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Review of Wood Drying Technologies

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***Abstract*- This article provides a comprehensive review of drying optimization in data centers by examining the limitations of drying methods and discussing advances proposed by scientists through whom we can provide a comparison between different drying systems with an emphasis on improving energy efficiency and thermal performance. Wood drying under atmospheric pressure has many advantages, including the ability to dry at lower temperatures (by reducing the likelihood of some drying defects), significantly reduced drying times, color preservation, increased energy efficiency, better control of volatile organic compound emissions, and the ability to dry very large cross sections. Previous studies have achieved some characteristics that distinguish vacuum from traditional drying, which is that the main driving force in the vacuum is the total pressure difference, the prevailing moisture transfer mechanisms and the bulk flow of water vapor. There is also a greater migration of water in the longitudinal direction and these characteristics distinguish vacuum drying mechanisms than traditional drying methods. Previous researches had focused on increasing the understanding of the fundamental mechanisms of vacuum drying applications for specific industries materials and species, many efforts have concentrated for improving existing methods by improving moisture control and the using of pretreatment to improve energy consumption and drying quality.**

***Keywords*- Vacuum drying; organic materials; moisture content; drying rate; Radio frequency; wood, renewable energy; superheated steam.**

Nomenclature

Symbol	Quantity
A	Surface Area (m2)
C	Specific Heat (kJ/kg. K)
De	Drying Efficiency (%)
E	Specific Energy Consumption
EU	Total Energy Consumption
h	Heat Transfer Coefficient (W/m2. K)
K	Thermal Conductivity (W/m. K)
t	Drying time (min)
L	Latent heat (J/kg)
M	Moisture Content (kg_{watrer}/kg_{solid})
m	Mass of Sample (g)
P	Pressure (mbar)
Q	Heat Quantity (W)
R	Vapor gas constant (J/ kg. K)
T	Temperature (℃)
W	Weight loss (kg)

Greek letters

Δ	Difference
η	Thermal efficiency of dryer
λ	Latent heat of evaporation
ω	Evaporation rate

Subscripts

a	Ambient
ev	Evaporation
f	Final
fg	latent heat of evaporation
i	Inlet condition
m	Material
o	Outlet

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p	Particle
q	Heat
s	Surface or Sample
t	Time
v	Vacuum

Abbreviations

DMC	Dimensionless Moisture Content
DR	Drying Rate
MC	Moisture Content

I. INTRODUCTION

Drying of organic materials is considered one of the most complex processes encountered in engineering, the drying of wood has a vital role in wood industry. The kiln drying of wood produces huge amounts of vapour. The vapour is released to the environment when the process purges some of the saturated hot air. To overcome long drying time, low energy efficiency and poor product quality associated with conventional drying, a Conductive Heating Vacuum Drying technology is proposed for drying wood Current vacuum drying technology has its beginning in 1962. Vacuum drying is not a new technology, and its use for drying wood has been suggested since the early 1900s, although extensive research on this drying approach has only been conducted since the mid-1980s. In vacuum drying, wood is placed in an airtight vessel under less than atmospheric pressure, while heat is transferred to the material using one of several methods. Generally, wood vacuum drying methods were grouped into four categories based on the heating method used: conductive heating vacuum drying (or hot plate vacuum), cyclic vacuum drying (or "convective" vacuum) superheated steam vacuum drying, and dielectric vacuum (which in turn can be classified into radio frequency vacuum drying and microwave vacuum drying). Some characteristics that differentiate vacuum from conventional drying are that in vacuum the primary driving force is total pressure difference, the prevailing moisture transfer mechanism is water vapour bulk flow, and there is greater water migration in the longitudinal direction.

A. Properties of wood

All parts of a living tree contain water. Water is a critical component in the process of photosynthesis leading to the formation of new tree cells and subsequent growth. Water often makes up over half the total weight of the wood in a tree. This water in the tree is sometimes referred to "sap." Although the sap contains a variety of minerals and other materials in solution from the drying perspective it is considered to be plain water. The water or moisture content (MC) of wood is expressed in percent as the weight of water present in the wood divided by the weight of dry wood substance. Green (freshly cut) wood may have an MC as low as 30% to as high as 250%. Sapwood usually has a higher MC than heartwood. Average greenwood MCs may vary considerably from one tree to another among boards cut from the same tree and with the time of cutting tree.

a. 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 three distinguishable parts: pith, wood and bark. Pith is normally located at the center of the stem of a tree. It varies in sizes and colors 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 [1]. 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 color than the outer layer. This portion is called heartwood and it normally consists 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 [2]. The peripheral portion is called sapwood and it is the growing and youngest cell of tree and function as sap conductor and wood storage of tree. 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 and the cells of hardwood consist mainly long and narrow with closed or pointed end.

Generally, there are three types of cells vessel members, fibers and parenchyma cells [3]. Vessels are a pipe like structure of indeterminate length formed by individual vessel cells or element and it appears as solitary pores or in multiple chains or cluster in a wood cross section. In addition to, its size greatly varies within growth ring and between species where the average ranges of vessel elements length from 0.2 to 0.5 mm and 20 to 400μm in diameter. Parenchyma performs the function as storage tissues in wood. Under microscope observation parenchyma cells are typically prismatic in shape and have simple pits. Fibers are long narrows cells with closed and mostly pointed ends. Its average length varies from 1 to 2 mm and its diameter ranges from 0.01mm to 0.05 mm. There are mainly two types of pits simple pit and bordered pit as shown in figure (1). Pits in hardwood are often bordered, the opening of pits is called pit aperture and the

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space between aperture and membrane is called pit cavity. For hardwood the cavity of bordered pits is narrow and abrupt toward the cell lumen. The center of pit membrane is called torus and it is thickened for the softwood.

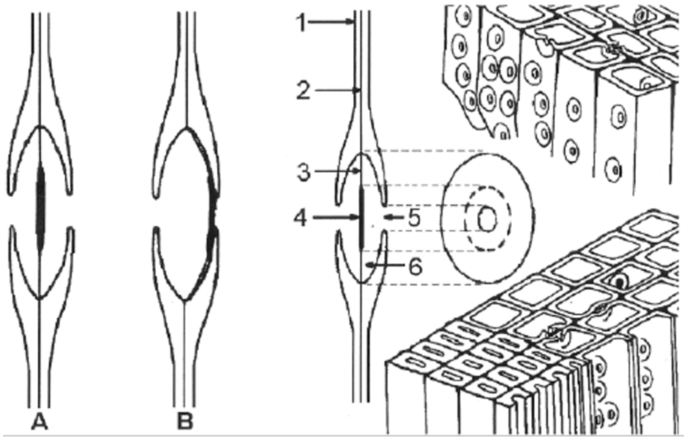

Figure 1. A) pit in opened state; B) closing of the pit during drying: Structure of the typical pit in early wood: 1 cell wall (secondary), 2 middle lamella (and primary wall), 3 margo, 4 torus, 5 porus, 6 inside area of the pit (after Petty 1970)[4].

B. 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 as shown in figure (2). The water in wood influences strength properties, shrinkage, weight, hardness, abrasion, machine ability, heat value, thermal conductivity, insect, fungi attack resistance and resistance of wood against decay[5].

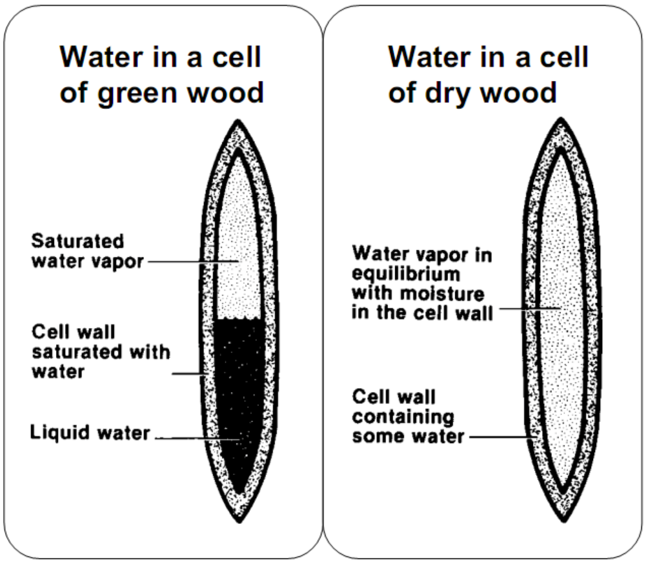

Figure 2. Water in wood cell [6]

Water in wood present in two conditions:

1) Bulk of water that contained in the cell cavities of wood 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 [7].
2) Liquid water in cell walls is called "bound" water. Water held in wood is by the attraction of water molecules by the hydroxyls (-OH) of its chemical constituents. The bound water is contained in the void of cell walls of wood [3].

Also, water may present in form of vapor contained in cell cavities. Normally these vapor constitutes only a small amount of total weight and negligible at normal temperature and moisture content. Moisture presented in a converted wood varies appreciably in different circumstance but the dry weight of wood substance in a given sample is constant. Moisture presented in a converted wood varies appreciably in different circumstance but the dry weight of wood substance in a given sample is constant. Moisture content of a sample can be expressed by the amounts of water presented in wood. It changes constantly according to the ambient condition and it may appear in three general forms:

(a) Free water in cell cavities.
(b) Hygroscopic bound water in void of cell walls.
(c) Vapor in cell cavities.

Moisture moves through many types of passageways such as cavities of the vessels, fibers and pit chamber. Moisture presented in a converted wood varies appreciably in different circumstance but the dry weight of wood substance in a given sample is constant [8]. The performance of wood is influenced by the amount of moisture which is expressed as a percentage of the weight of the dry wood substance.

$$M = \frac{Weight\ of\ wood\ sample - Weight\ of\ oven\ dried\ sample}{Weight\ of\ oven\ dried\ sample}$$

C. Mechanisms of Moisture Movement under Vacuum Drying Technology

We can define the energy state of moisture in wood as Potential and Kinetic energy. Since the flow of water within the wood is very slow, the potential for kinetic energy is typically very low [9]. Water flows continuously towards a decreasing potential energy. The moving force that creates moisture is created by the decrease in potential energy with increasing distance during the drying process. The wood is flooded with

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moisture as bound water in the cell wall capillary, water in liquid form, and water in gas form in the voids of wood as shown in figure (3). Capillary water bulk flow is a reference to the movement of liquid through the interconnected voids and across the top of a hard surface because of molecules of attraction that bind the liquid. In wood that is saturated, it has equilibrium with the capillary water at the same altitude.

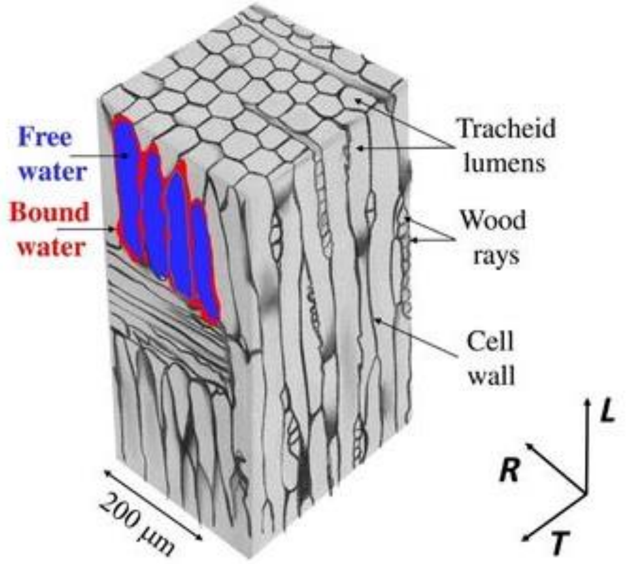

Figure 3. Free Water Bulk Flow (Movement of Liquid Water) [10]

The pressure is actually atmospheric and the suction power does not change. Untreated wood is subjected to suction or negative pressure, which corresponds to the negative pressure potential. Water loss can occur up to a certain threshold when larger pores begin to empty. The crucial section in soil science is known as air quantity. As the suction power increases, more water will be absorbed from the wood. These enlarged pores which cannot retain water drain through absorption. Gradually increasing the suction power will empty the small pores. At temperatures near or above the boiling point of water, rapid steam production can lead to large gradients in total pressure, as well as partial gradients in vapor pressure. Water vapor moves between low and high pressure areas with a difference in total pressure. It is like the free circulation of large amounts of water. Gas permeability is the primary consideration in the mass flux of water vapor. Although the density of water vapor may be negligible, its volumetric flow rate can be high at certain pressure ranges. A large amount of moisture can be transferred by increasing the flow of water vapor. During vacuum drying, fluctuations in overall pressure within the wood cause large amounts of water vapor to escape. There is a continuous flow of water vapor towards the boiling zone due to the process of water evaporation. Recent work has focused on the theoretical aspects of the driving force and mechanisms of moisture movement during the vacuum drying process that do not obey Fick's law[11]. The effect of pressure on drying was not taken into account in early studies. By increasing the permeability of the wood using a steam explosion, the vacuum drying rate of this treated wood was higher than the drying rate of the sample without such treatment at all moisture contents [12]. Permeability of wood is the dominant factor in controlling moisture movement in vacuum drying and bulk flow is thought to be the way by which most moisture is removed from wood.

A vacuum dryer has recently relied on the use of total pressure changes to determine the importance of the bulk flow mass transfer mechanism in pasta at temperatures above the boiling point of water [13]. Moisture transfer within hot concrete at high temperature is called pressure driven flow. Espinoza et al. [14] measured stresses within the wood during radio frequency vacuum drying. They drilled holes in the wood and inserted glass tubes connected to pressure gauges. In addition to, they found that there was a difference in pressure along the length and width while they were measuring the pressure distribution. They were not able to compare the pressure with the saturation pressure because they did not measure the temperatures. Liu et al. [15] studied the drying characteristics of thick lumber in a laboratory radio frequency vacuum dryer, they concluded that the temperature inside each board is higher than its surface. Furthermore, they investigated that appositive temperature gradient thus exists mostly along the length of the material and as a result, moisture transfer from the central parts of the board is increased. Most studies support the concept of a mechanism of moisture evaporation in wood during the drying process where the boiling temperature is reduced by vacuum. During the drying process using radio frequency vacuum drying technology, the temperature of the wood reaches the boiling point in a very short time [16].

Chen and Lamb [17] proposed the concept of boiling front. They achieved that boiling not only occurs inside the wood, but there is also a boiling front. They found that the pressure is less than the saturation pressure and moisture evaporates in the region of the boiling front to the surface of the wood. Also, boiling does not occur through the boiling front to the center of the wood because the pressure inside the wood is higher than the saturation pressure. In addition to, they noticed that the boiling front retreats from the surface towards the center as the drying process continues, and the speed of retreat depends on the heat source and the properties of the wood such as permeability and conductivity. Avramidis et al. [15] found that the internal pressure gradient is also important along the longitudinal direction during radio frequency vacuum drying. They concluded that moisture evaporates from the end grains as a result of the large permeability in the

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longitudinal direction. This phenomenon also results in a large temperature gradient along the longitudinal direction. This may cause faster drying rates during the vacuum drying technique. Sasaki et al. [18] They conducted a study on the process of pressure change inside wood as the drying process continues. They concluded that the pressure and time curves are divided into three periods: In the initial period of the drying process, the pressure drops rapidly depending on the permeability and location in the plate. In the second period of the compression process, the pressure remains almost constant. While in the third period, the pressure begins to decrease again approaching the low pressure in the room when the moisture content is less than the fiber saturation point. In vacuum drying, the total pressure gradient within the wood is a more important drying force than diffusion, unlike during the drying process using the conventional kiln technique. Srikiatden and Roberts [19]. They studied vacuum drying of foodstuffs at temperatures above the boiling point of water and used total pressure differences within a porous medium to determine the importance of the bulk flow mass transfer mechanism. The expected results were consistent with the experimental results. Liu et al. [20] concluded that during the vacuum drying process moisture migrates in a gaseous (vapor) state when wood is dried under fiber saturation point and they achieved that the drying force is the pressure difference between the vapor pressure in the Lumina and the ambient pressure. Moen and Martin [18] concluded that during the drying process of hot wood under vacuum, the drying rate is accelerated due to the pressure-driven flow and the wood surface releases significant heat through the evaporation of water within the porous structure when it is exposed to low pressure while at high temperatures, the pressure driven flow becomes a prevalent.

D. Drying of wood

In wood industry, drying of wood is the most energy extensive process that incurs a lot of cost and time, enhances the mechanical properties and protects the wood against fungal attack. Drying of wood has been a major part of wood industry for many years. Freshly felled trees have relatively high moisture content and they should be dried to a desirable level of moisture content usually below 20% [21]. Due to increasing of 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. So, it is important to study and understand the moisture movement from the core of wet wood to the surface and the mechanism of vapor removal from surface of wood. Drying will remove firstly unbound water because the weaker capillary force holds unbound water. The moisture content at which all unbound water has been removed from cell cavities is called fiber saturation point. 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. Movement of water vapor is possible for both above and below fiber saturation point and in accordance to diffusion law where vapor partial pressure gradient is the driving force.

a. Reasons for drying wood

There are two main reasons for drying wood:

Woodworking: when wood is used as a construction material whether as a structural support in a building or in wood working objects it will absorb or desorb moisture until it is in equilibrium with its surroundings. Equilibration too rapidly (usually drying) causes unequal shrinkage and damage in the wood. So, the equilibration must be controlled to prevent wood damage.

Wood burning: when wood is burned it is usually best to dry it first. Damage from shrinkage is not a problem here and the drying may proceed more rapidly than in the case of drying for woodworking purposes. Moisture affects the burning process with unburned hydrocarbons going up the chimney. If a 50% wet log is burnt at high temperature with good heat extraction from the exhaust gas leading to a 100 °C exhaust temperature and about 5% of the energy of the log is wasted through evaporating and heating the water vapor. With condensers, the efficiency can be further increased but for the normal stove the key to burning wet wood is to burn it very hot perhaps starting fire with dries wood [22].

In general, wood should be dried to moisture content within two percent of its in use MC. For furniture, cabinetry, millwork and other products used in homes or offices the in use MC is 6% to 8 % (equivalent to 30% to 45% relative humidity which is the typical range for interior climates in North America) [23]. Adjustments have to be made for drier humidity such as occur during the winter in heated buildings that are not humidified and for wetter humidity such as along the Southern and West coast.

Usually no fungal attack occurs when wood MC is 20% or less. Infected wood is sterilized at 65.56℃ or greater. Wood can be re-infected if rewetted. No insect attack at10% MC or less. Exceptions are dry wood termites and some beetles. Wood needs to be stress free with no checks or splits.

Examples with target MCs:

- Laminated timber: (10-12) % MC
- Softwood plywood: (3-5) % MC
- Furniture, interior millwork: (6-8) % MC

The relationship between humidity and wood moisture content is the critical factor in determining in use MCs. Temperature has no important effect. Based on spruce the following values were established:

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Table 1. Approximate relationship between φ and EMC at room temperature

Φ	EMC
-%-	-%-
0	0
15	3.5
30	6
50	9
65	12
80	16
90	20
95	24
100	28

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 and thermal insulation are better for dried wood.
b) Dry wood are less prone to insect, 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.

E. Methods of wood drying

Wood drying is a process that consumes a lot of energy and requires a lot of time and cost. Drying of wood world consumed as much as 70% of total energy required in wood processing [24]. The various methods used to dry lumber can be divided into two categories: the commonly used procedures of conventional kiln dryers and vacuum dryers. Although the primary objective of all drying methods is to remove water from wood, the selection of a particular procedure will depend on several other factors such as capital investment, energy sources, production capacity, drying efficiency, and end product. The special drying techniques are usually expensive and oriented to particular high-value end products. Some of the more common methods of drying processes are presented here.

a. 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 as shown in figure (4). 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.

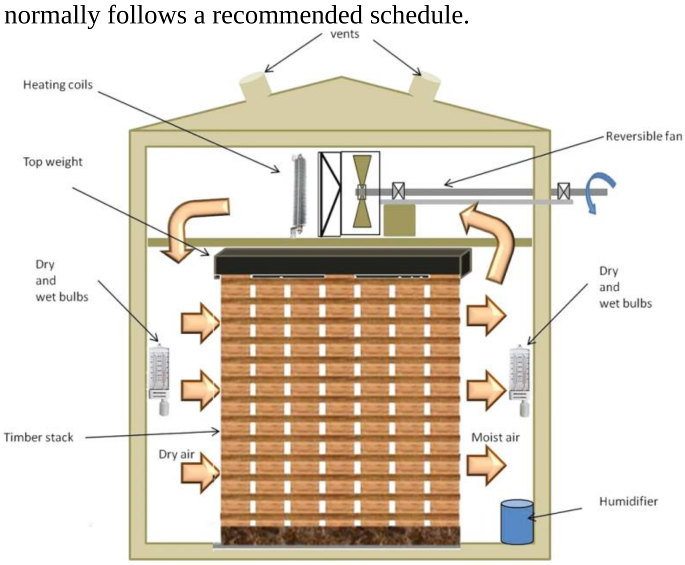

Figure 4. Conventional kiln drying [25]

b. Vacuum drying

Vacuum kiln drying is a tube with very low air pressure used for drying process. At this pressure, moisture can evaporate at much lower temperature as the boiling point of water is lower as shown in figure (5). Dehumidifiers are used to

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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. Vacuum drying can often be justified when drying thicker hardwoods.

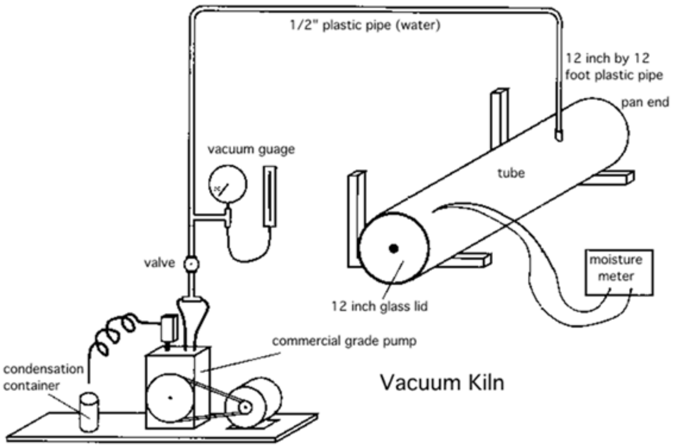

Figure 5. Vacuum kiln drying

The vacuum drying technology of wood is not a new technology it has been used since 1904, in this wood drying technology timber is placed inside an airtight vessel as shown in figure (6). Hence, after a long heating period water vapour from timber is quickly removed until a more or less perfect vacuum is obtained and cycle of heating vacuum is repeated until the timber is dried to the required extent [26]. In vacuum drying process, wood dries below atmospheric pressure, this condition at which water boils at a lower temperature. Faster drying is particularly relevant in a production environment where time and volume flexibility have become important competitive advantages [14]. Today, vacuum drying of wood is limited mainly to specialty applications, such as drying of very thick timber.

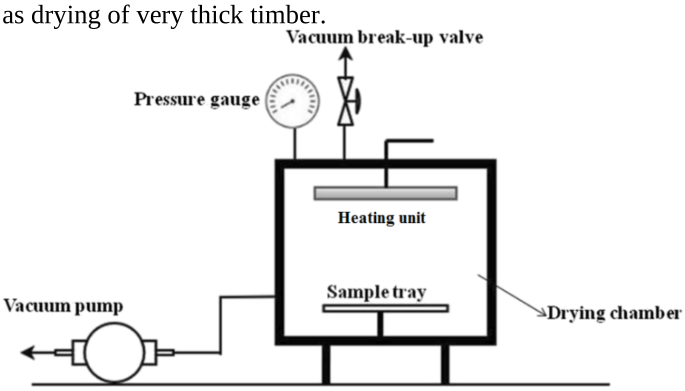

Figure 6. Schematic Diagram of Vacuum Drying Unit

In the near future, it is expected that there will be an increase in vacuum drying, which has recently gained remarkable interest in most areas of industry and scientific research in most countries of the world. Wood is theoretically dried by evaporation of moisture at low boiling temperatures (usually around 40°C). Many studies have been related to the vacuum drying techniques, it have proven that drying time is significantly reduced as a result of using the vacuum drying technique, especially for thick woods. Vacuum drying is often used for high value species or large sized woods due to the good drying quality resulting from the use of this technology. However, little work has been done on the theoretical aspects of vacuum drying. Water moves within the wood through bulk flow and diffusion. In general, moisture movement at moisture content (MC) above the fiber saturation point (FSP) is controlled by free water bulk flow (FWBF) and diffusion controls moisture movement at MC below FSP. Little information is known about the total water vapour bulk flow (WVBF) driven by the total pressure difference. Water vapour bulk flow depends strongly on the gas permeability of the wood. In vacuum drying, a mass of water vapour flows from the centre to the surface through the total pressure difference within the wood. It is necessary to study water vapour bulk flow in vacuum drying when water diffusion is not completely controlled. It is well documented that permeability affects the rate of vacuum drying, and that wood is more permeable in the longitudinal direction than in the transverse directions [27].

Generally, the drying process involves removing water and supplying heat to the wood, both of which affect the rate of vacuum drying. Since it is important to know how vacuum drying works. This in turn will help to understand the effect of sample length and thickness on the drying rate. It is not known how much water is transported longitudinally and removed from the surface of the finished grain during vacuum drying. Vacuum drying is rapid and the drying rate is determined by the heat source, which in turn is controlled by the ambient temperature. The drying rate increases with increasing ambient temperature, which leads to an increased rate of evaporation from the wood surface. It is interesting to note the effect of lowering the ambient temperature to room temperature on the vacuum drying rate. Although vacuum drying greatly reduces drying time, surface inspection and internal inspection remain a major problem. In addition to using the vacuum drying process, the moisture gradient along the thickness is very steep and higher than using traditional drying [28]. In order to understand the cause of defects such as screening, the mechanism of vacuum drying must be studied. This has been increasing steadily in the past decade, especially for drying valuable species. Since the vacuum drying process takes place at low drying temperatures with a high drying rate, almost as fast as high temperature drying over 100°C [29], which in turn increases its usability.

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In this paper, [Researchers have claimed other advantages from drying under vacuum that are discussed later in this paper, So the main objective of this paper is to comprehensively review the scientific literature about vacuum drying of wood, including major technologies, mechanisms of drying under vacuum, vacuum drying efficiency and improving the performance of vacuum dryers in terms of energy consumption].

II. Basics Of Vacuum Drying

A. History of Vacuum Drying

The history of the vacuum drying of wood can be traced back to early 1920's and a patent on the vacuum drying system of wood was registered in 1922 in Sweden [30]. In 1962, the first industrial vacuum dryer using cyclic technology was built [31]. In 1964, a small dryer was made with the electric resistance plates working under a continuous vacuum. Dryer with hot air heating was developed for the first time. The first radio frequency vacuum dryer was built in the early 1970's [32].

Recently, it has gained a renewed interest in both industry and research. An increase in vacuum drying is expected in the near future, especially in Europe and Asia. The technology of vacuum drying refers that the lumber is placed in a tight drying chamber and the vacuum system pulls a vacuum on the lumber. Wood is theoretically dried by evaporation of moisture at low boiling temperatures and when the wood reaches the required temperature, a vacuum is drawn over the wood. The drying process continues until the drying rate becomes very small by repeating the cycle several times. Researchers have done a great deal of experimental work in recent decades on vacuum drying of wood.

B. Definition of Vacuum Drying

The wood is placed in a sealed drying chamber during the vacuum drying process and then the vacuum drying system draws a vacuum on the wood so that the water in the wood boils and is drawn out of the wood [33]. In fact, vacuum drying depends on the fact that by decreasing the atmospheric pressure above the wood, the boiling point of water is significantly reduced. The relationship between saturation vapor pressure and temperature is approximated by the Clausius-Clapeyron equation (1) [34]:

$$e_s = e_o \exp\left[\frac{L}{R_v} * \left(\frac{1}{T_o} - \frac{1}{T}\right)\right] \qquad (1)$$

Where; the water vapor gas constant is R_v =461 J/K.kg, T_o=273.15 K, e_0 =0.6113kpa and L is latent heat parameter. Temperature in this equation must have units of kelvin. This relation is graphically presented in figure (7).

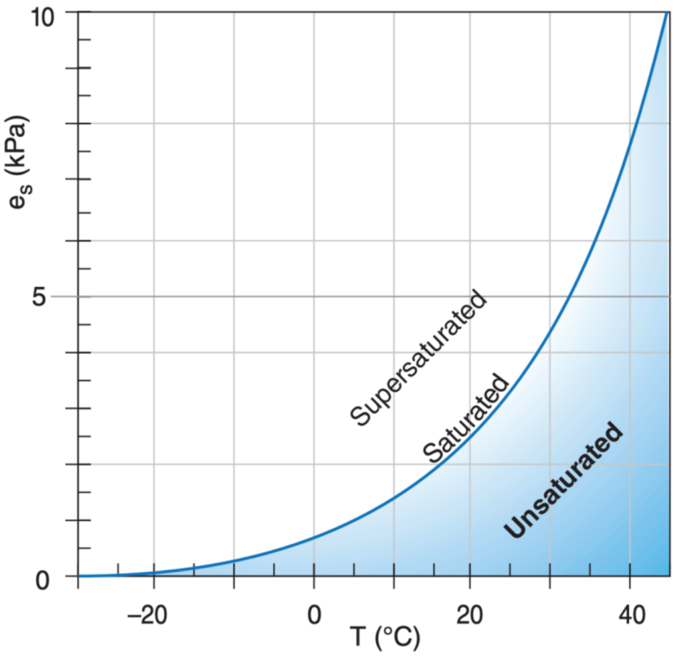

Figure 7. Water saturation vapor pressure over a flat water surface [34]

C. Main Vacuum Drying Techniques

Wood drying technology which using vacuum drying systems can be divided into main three types depending on the method of heat transfer to wood:

- Conductive heating methods such as hot plate vacuum drying.
- Convection heating methods such as superheated steam vacuum.
- Cyclic vacuum drying such as radio frequency or microwaves vacuum drying.

Wood drying techniques are evaluated based on the degree of reduction in drying time, adequate drying quality, efficient energy use and reasonable drying costs [14]. Various major wood drying technologies and their performance are discussed in this section.

a. Conductive Heating Vacuum Drying

In conductive heating wood vacuum drying, heat is transferred to the wood by direct contact with a heated surface such as “Hot plate” vacuum drying technique, in which planks of wood are placed between metal plates (usually aluminium for rapid heat transfer) that are heated by a hot liquid flowing through them as shown in figure (8).

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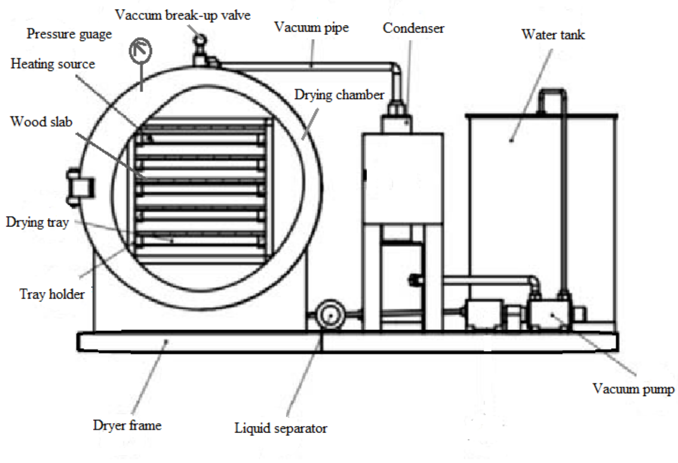

Figure 8. Schematic Diagram of Conductive Heating Vacuum Dryer

This system provides uniform heating of the wood and good control of the temperatures which are used. However, loading and unloading the kiln is time consuming, if done manually and the panels require periodic maintenance or replacement which increases the cost. Therefore, some furnace manufacturers offer automatic systems for stacking wood and hot plates. The hot plate vacuum drying technique has been used to dry oak wood by many researchers and this type of wood is susceptible to checking, distortion and stains during drying. Researchers achieved much faster drying rates for vacuum-dried oak than with conventional drying, 20% to 50% shorter for 40 mm thick oak and 243% to 433% faster for 28 mm thick red oak [35]. The two and a half inch thick oak (51 mm surface) was also dried in 300 hours to obtain satisfactory quality. Chen and Lamb [17] were able to achieve drying rates between 0.32% and 2.2% per hour for green red oak, where the drying rate was dependent on the sample size. Autengruber et al.[36] investigated a finite element based on moisture transport model for wood including free water above the fiber saturation point and they concluded that: The exchange processes between the three different water phases were defined explicitly for the description of the evaporation or condensation rate and a new water vapor concentration dependent reaction function was introduced, the numerical implementation of the processes in the user element is modular and future improvements of infiltration models can easily be implemented into the proposed model and the developed model was able to describe seven different validation experiments and simulations for both drying and infiltration situations quite well and numerically stable.

b. Convection with Steam at high Temperatures Vacuum Drying (Superheated Steam Vacuum Dryer)

During this vacuum drying technique superheated steam (water vapor at a temperature above the boiling point) is used under low pressure conditions and forced through layers of wood. Heating can be achieved by convection and continuous vacuum drying process. This process is known as superheated steam vacuum drying or thermal vacuum drying as shown in figure (9). Superheated steam has better heat transfer properties than heated air at the same temperature [37].

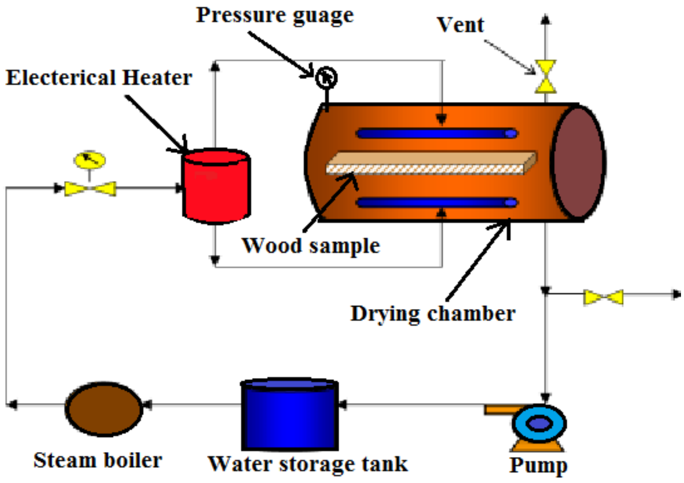

Figure 9. Schematic of superheated steam drying operation

However, steam under vacuum has a lower heat capacity (due to lower density) and drying rates are lower than hot humid air as in conventional drying. This can be compensated by circulating air at high speeds of about 10 m/s, and by frequent fan reversals [38]. The "reversal temperature" of superheated steam (when the steam temperature exceeds the reversal point the superheated steam vacuum drying speed exceeds the air drying speed) was observed when drying 100 x 100 x 40 mm Mason pine with initial moisture contents ranging from 140% to 147%. Some of the advantages of superheated steam vacuum drying mentioned in the literature include energy savings due to the potential to recycle latent heat of steam via condensation and improved drying quality by reducing case hardening, warping and splits [39]. One disadvantage of superheated steam vacuum drying is that similar to conventional drying which produce high values of final MC in the kiln coincide with regions of relatively low air velocity [14]. Khouya et al. [40] found that beech, spruce and Scots pine dried three times faster at superheated steam vacuum than at atmospheric pressure and the drying times for oak wood did not differ from conventional drying times. However, more than 45% of beech and oak were dried in a similar manner which leads the authors to believe that the vacuum only accelerates the hygroscopic drying process. The researchers suspect that when the superheated steam vacuum dries out, the air in the cavity keeps the pressure high and preventing the water from boiling. Thick (100*100*40 mm)

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pine wood is dried at an undisclosed rate faster than conventional drying [41].

Rubber wood was found to dry 8.4 times faster using superheated steam vacuum compared to traditional methods. Although faster drying rates 30%to40% higher were achieved using superheated steam vacuum compared to conventional drying of pine and birch Radiata wood [42], a greater variation in the final moisture content of wood dried by superheated steam vacuum was observed. It has been suggested that the greater variation in moisture content was due to a greater temperature drop via convection most likely due to fan non-reversal. In the same experiment, shrinkage was measured and the values were lower for vacuum drying as the volumetric shrinkage of 5% MC. Green reached 12% and 13% for vacuum drying and conventional drying of planted birch plantations and respectively 12.8% or 13.4% for sawn wood from natural forests [43]. Australian eucalyptus plantings dry 60% faster than conventional drying. However, there was a need to improve the quality of the wood which the authors believe could be achieved by controlling drying conditions. In order to better understand and optimize the process, mathematical models for superheated steam vacuum drying have been developed [44]. Ananias et al. [45] modelled superheated steam vacuum drying of radiation pine and validated the model by experimental operation at 0.2 bar (20 kPa) and 70 °C. Alustondo et al. [46] evaluated three superheated steam vacuum drying models and they found that the most accurate model is based on heat transfer and moisture migration where the drying rate is proportional to the wet bulb depression and the difference between the actual moisture content and the equilibrium moisture content.

c. *Dielectric Heating Vacuum Drying*

a) *Dielectric Heating Vacuum Drying*

In the radio frequency vacuum (RFV) drying process, wood insulation can be placed between electrodes or metal sheets as shown in figure (10). When a radio frequency electrical charge is produced these molecules periodically change their direction which causing rapid movement of the molecules. In this process, radio frequency generates significant temperature in the wood at a short time.

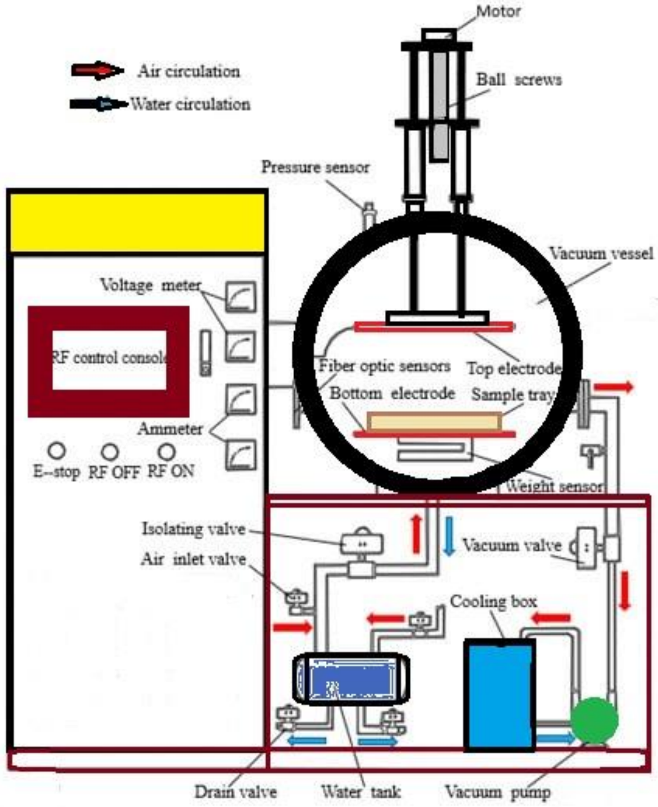

Figure 10. Schematic of radio frequency vacuum drying operation

High-frequency vacuum (RFV) drying is performed at frequencies below (100 MHz) RFV drying involves exposing wood to an alternating electromagnetic field which causing polar water molecules in the wood to move in the direction of the changing field. These movements absorb energy that is released in the form of heat and this phenomenon increases the temperature of the wood to such an extent that the driving forces for moisture migration are stimulated. The intensity of heating depends on the moisture content of the wood and the electric field and the movement of moisture depends on the permeability and internal pressure gradient. In contrast to conventional drying, in radio frequency vacuum drying energy transfer as the main resistance above the fiber saturation point becomes negligible as vacuum enhances internal mass transfer due to pressure differences. The mass transfer mechanisms are capillary and mass flow above the fiber saturation point and limited water diffusion below the fiber saturation point. Heat transfer is also very effective in radio frequency vacuum drying, so internal stresses can build up quickly exceeding the mechanical strength of the wood fibers. Drying programs for RFV drying depend largely on an energy density limit (energy per unit volume of wood usually expressed in kWh/m^3). In fact, the rate of energy absorption is proportional to the electrode potentials and the energy density depends

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on the type (permeability) and is also affected by the cross section of the material to be dried. As wood dries, energy loss decreases which was a measure of the material's ability to absorb heat in an electromagnetic field which in turn slows the drying process. Therefore, there were two ways to control the drying speed: by constant or variable voltage and the latter can be implemented gradually or in stages. Several methods have been proposed to monitor drying conditions during RFV drying.

Zhang et al. [47] found that for hemlock squares wood, when the tension remains constant the wood loss factor decreases as the MC decreases which slowing the drying rate. This can be compensated for by increasing the tension thus keeping the energy density per unit volume of wood constant. Drying times were 80% shorter than conventional drying times and the final MC along the samples was between 12% and 16%. There was no internal, final or surface control and no collapse or internal stress when power density less than 10 kW/m^3. Xiao et al. [48] reported that the relative humidity is affected by the dry bulb and wet bulb temperatures and the difference between the air temperature and the water temperature in the condenser. The relative humidity is only slightly affected by the pressure. Cai and Hayashi [49] used temperature and pressure measurements in wood as a means of monitoring MC during RFV drying. Their measurements were very close to those obtained using the oven drying method with absolute errors ranging from 0.8% to 1.8% depending on the position in the cross section. A similar study used the relationship between temperature, pressure and EMC for real time MC measurement under RFV drying, as the authors concluded that their method could be used on MC under FSP and that the measurement accuracy was not affected by the drying schedule or by the measurement location [50]. Koumoutsakos et al. [51] described the development and experimental validation of a one dimensional mathematical model for simulating RFV drying transport phenomena. Their model derived and solved the initial heat and mass transfer equations, taking into account internal heat generation and the effect of pressure gradients in the gas phase. It has been shown that the one dimensional model can satisfactorily predict the average MC and drying time. Wood drying by RFV was then modeled based on heat and mass transfer theory and conservation equations. The model calculated each independent variable independently and curves were calculated for different parts of the wood sample. Simulated data for MC and temperature were compared with experimental results using Sugi wood and the researchers came to the conclusion that their model adequately describes the drying behaviour. In another experiment, the dielectric energy conversion in evaporating water was modeled using well known heat and mass transfer equations to predict thermal efficiency. The model was able to illustrate the idea of “drying from the inside out” and increase the drying speed while increasing the gas permeability of the wood. Finally, the model provided a basis for classifying the difficulties of drying species using radio frequency vacuum drying [52].

In general, studies have shown that the use of RFV drying leads to shorter drying times and reduced MC fluctuations, ultimately leading to higher economic returns. When comparing RFV to conventional drying of lumber and filled frame pieces with pieces cut before and after drying by both methods the highest yields were achieved when raw wood was dried with RFV and then cut into pieces. Radio frequency vacuum drying produced less deformation than conventional drying which the researchers attributed to lower shrinkage of materials dried with radio frequency vacuum drying [53].

b) Microwave Vacuum Drying

Microwaves are another form of dielectric heating that occurs at frequencies above 300 MHz that can be used as a wood drying technique [54]. Unlike conventional drying in microwave vacuum drying where almost the entire drying process goes through a period of constant drying rate which appears to be less than the average moisture content and less than the fiber saturation point [55]. Compared to radio frequencies, microwaves have a shorter and more uniform wavelength which leads to faster drying, primarily due to the higher energy density. Microwave vacuum drying has been used successfully for drying beech, oak and Scots pine. Limitation of using standard microwaves for heating is poor penetration especially for low loss materials. To solve this problem, the researchers proposed using a continuous process. A continuous process using a conveyor belt moving through the chamber at a speed of 20 m/hour has been successfully used to dry beech and oak wood from 32% to 8% MC and from 79% to 12% MC within 120 to 360 second [56].

III. Efficiency in Vacuum Drying

Wood drying requires energy to evaporate and remove water from the wood surface. In addition, energy is needed to heat the material, compensate for energy loss and move the air. Vacuum drying is more energy efficient than traditional methods because it is a closed system that does not require ventilation and requires lower drying temperatures. Elustondo et al. [52] developed a mathematical model to estimate the energy efficiency (the percentage of electromagnetic energy actually used to produce water vapor) of radio frequency vacuum drying. The energy required for water evaporation divided by the total energy transferred to the wood varied from 36% to 81% for wood with a cross section of 105 × 230 to 310 × 310 mm. The energy efficiency of microwave vacuum drying of beech, spruce and maple trees was estimated by Leiker and Adamska [57] and was between

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70% and 80% during most of the drying process. Seyfarth et al. [56] attempted continuous microwave vacuum drying and found that the electrical energy consumption was similar to that of conventional drying. A special drying process called the "Muldrop process" which uses extremely hot steam under vacuum has been proven to use 55% less electricity to dry pine or spruce on moisture content between 80% to 18% and 72% less electricity to dry 50mm Pine. The energy requirements for commercial scale radio frequency vacuum drying were calculated based on the energy required to remove a given amount of water (kWh/kg water). It has been found that vacuum drying of 101 mm thick wood consumes 83% less energy than drying 50 mm thick wood in a conventional kiln and 20% to 60% less energy is used for moisture drying (including drying 50 mm thick wood) [58].

Avramidis and Zwick [59] showed that as efficiency decreases the energy cost increases exponentially and linearly with the initial moisture content and gradually decreases with increasing absorbed energy density (kW/m^3).

IV. Improving the Performance of Vacuum Dryers in Terms of Energy Consumption

The drying process consumes large amounts of energy for several reasons, the most important of which is the widespread use of drying technology in most industrial applications, as a typical thermal dryer is expected to consume at least 1 MW of thermal energy per ton of evaporation [60]. So, many companies view dryers as popular targets in their energy conservation programs. The recent escalation in the price of oil and natural gas has naturally provided an added incentive.

The thermal efficiency of a dryer can be expressed in several ways. A typical measure is:

$$\eta = 100\,\frac{Q_{ev}}{Q_{htr}} \tag{2}$$

Where, Q_{htr} refers to the total rate at which thermal energy is supplied to the dryer and Q_{ev} is required to provide the latent heat of evaporation. Alternatively, the specific energy consumption E_s of the dryer is defined as the thermal energy required for evaporation unit mass of water:

$$Q = 0.001\,\frac{Q_{htr}}{\omega_{ev}} \tag{3}$$

Where, ω_{ev} refers to the evaporation rate. Baker and McKenzie [61] showed that the specific energy consumption $E_{s,a}$ of such a dryer is not fixed in the absolute sense, but rather that it depended on the temperature and humidity of the outlet air:

$$EU_{s,a} = 0.001\left[C_{pg}\left(\frac{T_o - T_a}{Y_o - Y_a}\right) + \lambda_{ref}\right]$$
$$= C_{pg}\xi + \lambda_{ref} \tag{4}$$

Vacuum dryers are the mainstay of production. Heat sensitive materials are placed in trays on separate racks in a vacuum chamber. The chamber then activates the low pressure system. The boiling point decreases as the pressure increases. Therefore, drying temperatures can be controlled thermostatically to maintain product integrity. In order for pilot dryers to make a special contribution to increasing efficiency, there are initially equipped with a vacuum chamber inside which there are directly heated frames, usually made of stainless steel which facilitates the dissipation of high heat towards the material to be dried. Heating plates and heating racks play a vital role in the drying processes within a vacuum dryer. There are often made of stainless steel and ensure temperature uniformity which is a crucial factor when working with heat sensitive materials. Direct heat transfer from these components to the dry materials ensures that drying temperatures remain constant, preventing product damage as the heat is provided by a medium flowing through tubes inside the heating plates. The medium is usually hot water, steam or thermal oil. Generally, we can illustrate most equations used for estimating energy efficiency and drying efficiency for different dryers through the following equations [62]:

Energy efficiency (η_e) at any time during the drying process can be calculated by equation “(5)”[63]:

$$\eta_e = \left(\frac{E_{ev}}{EU}\right) * 100 \tag{5}$$

Where, E_{ev}[kJ] Energy consumed to evaporate moisture from drying samples, EU[kJ] is Total energy consumption. The energy consumed to evaporate moisture from drying samples (E_{ev}) at any time during the drying period can be calculated from equation”(6)”[64]:

$$E_{ev} = h_{fg} * M_w \tag{6}$$

Where, h_{fg}[kJ/kg] Latent heat of vaporization and M_w[kg] is the mass of evaporated water from the product.

Drying efficiency (De) for the drying process can be calculated from equation “(7)”[65]:

$$De = \left(\frac{E_{ev}+E_{heating}}{EU}\right) \tag{7}$$

Where, (De) Drying efficiency of the drying process, E_{ev}[kJ] is the energy consumed to evaporate moisture from drying samples and $E_{heating}$[kJ] is the energy for the material heating where we can calculate it from equation” (8)”[66]:

$$E_{heating} = W_d C_m \Delta T \tag{8}$$

Where, W_d [kg]The mass of the dry material, ΔT[K] is the temperature difference and C_m[kJ/kg.K] is the specific heat of the material where we can calculate it for microwave vacuum drying from equation” (9)”[67]:

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$$C_m = \frac{4.18WC_p\Delta P}{t} \quad (9)$$

Where, w [kg]is the weight loss, ΔP [mbar] is the differential pressure and t [min] is the drying time. Although, we can calculate C_m for infrared vacuum drying from equation" (10)"[67]:

$$C_m = 1465 + 3560\left(\frac{M_P}{1+M_P}\right) \quad (10)$$

Where, M_P [kg_{water}/kg_{solid}] is the particle moisture content which we can calculate it from equation" (11)"[68]:

$$M_P = \frac{W_w - W_d}{W_d} \quad (11)$$

Where, W_w [kg] stands for the initial mass and W_d [kg] represents the mass of the dry sample.

The low pressure environment inside the chamber reduces the boiling point of the solvent to be dried from the raw material to be dried which leads to improving the efficiency of the drying process as the vacuum conditions inside the dryer accelerate the moisture removal process at lower temperatures and pressures than traditional drying methods. This ensures faster drying in addition to enhance the efficiency of the process. Vacuum dryers have much lower energy consumption due to lower temperature and pressure requirements. This translates into lower operating costs and increased thermal efficiency. Hence to improve the performance of vacuum dryers we must apply the following steps:

1) Reduce evaporation load, by upstream dewatering to reduce initial moisture content or avoid over drying.

2) Increase dryer efficiency, by improving insulation and reducing heat loss, installing a heat recovery system and changing operating parameters.

V. CONCLUSION

Vacuum drying has been used for drying wood since the early 1900s; extensive research on this drying technology has been conducted since mid-1980s, so it is not a new technology. In this drying technology, wood is placed in an airtight vessel under less than atmospheric pressure while heat is transferred to the pad material using one of the several methods of heat generation. In this paper, wood vacuum drying techniques can be grouped as conductive heating method such as hot plate vacuum drying, Convection heating methods such as (superheated steam vacuum and cyclic vacuum drying) and vacuum drying for dielectric heating, where radiofrequency or microwaves are used.

Characteristics that differs vacuum drying technique from conventional kiln drying are:

- Primary driving force is total pressure difference.
- Prevailing moisture transfer mechanism is water vapor bulk flow.
- In the longitudinal direction there is greater water migration.

Major advantages of wood vacuum drying technology reported in the literature are:

- Drying process occurs at lower temperatures than conventional drying (which in turn may lead to less drying defects).
- Drying times are reduced greatly (especially for hardwoods and very large sections) in addition to improving color preservation.
- Vacuum drying technology has higher energy efficiency (because of the dramatically reduced heat losses).
- Vacuum drying has a better control of volatile organic compound emissions in addition to dry very large cross sections.

Any drying technology's attractiveness for the industry is greatly affected by the economics and energy efficiency of vacuum drying, knowing that little research has addressed this part during vacuum drying process. Many companies will have to pay attention to studying vacuum drying more widely in order to provide more customized products to the market and reduce the energy consumed in the drying process in order to save fuel and preserve the environment.

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