equation. This model had it's limitation, that is the diffusion coefficient derived are limited to a range of relative humidity and the model give some errors reading when relative humidity reaches near ambient condition.

Ni *et al* (1999) developed a multiphase porous media model to predict moisture transport of biomaterials during microwave heating. Due to the high temperature and high intensity drying using microwave, there will be a rise in internal pressure gradient which in turn enhance the transport and promote a condition where water is forced out from the porous media which the authors termed "pumping". The model was consists of a series of equation of temperature, pressure and saturation. The model was solved using finite difference method with central space differencing for diffusion terms, Upwind differencing for convection term and Crank-Nicholson time differencing. The model proposed here has taken into consideration many phenomena that happened during drying; hence it needs a very powerful computer to calculate to obtain good results.

In another paper by Datta *et al* (2002), the authors further developed the previous model by incorporating infrared as the extra energy to dry biomaterials. The author studied varies effects of using infrared in drying and found that infrared heat can reduce surface moisture and increase surface temperature. However, in wood drying, a big difference of moisture content between surface and internal of wood piece is not desirable, as this will encourage checks and warps of wood

Erriguible *et al* (2004) had presented a method of coupling the model of porous medium with model of the external flow. This is done by deducing the boundary conditions from the resolution of the Navier-Stokes equation in the environment and writing the boundary condition at the porous medium/environment interface. In this paper, the authors also presented a method to determine the expression of the heat and mass fluxes and a numerical simulation, which enable one to study the complex processes such as vacuum drying. The uniqueness of the method proposed by the authors is the oxygen molecules and nitrogen molecules are separately taken into consideration, hence energy level of drying air would be different if the chemical composition changes. This can be useful if experiments are carried out in environment where these chemical composition need to be adjusted but may not be useful if normal air are used.

A work by Hadrich *et al* (2004) shown that modeling and simulation of heat and mass transfer can be done by decoupling of heat and mass transfer phenomena. While most work by previous researchers was done by coupling these phenomena, the decoupling of the heat and mass transfer prove to be a simpler hypotheses but results from the paper shows that there is not a concordance between the simulated and experimental result. However, this mathematical model can predict the distribution of water in the drying sample during drying process effectively.

Dincer (1998) proposed an analytical technique to determine the moisture diffusivities and moisture transfer coefficient during drying of wood slab. In this paper, Biot number and Fourier number were used as the criteria to define transient heat transfer and transient moisture transfer, respectively. Modeling was based on an infinite slab wood being dried and moisture diffusion was assumed occur in the thickness direction of the wood slab only. This paper, which used Fick's equation as governing equation, presented a simplified way to model the moisture diffusivity and moisture transfer coefficient but not simulate the moisture distribution inside the wood slab during drying process.

Dedic (2000) presented a method to simplify the modeling of convective heat and mass transfer by introducing characteristic transfer coefficient. By using the single direction of Luikov's model, the author linearized the differential equations of moisture transport in wood to obtain a simplified representation of drying coefficient and coefficient of moisture conductivity. A specially designed computer codes was then used to calculate the coefficient of moisture conductivity