Curr Forestry Rep (2016) 2:223–235
DOI 10.1007/s40725-016-0045-9

Vacuum Drying of Wood—State of the Art

Omar Espinoza[1] · **Brian Bond**[2]

Abstract In this paper, we review the literature published on vacuum drying of wood. Vacuum drying is not a new technology, and its use for drying wood has been suggested since the early 1900s. Technologies for vacuum drying of wood can be classified by the heating method used. In this paper, we define vacuum-drying methods in four groups: conductive heating vacuum, cyclic vacuum, superheated steam vacuum, and dielectric vacuum. Advantages of drying wood below atmospheric pressure are the ability to dry at lower temperatures (and thus lower the probability of developing some drying defects), greatly reduced drying times, color preservation, greater energy efficiency, better control of volatile organic compound emissions, and the ability to dry very large cross sections. Some characteristics that differentiate vacuum from conventional drying are that in vacuum the primary driving force is the total pressure difference, the prevailing moisture transfer mechanism is water vapor bulk flow, and there is greater water migration in the longitudinal direction. While past research has focused on increasing the understanding of the fundamental mechanisms for vacuum drying and applications to specific industries and species, more recent efforts have concentrated on improving existing methods, for example, by improving moisture control and the use of pretreatments to improve drying quality.

Keywords Vacuum drying · Wood · Lumber · Radio frequency · Superheated steam

Introduction

Vacuum drying of wood is not a new technology. A US patent for a "Process for Drying Timber" was issued in 1904, in which timber is placed inside an airtight vessel and, after a long heating period, "air and vapor are 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" [1]. In vacuum drying, wood dries at pressures well below atmospheric pressure, conditions at which water boils at a lower temperature. Faster drying is particularly relevant in a production environment where time and volume flexibility (i.e., small batches and very short lead times) have become important competitive advantages [2•]. Researchers have claimed other advantages from drying under vacuum that are discussed later in this paper. However, today, vacuum drying of wood is limited mainly to specialty and niche applications, such as drying of very thick stock. The objective of this paper is to comprehensively review the scientific literature about vacuum drying of wood, including major technologies, fundamental drying mechanisms, drying quality, and industrial applications.

This article is part of the Topical Collection on *Wood Structure and Function*

✉ Omar Espinoza
espinoza@umn.edu

Brian Bond
bbond@vt.edu

[1] Bioproducts and Biosystems Engineering Department, University of Minnesota, 2004 Folwell Ave, St Paul, MN 55108, USA

[2] Department of Sustainable Biomaterials, Virginia Polytechnic Institute and State University, 1650 Research Center Drive, Blacksburg, VA 24060, USA

Fundamentals of Vacuum Drying

Vacuum drying is a method significantly different from conventional drying. In conventional lumber drying, heat and moisture transfer occur mainly in the transverse direction resulting in the development of cross-sectional temperature and moisture gradients. The moisture gradients between the surface and center of the wood are the driving force in conventional drying [3]. Optimal drying requires conditions to be adjusted such that moisture gradients are not too high, since case hardening or checking may occur, or too small, leading to uneconomical drying times [4]. Moisture movement occurs in four ways in drying of wood: (1) liquid water moving through cell structure by capillary action, or free water bulk flow; (2) water vapor moving from high-pressure to low-pressure zones, or water vapor bulk flow; (3) water vapor diffusion, due to relative humidity gradients; and (4) water molecules from cell walls through diffusion due to differences of moisture content [5, 6]. Above the fiber saturation point (FSP), the limiting factor is energy transfer; below the FSP, mass transfer becomes the controlling factor [7]. As drying progresses, less free water is available and most of the mass transfer occurs by diffusion, which is a much slower process than bulk flow [8]; thus, temperature is increased significantly in the later stages of drying to maintain an optimum drying rate. Although longitudinal diffusion is 10 to 15 times faster than transversal diffusion, this is more than offset by the relatively large ratio between length and width (or thickness) of lumber. Longitudinal diffusion only contributes significantly to the drying of short pieces and the ends of longer boards.

In vacuum drying of wood, the boiling point of water is reduced by drawing a vacuum, allowing for drying at lower temperatures than conventional drying. Thus, the benefits of high-temperature drying are achieved, i.e., less warp and much reduced drying time [9], but at lower temperatures [10]. For example, at 10 % of the atmospheric pressure (102 mbar), water boils at 99 °F (37 °C). By comparison, a typical drying schedule for oak in conventional drying starts at 110 °F (43 °C) and may exceed 160–180 °F in the final stages of drying [11]. Wood strength is inversely proportional to temperature and moisture content (MC); thus, lumber is most susceptible to developing drying defects, especially checking and honeycomb, early in the drying process [11]. Another benefit of drying at lower temperatures is that wood retains its original color because of the lack of oxygen [12].

In addition to enabling lower drying temperatures, vacuum drying has other differences from conventional drying. The pressure gradient that can exist can increase the drying rate at various stages of drying; for example, Moyne and Martin [13] determined that for silver fir, a gas pressure gradient increases the drying rate at high free moisture content. Others have suggested that, while the primary driving force in vacuum drying of wood is total pressure difference rather than diffusion as in conventional drying, the prevailing moisture transfer mechanism is water vapor bulk flow from the ends and diffusion through the lateral faces [6, 14•]. Moreover, when temperatures approach the boiling point of water, steep total pressure differences are caused by the fast generation of vapor [14•], accelerating the process. Free water in both liquid and vapor phases travels in the longitudinal direction, and bulk flow is accelerated by the much greater longitudinal permeability (longitudinal-to-transverse ratios ranging between 30,000 and 400,000,000) [15]. This causes water to migrate lengthwise, leaving the individual lumber pieces through the ends [16, 17]. Neumann [18] found that, up to 40 % MC, the drying rates for both conventional and vacuum drying were similar but, below this point, vacuum drying accelerated significantly. He hypothesized that as long as cell lumens contain free water, water migration is not affected by total pressure. Results were similar for a study in birch wood [19], where drying rates down to 30 % MC were similar for both vacuum and conventional drying (a ratio of 0.9 to 2.3 between drying rates for both methods), but below this point, vacuum drying accelerated significantly (ratio from 3.1 to 4.7).

Chen and Lamb [20] proposed the existence of a “boiling front” in wood during vacuum drying. From the boiling front to the surface, water boiling temperature is lower than the temperature of the substrate; thus, water boils in this region. From the boiling front to the center of the material, pressure inside the wood is higher than the saturation vapor pressure. As drying progresses, the boiling front retreats towards the center, at a rate dependent on heat supplied and wood permeability and conductivity [20]. The boiling front retreats more slowly when the initial MC is high. Results by Neumann and Defo et al. [21•] appear to contradict the boiling front hypothesis, since they found that internal pressure at different depths was always higher than the saturation pressure at the same temperature. A series of modeling equations for heat and mass transfer for vacuum drying, based on the existence of an “evaporation front” and two drying zones on the longitudinal direction, were developed by Audebert et al. [22], where the temperature and pressure curves calculated proved the linearity between the average drying velocity and MC [22].

The equilibrium moisture content (EMC) in vacuum drying is generally lower than that for conventional drying [23]. Research has shown that there is a direct relationship between pressure and the EMC at constant temperature and an inverse association between temperature and the EMC at constant pressure [24, 25]. Under atmospheric conditions, the EMC depends primarily on temperature and relative humidity, but in vacuum drying, the EMC depends mainly on total pressure and temperature. At atmospheric conditions, relative humidity is the ratio between partial vapor pressure and saturated vapor pressure for a temperature. In vacuum, since there is little air, the absolute pressure can be assumed to be the water vapor pressure, and relative humidity is calculated as the ratio between absolute pressure and saturated vapor pressure [25]. Research confirmed that the EMC is inversely proportional to ambient pressure [26]. This effect is greatest under 50 kPa of pressure [27].

Several mathematical models describing the fundamentals of vacuum drying have been developed. These efforts are presented throughout this paper in the context of the relevant vacuum technology.

Major Vacuum-Drying Technologies

Wood-drying technology can be classified by the method of heat transfer to the wood, or how moisture is removed from the drying chamber. Based on the method of heat transfer to the wood, vacuum-drying technologies can be grouped as conductive heating methods, such as hot platen vacuum drying; convection heating methods, such as superheated steam vacuum and cyclic vacuum drying; and dielectric heating vacuum drying, where radio frequency or microwaves are used. Wood-drying technologies are evaluated based on the degree to which they shorten drying time, produce adequate drying quality, make efficient use of energy, and have reasonable drying costs [28, 29]. The major wood vacuum-drying technologies and their performance are discussed in this section.

Conductive Heating Vacuum Drying

In conductive heating, heat is transferred to the wood by direct contact with a hot surface. “Hot plate” vacuum drying is one such technology, where the stacks of wood are laid between metal plates (usually aluminum) heated by a hot fluid flowing through them [30]. This system provides uniform heating of the lumber and good control of the temperatures used. However, kiln loading and unloading are time-consuming, if done manually, and plates require periodic maintenance or replacement, adding to the cost. Some kiln-manufacturing companies offer automatic systems for stacking the lumber and hot plates.

Several researchers have investigated the use of hot plate vacuum drying to dry oak, a species prone to check, warp, and stain during drying. Significantly faster drying rates were achieved for vacuum drying of oak than conventional drying, 20 to 50 % shorter for 40-mm-thick [31] and 243 to 433 % faster for 28-mm-thick red oak lumber. Two and a half inches thick (surfaced to 51 mm) oak was also dried in 300 h with satisfactory quality [32]. Chen and Lamb [33–35] 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 size of the specimen.

The conductive process has been modeled several different ways. Fohr et al. [31] developed a diffusive model based on general conservation equations, with a boundary equation that states the hygroscopic equilibrium between vapor and wood surface. Defo et al. [36] developed a two-dimensional finite-element model for vacuum-contact drying of wood based on the water potential concept to simulate the moisture content, temperature, and total gas pressure evolution. Differences between experimental and calculated data existed and were attributed to the boundary conditions used and the lack of considering heat transfer by convection [36].

Cyclic Vacuum Drying

In cyclic vacuum drying, also known as discontinuous vacuum drying, lumber is heated using conventional methods (i.e., by convection, forcing hot air through the empty spaces between layers of lumber, separated by “stickers”). After a heating phase, a vacuum is drawn. Drying occurs during the vacuum periods, while there are enough temperature and pressure differences between ambient conditions and in the wood. When the wood temperature drops, the heating cycle is repeated. There are two distinct phases in cyclic vacuum drying: an initial rapid drying and then a slowing down of drying as the pressure inside the material approaches the ambient pressure [37]. Jomaa and Baixeras [38] have shown that cyclic vacuum drying can dry 27-mm-thick oak in 10 days, compared to 30 days with conventional drying. The authors also modeled the process at the scale of the material and the kiln, with satisfactory results [38].

Superheated Steam Vacuum Drying

Both heating by conduction and cyclic drying have drawbacks. For example, in conductive heating, manual stacking of lumber can take a considerable amount of time and, in cyclic vacuum drying, drying does not occur during the heating periods. If superheated steam (water vapor at temperature higher than the boiling point) is used under low-pressure conditions and forced through layers of lumber, heating by convection and a continuous vacuum-drying process can be achieved. This process is known as superheated steam vacuum drying (SSV) or convective vacuum. Superheated steam has better heat transfer properties than hot air at the same temperature [39]; however, steam under vacuum has lower heat capacity (due to lower density) and drying rates are lower than with hot moist 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 [40]. The existence of an “inversion temperature” of the superheated vapor (when steam temperature exceeds the inversion point, speed of

SSV drying exceeds speed of air drying) was noted when drying 100 × 100 × 40-mm Masson pine with initial moisture contents from 140 to 147 %. Some advantages of SSV claimed in the literature include energy savings due to the possibility of recycling the latent heat of steam by condensation and better drying quality, through reduced case hardening, warp, and splits [41]. One disadvantage of SSV drying is that, similarly to conventional drying, high values of final MC in the kiln coincide with regions of relatively low air velocity [42].

A number of studies have explored using SSV drying for specific species, sizes, and products. The remainder of this section is dedicated to those applications. Neumann et al. [43] found that beech, spruce, and Scots pine dried approximately three times faster in SSV than at atmospheric pressure and that drying times for oak were no different than for conventional drying. However, above 45 % of MC beech and oak dried similarly, leading authors to suggest that vacuum only accelerated hygroscopic drying. The authors suggested that during SSV drying, air contained in the lumen keeps the pressure up, thus preventing water from boiling. Thick stock (100 × 100 × 40 mm) Masson pine was dried at an unreported faster rate than conventional drying [41]. Rubberwood has been found to dry 8.4 times faster using the SSV than using conventional methods [44]. While faster drying rates for SSV than conventional drying have been achieved for both radiata pine sapwood [45] and birch lumber (30 to 40 % higher) [19], a higher variability in final MC was observed for SSV-dried lumber. The higher MC variability has been suggested to be due to a greater temperature drop across the load, which most likely was due to the lack of fan reversal [45]. In the same experiment, shrinkage was measured, and values were smaller for vacuum drying, with volumetric shrinkage from green to 5 % MC of 12 and 13 % for vacuum and conventional drying of plantation-grown birch, respectively, and 12.8 and 13.4 % for lumber from natural forests [46]. Plantation eucalyptus in Australia [47] has been dried 60 % faster than conventional drying; however, lumber quality needed improvement, which the authors suggested could be achieved through the manipulation of drying conditions.

Mathematical models of SSV drying have been developed as a method to better understand and improve the process. Models that matched experimental data were developed by Defo et al. [48] who developed a model based on water potential (for moisture and heat) and unsteady-state mass conservation of air (for pressure) and Ananias et al. [49], who modeled SSV drying of radiata pine and validated the model with an experimental run at 0.2 bar (20 kPa) and 70 °C. Elustondo et al. [50] evaluated three models for SSV drying and found that the most accurate model was based on heat transfer and moisture migration, in which the drying rate is proportional to wet bulb depression and the difference between actual MC and EMC [50].

Radio Frequency and Microwave Vacuum Drying

Conductive heating in vacuum drying needs heating platens, and cyclic vacuum drying and SSV drying require the use of stickers between layers of lumber, whereas dielectric heating eliminates the need for stickers or platens, since heating with electromagnetic waves does not depend on the thickness of the lumber but rather on its dielectric properties [17]. Frequencies are categorized in two groups, radio frequencies, at below 100 MHz, and microwaves, at frequencies above 300 MHz [51, 52]. Application of radio frequency and microwave to vacuum drying has been studied extensively, and such efforts are described in this section.

Radio-Frequency Vacuum Drying

Most commercial applications of dielectric heating for lumber drying use radio frequency, in a technology known as radio-frequency vacuum (RFV) drying. During RFV drying, wood is subjected to an alternating electromagnetic field, which causes the polar water molecules in the wood to shift, following the changing field direction. These displacements cause energy absorption, which is dissipated as heat [53]. This phenomenon raises wood temperature enough to start the driving forces for moisture migration. The intensity of heating depends on the MC of wood and the electric field, and the moisture movement depends on the permeability and the internal pressure gradient [51]. Unlike conventional drying, in RFV drying, energy transfer as a major resistance above the fiber saturation point becomes unimportant because of the "volumetric heating," and vacuum enhances internal mass transfer due to the pressure differences. Therefore, the controlling resistance becomes the internal mass transfer [7], and the mechanisms for mass transfer are capillary and bulk flow (above FSP) and bound water diffusion (below FSP).

Heat transfer is very efficient in RFV drying; in fact, internal pressure may develop so fast that it exceeds the mechanical strength of wood fiber, potentially causing failure and in turn honeycomb. This is aggravated by the fact that, typically, in vacuum drying, there is little or no visual control of the material being dried [17]. Therefore, drying schedules for RFV drying depend largely on the threshold power density (energy per unit volume of lumber, normally expressed as kWh/m^3) below which no honeycomb occurs. This is because the rate of energy absorption is proportional to the electrodes' voltages. Power density is species-dependent (permeability) and is also affected by the cross-sectional area of the material being dried. As wood dries, its power loss (a measure of the heat-absorbing capacity of the material under an electromagnetic field) decreases, slowing down the process [54]. Thus, two options exist to control the drying rate: using constant or variable voltage. The latter can be carried out gradually or in steps. Liu et al. [54] tested both strategies and their effect on the drying rate and drying quality of 3.5 × 3.5 in. (89 × 89 mm) hemlock squares. When voltage was kept constant, the loss factor of wood decreased as MC decreased, thus slowing down the drying rate; this can be countered by raising the voltage, thus keeping the power densities per unit volume of lumber constant. Drying times were 73 to 87 % shorter than those of conventional drying, and the final MC along the length of the specimens ranged from 12 to 16 %. There were no internal, end, or surface checks, no collapse, and no internal stresses when power densities were below 10 kW/m^3 [54].

Several methods have been proposed for monitoring the drying conditions during RFV drying. Hui and Ying-chun [55] stated that RH was influenced by dry and wet bulb temperatures and the difference between the air temperature and the temperature of the water in the condenser, and RH was only slightly influenced by pressure [55]. Cai and Hayashi [56] used temperature and pressure measurements in wood as a method for monitoring MC during RFV drying. Their measurements were very close to those determined by the oven-dry method, with absolute errors between 0.8 and 1.8 %, depending on the location in the cross section [56]. A similar study used the relationship between temperature, pressure, and EMC for real-time MC measurement under RFV drying, [57], where the authors concluded that their method could be used at MCs below FSP and that the measurement accuracy was not affected by the drying schedule (two were tested) or measurement location [57].

Several modeling efforts of RFV drying have been conducted. In a three-part report, Koumoutsakos et al. [7, 12, 58, 59] described the development and experimental validation of a one-dimensional mathematical model to simulate transport phenomena for RFV drying. Their model derived and solved the primary heat and mass transfer equations, and incorporated internal heat generation and the effect of gas phase pressure gradients [7]; the one-dimensional model was shown to be able to predict the average MC and drying time satisfactorily [12]. RFV drying of square-edged timber was then modeled based on mass and heat transfer theory and conservation equations. The model calculated each independent variable independently, and curves are computed for different parts of the wood specimen. Simulated data for MC and temperature was compared to experimental results with Sugi wood, and the authors concluded that drying behavior was adequately described by their model [60•]. In another effort, the transformation of dielectric energy into evaporated water was modeled using well-known heat and mass transfer equations, with the objective of predicting the thermal efficiency. The model was able to elucidate the "drying from the inside" idea and the increase in drying rate with increasing wood gas permeability. Lastly, the model provided a basis to classify species' difficulty to dry with RFV [61].

RFV drying has been proposed for several unique applications including redrying "wets" in certain west coast softwood species, upholstered furniture parts, logs, utility poles, and difficult-to-dry species. The use of RFV for re-drying wets consists of selecting boards, dried in a convention kiln, with a higher than the maximum MC allowed by the standard, and re-drying them in a RFV chamber. Industrial-scale tests and stochastic modeling showed that this strategy improves drying time and quality and economical feasibility if the RFV chamber closely matched the volume of wets generated [62, 63]. Presorting in combination with RFV was also claimed to further reduce drying time and MC variability, ultimately leading to higher economic returns [64]. When RFV was compared to conventional drying for both lumber and parts for upholstered frames, and cutting parts before and after drying with both methods, the highest yields were obtained when green lumber was RFV-dried and then cut into parts. RFV produced less warp than conventional drying, which the authors attributed to the reduced shrinkage of material dried with RFV [65]. RFV drying was also proposed to dry log cross sections of Japanese larch and locust [66–68]. An even distribution of moisture throughout the drying process was obtained for larch but less so for locust, and checks and V-shaped splits occurred in 27 % of the samples. RFV has been used to dry utility poles from 80 % MC to less than 25 % in less than 16 h with a uniform final MC and satisfactory quality [69]. *Eucalyptus globulus* has been dried from green (58 to 86 % MC) to 10 % MC in 5 to 13 days (longer for high initial MCs), with adequate drying quality [70].

Literature suggests that the main advantage of RFV drying over other drying methods is volumetric heating, which leads to a more uniform MC distribution across the lumber cross section [51]. This is one reason why RFV is used in certain applications. For example, when drying Chinese ash for baseball bats, it was determined that the drying time with RFV was about 30 % of that obtained with conventional drying, tangential and radial shrinkage with RFV was 40 and 25 % less, and end and internal checks were minimal. Samples were tested for impact bending, an important quality in bats, and RFV-dried pieces showed better performance than kiln-dried ones (14 % higher) [71].

As stated elsewhere in this paper, red oak is one of the most difficult to dry species [72]; therefore, it is a good species to evaluate the drying performance of alternative methods compared to conventional drying. RFV drying has been shown to dry 7 ft (2.13 m) long red oak lumber 1 in. thick (25.4 mm) from green to 8 % MC 14 times faster than dehumidification drying [23], and the ratio between drying time with RFV and conventional drying was 1:17 for 2-in.-thick (50.8 mm) lumber [73]. Surface-core moisture gradients were similar for both cases, low in the surface and high at the center, although there was a higher gradient between the outer layer and the layer immediately below for RFV drying. Radial and tangential shrinkage were lower for RFV (5.6 and 10.3 %, respectively) compared to those for conventional drying (6.4 and 11.6 %).

Other research has reported, however, that MC variation among red oak boards is high, wet pockets are relatively common, and a significant part of the boards were case hardened, possibly because the RFV system used did not provide for a way to equalize or condition lumber [74].

Microwave Vacuum Drying

Microwaves are another form of dielectric heating and can be used in combination with vacuum to dry wood. As opposed to conventional drying, in microwave vacuum drying, almost all of the drying process is governed by a constant drying rate period, which seemed to go below an average MC below the FSP. Microwaves have shorter wavelength and are more uniform compared with radio frequency, leading to potentially faster drying [75], mainly because there is a higher energy intensity [52].

Microwave vacuum drying has been successfully applied to beech [47, 76, 77], oak [76], and Masson pine [77]. One limitation of using standard microwaves for heating is the low penetration, especially in materials with a low loss factor. To overcome this, researchers have suggested using a continuous process [76]. A continuous process using a conveyor belt moving through the chamber at a speed of 20 m/h was successfully used to dry beech and oak in 2 to 6 min from 32 to 79 % MC to 8–12 % final MC [76].

Special Methods

A number of research projects have explored combining vacuum drying with other heating methods or pretreatments, with the purpose of improving time, quality, and energy usage. A summary of those methods follows.

Vacuum-Press Drying

A combination of mechanical compression and vacuum drying has been suggested as a way to increase heat transfer during drying. Jung et al. [78] used the technology to dry wood from green to 15 % in 4 days for white pine, 5 days for red pine and Western hemlock, and 6 days for larch [78]. Li and Lee [79, 80] found that a compressive load of 0.092 MPa resulted in increased dimensional changes in the direction of loading while those perpendicular to the loading were decreased. Tangential and radial shrinkage of loaded specimens were 1.5 times those of unloaded samples [79, 80]. The same authors conducted a similar experiment with oak blocks and noted that differences of up to 14 % existed between loaded and unloaded specimens. It was suggested that when using compressive loading, wood should be sorted based on grain direction [81].

Freeze Vacuum Drying

The idea behind freeze-drying is to remove water in frozen state under vacuum by sublimation (avoiding the liquid state). This method is common in the food industry; however, when used with wood, it can cause cell damage, even leading to collapse [82]. Yang et al. [83] determined that freeze-drying in combination with vacuum, or freeze vacuum drying (FVD), allows the preservation of desirable organic compounds in *Dalbergia bariensis* wood, as compared with conventional drying. FVD was also compared with high- and low-temperature drying for Chinese fir [82]. Results indicated that the relative storage modulus and the relative loss modulus were lowest for the FVD method, meaning reduced mechanical properties, which the authors suggest may be caused by damage to the cell wall drying freeze vacuum drying.

Combined Radiation and Contact Heating

Some authors have suggested combining radiative and conductive heating under vacuum to improve drying performance. Jung et al. [10] compared different heating methods in an experiment, namely conduction, radio frequency, and hybrid heating (combination of radio frequency and conduction). The hybrid method provided the highest moisture removal rate and the lowest moisture gradient (cross sectional and longitudinal). The use of infrared (IR) radiation, at temperatures close to 600 K (327 °C), has been proposed as a heating method to overcome limitations of conductive heating vacuum methods [84, 85]. Radiative "heating devices," commonly used in the paper industry, are placed between layers of lumber instead of heating blankets. The heating devices can be designed in a way that provides a free path for moisture to leave the wood surface. The two models captured most of the observed trends, with differences in the computational speed [84, 85]. Lopatin et al. [86] determined that the application of LRF heating along with contact drying enhances moisture transport significantly and reduces the drying time of wood over 25–30 % MC. The authors suggested that the application of the LRF and contact vacuum drying should decrease the risk of bending and cracking due to equalizing the non-uniformity of moisture distribution [86].

Pretreatments

Pretreatments, such as ultrasound, end coating, steam explosion, and kerfing, have been suggested as methods to improve performance of certain vacuum-drying systems. For example, the application of ultrasonic energy as pretreatment or during vacuum drying [87–89] [90] is believed to improve mass transfer due to several phenomena, such as causing pressure variation at solid-fluid interfaces, the creation of microscopic channels, and cavitation, which decreases the thickness of the boundary layer. Experiments have shown significant increases in water migration rates, with increasing drying rates at higher wave frequency and treatment time. RFV in combination with end coating and low-pressure steam explosion resulted in shorter drying times and lower shrinkage for 3-in.-thick (76 mm) Japanese cedar that was pre-treated with steam explosion compared with conventional methods; however, most samples exhibited heart checks [91]. When comparing steam explosion and longitudinal kerfing on drying properties, Lee and Luo [92] found that steam explosion pre-treatments sharply accelerated the drying rate in samples with high initial MC and in the early stages of drying. The final moisture gradient along the transverse direction was lower for the steam-exploded samples than those with longitudinal kerf. Samples with longitudinal kerf had smaller moisture gradients along the longitudinal direction. [92]. Lee et al. [93] tested a high-temperature-low-humidity (HT-LH) pretreatment (120 °C and 3.3 % EMC for 64 h, preceded by steaming at 95 °C for 12 h) and kerfing (longitudinal cuts 3 mm wide and 50 mm deep) on the final quality of drying. Drying times ranged from 150 to 190 h [93].

Vacuum Drying and Wood Property Changes

Any wood-drying technology should be evaluated, among other factors, based on how well it maintains or enhances the wood's properties. In this section, we include the findings from research literature regarding the effects of vacuum drying on some wood properties, namely color, checking, and mechanical properties.

Vacuum Drying and Color

Color change during drying is a problem for some high-value species and uses, and different methods have been tried over the years to preserve or enhance color. Research has shown that high temperatures, particularly when used above the fiber saturation point, are associated with greater color change; thus, drying under vacuum with lower temperatures has been suggested as a solution. The lower temperatures and possibly the low-oxygen atmosphere of vacuum drying may contribute to less discoloration. For example, the microwave drying of beech, spruce, and maple has been shown to result in no color changes, attributed to the short drying time and absence of oxygen [52, 77]. The lumber of vacuum-dried softwoods, Pacific Coast hemlock, Douglas fir, and Western red cedar, has been shown to be the same color as undried material [16, 94]. Somewhat contradictory, Kang [95] reported that the total color difference (ΔE^*) of microwave vacuum-dried Japanese pine, Korean pine, and larch yielded values lower than high-temperature drying but higher than conventional drying; for "lightness" (L^*), it was lower than that of conventional drying and higher than that of high-temperature drying.

The lighter color of wood that has been vacuum dried has also been demonstrated for red oak. Chen and Lamb [35] reported no color change in green and vacuum-dried red oak parts [35]. In RFV drying of oak lumber and cuttings for upholstered furniture, researchers indicated that for both lumber and cuttings, the RFV-dried material showed a much brighter color than the conventionally dried wood, although this was only superficial and the differences disappeared after planing [65]. Sandoval and Jomaa [96] found that lightness in red oak increased as temperature increased, which the authors attributed to the thermal degradation of extractives, in turn allowing a yellow tone and clarifying the surface.

To understand how microscopic features correlate with the darkening process of silver birch [97], vacuum and conventional drying were compared. Darkening of this species in conventional drying was associated mainly with wide latewood, while for vacuum drying, the factors identified were thickness of the vessel cell wall, broad rays, and large amount of axial parenchyma. [97]. Hiltunen et al. [98] investigated the influence of Brauns' lignin on the color change of birch that takes place during vacuum drying and determined that Brauns' lignin underwent a chemical change during vacuum drying of the wood and that this change may have affected the color of the wood [95]. Möttönen and Luostarinen determined that the plantation *Betula pendula* color was consistently darker for vacuum-dried lumber than conventionally dried lumber, which was partly explained by the relatively high initial temperatures used in vacuum drying. Felling season and storage had an effect on discoloration. The authors noted that schedules used were intended to form some discoloration [19, 99]. Hermawan et al. [100] determined that no differences existed in color change for both sapwood and heartwood between the atmospheric and vacuum pressure drying [100] for Sugi wood.

In general, research seems to support the assertion that vacuum helps in the preservation of color in wood drying. However, most of the authors reporting no color changes seemed to base their assessment on simple visual inspection and not a systematic measurement (such as sensorial analysis of CIELab parameters) and comparison with conventional methods.

Vacuum Drying and Checking

Surface and internal checking occur in wood drying when the stresses that develop as the material dries exceed its strength [5]. Checking was used for the assessment of drying quality in several studies. In three experiments carried out with red oak, a check-prone species, and conductive vacuum drying, authors found that it was possible to vacuum dry wood with no or very little occurrence of surface and internal checking [32, 33, 35]. One article reported on the drying quality of plantation eucalyptus dried with conventional methods and superheated steam and vacuum (SSV). No internal checking was noted for the two methods; however, the percent of boards free of surface checks was between 43 and 93 % for the conventional methods and 64 and 89 % for SSV [47].

Some authors have stated that RFV drying is associated with a lower occurrence of checking, with some suggesting that this is because dielectric heating produces rapid increases in internal pressures and vapor pressure [54] that are higher than in the outer layers. A study using RFV to dry green *E. globulus* (86 % MC), a species with tendency to checking and collapse, reported that the least amount of cell collapse or checking was achieved when the ratio between the wood temperature and the boiling point of water was 1.2 [70]. Successful drying without checks has been demonstrated for RFV for hemlock (91 × 91 mm) [54]; 30-mm-thick log cross sections (discs) of larch, locust, and Chinese mahogany [66–68]; and Korean ash (1000 × 66 × 66 mm) [71]. Little to no occurrence of checking has also been reported for using microwave vacuum drying of beech, maple, and spruce of different thicknesses [52, 77].

RFV press drying resulted in only fine end checking, slight surface checking (mostly for larch), and no internal checking for hemlock, red pine, larch, and white pine. When using steam explosion and kerfing pre-treatments in combination with RFV to dry Korean larch pillars (100 × 100 mm), longitudinal kerfing resulted in the reduced severity of checks compared to wood treated with steam explosion [92]. When Japanese cedar of 150 × 150 mm cross section was pretreated with high temperature and kerfing, the authors reported no observed surface checking in kerfed samples but some internal checks [93]. Jung et al. [10] investigated vacuum drying of radiata pine timbers of 140 × 140 mm in cross section with different heating methods, namely conduction, RFV, and a “hybrid” method that combined the first two. No end or internal checks were noted for the three methods, and no surface checks for the hybrid method [10].

In general, studies that reported surface or internal checking among their results agree that it is possible to vacuum dry wood with minimal surface and internal checking. Experiments involving large cross sections, which are very difficult and time-consuming to dry by conventional methods, seem to show that vacuum drying is particularly suited for such materials.

Vacuum Drying and Mechanical Properties

For some applications, the preservation or enhancement of mechanical properties of wood is critical. Drying can affect mechanical properties of wood through internal stresses, the direct effect of temperature on the material, and the effect of moisture loss [101].

In a recently reported study, experiments on vacuum-dried and conventionally dried yellow birch determined that vacuum-dried wood performed better in the modulus of elasticity and modulus of rupture; dynamic mechanical analysis (DMA) showed that conventional drying yielded more changes to the chemical structure than vacuum drying [102]. A similar study used DMA to understand the dynamic mechanical properties of plantation Chinese fir under three drying methods, namely high- and low-temperature drying and freeze vacuum drying (FVD). The authors concluded that the storage modulus and loss modulus were the lowest for FVD, which they suggested was due to damage to cell walls during the freezing process [82]. Ouertani et al. [103], in research involving jack pine lumber and vacuum drying with conductive heating, determined that drying temperature, vacuum pressure, and lumber grade all affected the mechanical properties of the resulting material. The mechanical properties of vacuum-dried wood (namely modulus of elastic, maximal strength, and modulus of rupture) were also compared with those of conventionally dried material, and no statistical differences were found [103]. In another study, the effect of SSV drying on the mechanical properties of rubberwood was investigated and compared with that of conventionally dried wood. The authors noted significant improvements relative to conventional drying, specifically in hardness (32 %), compression parallel to the grain (12 %), and shear parallel to the grain (88 %), and attributed these differences to the less severe temperatures and shorter exposure under SSV [44]. In a comparison of mechanical properties of red oak lumber dried using RFV and dehumidification (DH) technologies, specific gravity and EMC of DH-dried lumber were found to be slightly but significantly higher than those of lumber dried with RFV. No statistical differences were noted for bending stiffness and strength, shear strength, and hardness, with the exception of compressive strength, where DH yielded lumber with slightly higher numbers [23]. Similar research compared properties of white pine lumber dried with RFV and conventional methods, with results showing a lower compressive strength existed for RFV-dried lumber, while no differences were found for static bending, shear, hardness, or specific gravity [104].

Very few refereed papers on vacuum drying reported the effect of this technology on the mechanical properties of wood. While these reports do not provide enough evidence to conclude that vacuum drying produces wood with superior mechanical properties than other methods, authors seem to agree that vacuum methods in general do not have a negative impact on those properties.

Environmental Issues

Environmental impacts from lumber drying originate chiefly from two factors: energy consumption and volatile organic compound (VOC) emissions. Lumber drying is the most energy-consuming process in the manufacturing of many wood products; for example, drying represents more than 80 % of the total energy inputs in lumber production [105]. From the environmental and health perspectives, VOCs are carbon-based compounds that occur naturally in wood and are released during drying. These compounds can be harmful to the environment and health, and their release is regulated [105, 106].

Energy Use

Lumber drying requires energy to (1) initiate driving forces, (2) evaporate water, and (3) remove water from the lumber surface [28]. Additionally, energy is needed to heat up the material, cover energy losses, and move the air. Vacuum drying has been considered more energy efficient than conventional methods since it is a closed system (not requiring venting) and requires lower temperatures for drying and transmission losses [107].

Elustondo et al. [61] developed a mathematical model to predict energy efficiency in RFV drying (percent of the electromagnetic energy that is actually used to generate water vapor). The energy used for evaporation of water divided by the total energy transferred to wood ranged from 36 to 81 %, for timbers of sections from 105 × 230 to 310 × 310 mm [61]. Energy efficiency of microwave vacuum drying of beech, spruce, and maple was estimated by Laiker and Adamska [52] and ranged from 70 to 80 % during most of the drying process. Factors for energy efficiency were species (lower for spruce and highest for beech), initial MC (highest for high initial MC), and initial power applied (higher for higher initial power) [52]. Seyfarth et al. [76] experimented with a continuous microwave vacuum-drying process and found that the electric energy consumption was similar to that of conventional drying. One particular drying process, known as the “Moldrup process,” which uses superheated steam and vacuum, demonstrated that this process used 55 % less electricity to dry pine or spruce from 80 to 8 % MC, and 72 % less for 50 mm pine [108]. For commercial-scale RFV drying, energy needs were calculated according to the energy required to remove a certain amount of water (kWh/kg of water). It was determined that vacuum drying 101-mm-thick lumber consumed 83 % less energy than conventional kiln drying 50-mm-thick lumber, and 20 % more to 60 % less for dehumidification drying (also drying 50 mm lumber) [109]. Avramidis and Zwick [110] showed that energy costs grew exponentially with decreasing efficiency and linearly with initial MC, and decreased slowly with increasing absorbed energy density (kW/m^3), but below 2.5 kWh/m^3, energy costs increase rapidly [110].

Research papers on energy efficiency of vacuum drying are scarce but seem to support some advantages of this technology over conventional drying. Little transmission losses (closed system), lower thermal energy needs to heat drying medium, and lower process temperatures are some of the reasons suggested.

VOC Emissions

The amount of VOCs released during conventional lumber drying varies widely with species; for example, red oak drying releases about 13.74 lb per thousand board feet (lb/MBF, or 2642 g/m^3), while that figure is 0.71 lb/MBF (137 g/m^3) for yellow poplar [111] and 1.42 lb/MBF (273 g/m^3) for southern pine [112]. The amount of VOCs released is also positively correlated with drying temperatures. Milota and Mosher [112] found that emissions of VOCs are significantly higher for high-temperature drying; for example, ponderosa pine emits 1.59 lb/MBF (306 g/m^3) of VOCs at 170 °F (77 °C) and 3.00 lb/MBF (577 g/m^3) at 235 °F (113 °C).

Most vacuum-drying units are closed systems; thus, very little or no VOC emissions exist. However, the condensate from the process contains these compounds in quantities that may require treatment before discharge to the environment; for example, a study drying Douglas fir, Western hemlock, and Western red cedar using RFV technology concluded that the condensate required treatment before discharge, as it contained high levels of toxic compounds [113]. When SSV drying radiata pine, McDonald et al. [114] found similar conclusions, mainly due to the presence of monoterpenes, acetic acid, formaldehyde, and methanol totaling 17.6 g/m^3 or 0.09 lb/MBF [114]. The central characteristic of vacuum drying, fast drying at relatively low temperatures, may translate into smaller amounts of VOCs, reducing the environmental impact of drying. However, this has not been conclusively confirmed in the literature.

Economics of Vacuum Drying

The economics of drying lumber with vacuum technologies, as with other drying technologies, should be assessed in terms of operating costs and costs associated with drying degrade. Few studies have been carried out about the economics of vacuum drying, and most are reported in trade journals rather than peer-reviewed journals. In this section, a few reports with cost information are presented. Monetary figures were adjusted for inflation to 2016 and using the US Bureau of Labor Statistics conversion tool (http://data.bls.gov/cgi-bin/cpicalc.pl).

In a decades-old report, an equipment manufacturer reported successful operations drying a thick stock of hardwoods [115]. Costs ranged from $175 ($437 in 2016 dollars) per thousand board feet (MBF, or \$74/m^3) for 1.5-in. (38 mm) red oak to \$300/MBF (\$749/MBF in 2016 dollars) (or \$127/m^3) for very thick stock (3 or 4 in., 76 or 102 mm). In a commercial-scale experiment with RFV drying, softwood species from the US West Coast were dried. Drying costs were \$187.4/MBF (\$281/MBF in 2016 dollars) (\$79.4/m^3) for 101 × 101 mm Western red cedar in a 55-m^3 RFV kiln, compared to \$218.3/MBF (\$328/MBF in 2016 dollars) (\$92.6/m^3) in a conventional kiln [109]. Zwick and Avramidis [17] reported drying costs for RFV drying very thick softwood timbers (4 in. thick, 102 mm, or thicker) in a 50-m^3 chamber. Costs per cubic meter ranged from \$13.6 (12-in., 305-mm, spruce timbers, drying from 35 to 17 % MC) to \$31.7 (12-in. fir timbers, from 45 to 17 % MC) (\$19 to \$44 in 2016 dollars) [17]. Innes and Redman carried out an economic evaluation for drying *Eucalyptus pilularis* and *Corymbia maculata*, two Australian hardwoods, with different drying methods and fuels [116]. They found that vacuum dryers provide significant savings compared to most other drying technologies due to the more efficient use of energy, because they operate at low temperatures for relatively short times. Capital requirements, however, were much higher for vacuum drying than for any other method (on a per-unit-volume basis) [116].

Comparing lumber drying costs of different drying technologies is a difficult task, as it changes with numerous factors, such as kiln capacities, species (softwood vs. hardwoods), initial and final moisture content, fuel used, and prevailing external temperatures, just to name a few. Moreover, in vacuum drying, a fair comparison must consider the potential savings in inventory-carrying costs from shorter drying times compared to conventional drying (especially for some species and dimensions) [2•]. Literature is very scarce about economic performance of vacuum drying and it is a topic in need of attention.

Summary and Conclusions

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. In this paper, 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 vapor bulk flow, and there is greater water migration in the longitudinal direction. Major advantages of vacuum drying wood reported in the literature are the ability to dry at lower temperatures than conventional drying (which in turn may lead to less drying defects), greatly reduced drying times (especially for hardwoods and very large sections), improved color preservation, higher energy efficiency (because of the dramatically reduced heat losses), better control of volatile organic compound emissions, and the ability to dry very large cross sections. While past research has focused on increasing the understanding of the fundamental mechanisms for vacuum drying and applications to specific industries and species, more recent efforts have concentrated on improving existing methods, for example by improving moisture control and the use of pretreatments to improve drying quality.

Very little research has been found that addresses the economics and energy efficiency of vacuum drying, two very important dimensions that greatly affect any drying technology’s attractiveness for the industry. Also scarce is the research that investigates how vacuum fits in an industrial system including supply chain implications.

Although vacuum drying has been around for a long time, it has not yet become a mainstream wood-drying method. Its application is still limited to high-value species, large cross sections, and specialty applications. We believe that as the pressure to streamline supply chains and deliver more customized products to the market grows, companies will be compelled to give vacuum drying serious consideration. Therefore, further research on specific industrial applications and species/dimensions will be needed.

Compliance with Ethical Standards

Conflict of Interest Drs Espinoza and Bond have no conflicts of interests to declare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

References

Papers of particular interest, published recently, have been highlighted as:

- of Importance

1. Gray, A., Process of drying timber. U.S.P. Office, Editor. United States; 1904 p. 3.
2.• Brenes-Angulo OM et al. The impact of vacuum-drying on efficiency of hardwood products manufacturing. Bioresources. 2015;10(3):4588–98. **The majority of vacuum drying research has been focused on modifying a technique that has been available and used for many decades. This work introduces a new**

research direction regarding the adoption of vacuum drying for what would typically be considered a prime use of conventional dry kiln technology.

3. Langrish T, Walker JCF. Drying of timber. In: Walker JCF, editor. Primary wood processing. Dordrecht: Springer Netherlands; 2006. p. 251–95.
4. Hildebrand, R., Kiln drying of sawn timber, ed. R. Hildebrand. 7446 Oberboihingen/Wuertt., 744 Nuertingen: Robert Hildebrand Maschinenbau GmbH.; 1970 199 pp.
5. Simpson, W.T., Dry kiln operator's manual, ed. W.T. Simpson. Madison, Wis: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory; 1991.
6. Chen Z. Primary driving force in wood vacuum drying, in wood science and forest products. Blacksburg, VA: University Libraries, Virginia Polytechnic Institute and State University; 1998. p. 185.
7. Koumoutsakos A, Avramidis S, Hatzikiriakos SG. Radio frequency vacuum drying of wood. I Mathematical model Drying Technology. 2001;19(1):65–84.
8. Rosen HN. Recent advances in the drying of solid wood. In: Mujumdar AS, editor. Advances in drying. Washington: Hemisphere Pub. Corp; 1980.
9. Gerhards CC. High-temperature drying of southern pine 2 by 4's: effects on strength and load duration in bending. Wood Sci Technol. 1986;20(4):349–60.
10. Jung HS, Eom CD, So BJ. Comparison of vacuum drying characteristics of radiata pine timber using different heating methods. Dry Technol. 2004;22(5):1005–22.
11. Denig J, Wengert EM, Simpson WT. Drying hardwood lumber. Vol. gen. Tech. Rep. FPL–GTR–118. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 2000. p. 138.
12. Koumoutsakos A, Avramidis S, Hatzikiriakos SG. Radio frequency vacuum drying of wood. II. Experimental model evaluation. Dry Technol. 2001;19(1):85–98.
13. Moyne C, Martin M. Etude experimentale du transfert simultane de chaleur et de masse au cours du sechage par contact sous vide d'un bois resineux. Int J Heat Mass Transf. 1982;25(12):1839–48.
14. • Waananen KM, Litchfield JB, Okos MR. Classification of drying models for porous solids. Dry Technol. 1993;11(Compendex):1–40. **This paper describes the different drying models for porous solids, including their assumptions, coefficient determination methods, and model solution and validation approaches. It also provides a comprehensive list of papers on the topic. The paper ends with a list of elements that any effort to develop a fundamental drying model should accomplish**.
15. Siau JF. Transport processes in wood. Berlin; New York: Springer-Verlag; 1984. p. 245.
16. Avramidis S, Zwick RL. Exploratory radio-frequency/vacuum drying of three B.C. coastal softwoods. For Prod J. 1992;42(7/8):17–24.
17. Zwick RL, Avramidis S. Commercial RFV kiln drying: recent successes. In 51st Western Dry Kiln Association Meeting. Reno, NV: Western Dry Kiln Association; 2000.
18. Neumann R, Mielke A, Bohner G. Comparison of conventional and convective vacuum drying of beech. In: Vanek M, editor. 3rd IUFRO International Conference on Wood Drying. Vienna, Austria: International Union of Forestry Research Organizations - IUFRO; 1992. p. 222–6.
19. Mottonen V. Variation in drying behavior and final moisture content of wood during conventional low temperature drying and vacuum drying of *Betula pendula* timber. Dry Technol. 2006;24(11):1405–13.
20. Chen Z, Lamb FM. Investigation of boiling front during vacuum drying of wood. Wood Fiber Sci. 2001;33(4):639–47.
21. • Defo M, Cloutier A, Fortin Y. Modeling vacuum-contact drying of wood: the water potential approach. Dry Technol. 2000;18(8):1737–78. **This paper provides an excellent review of the different vacuum-drying modeling efforts, and then clearly presents the authors' own modeling work, based on the water potential concept and with parameters obtained experimentally**.
22. Audebert P et al. Vacuum drying of oakwood: moisture, strains and drying process. Dry Technol. 1997;15(9):2281–302.
23. Lee AWC, Harris RA. Properties of red oak lumber dried by radio-frequency/vacuum process and dehumidification process. For Prod J. 1984;34(5):56–8.
24. Yi S-L et al. Experimental equilibrium moisture content of wood under vacuum. Wood Fiber Sci. 2008;40(3):321–4.
25. Chen Z, Lamb FM. Theoretical equilibrium moisture content of wood under vacuum. Wood Fiber Sci. 2002;34(4):553–9.
26. Liu H et al. Effect of EMC and air in wood on the new in-process moisture content monitoring concept under radiofrequency/vacuum (RF/V) drying. J Wood Sci. 2010;56(2):95–9.
27. Liu H et al. Equilibrium moisture content under vacuum conditions. Wood Fiber Sci. 2015;47(4):345–54.
28. Ressel JB. New developments in vacuum drying and press drying of timber, in International Conference of COST Action E15 Wood Drying. Santiago de Compostela, España. Santiago de Compostela, España: European Co-operation in the Field of Scientific and Technical Research; 2002. p. 26.
29. Wengert EM. Vacuum drying/microwave drying, in the wood doctor's Rx. Blacksburg, VA: Dept. of Forest Products, Virginia Polytechnic Institute and State University; 1988. p. 51–3.
30. Kanagawa Y, Yasujima M. Effect of heat sources on drying time in vacuum drying of wood. Vacuum Drying of Wood. 1993;93:292.
31. Fohr JP et al. Vacuum drying of oak wood. Dry Technol. 1995;13(8–9) 1675-1675.
32. Simpson WT. Vacuum drying northern red oak. For Prod J. 1987;37(1):35–8.
33. Chen Z, Lamb FM. Vacuum drying of small wood components at room temperature. For Prod J. 2001;51(10):55.
34. Chen Z, Lamb FM. Analysis of the vacuum drying rate for red oak in a hot water vacuum drying system. Dry Technol. 2007;25(3):497–500.
35. Chen ZJ, Lamb FM. A vacuum drying system for green hardwood parts. Dry Technol. 2004;22(3):577–95.
36. Defo, M., A. Cloutier, and Y. Fortin. Modeling vacuum-contact drying of wood: the water potential approach. In Drying of wood. Marcel Dekker Inc.; 2000.
37. Chen Z, Lamb FM. Analysis of cyclic vacuum drying curve. Wood Sci Technol. 2003;37(3–4):213–9.
38. Jomaa W, Baixeras O. Discontinuous vacuum drying of oak wood: modelling and experimental investigations. Dry Technol. 1997;15(9):2129–44.
39. Kudra T. Advanced drying technologies, ed. A.S. Mujumdar. Vol. vii. New York: Marcel Dekker; 2002. p. 459.
40. Pang S, Pearson H. Experimental investigation and practical application of superheated steam drying technology for softwood timber. Dry Technol. 2004;22(9):2079–94.
41. Yi S et al. Drying characteristics of wood under vacuum-superheated steam. Forestry Studies in China. 2004;6(2):41–5.
42. Ledig, S.F. and K.E. Militzer. Measured gas velocity and moisture content distribution in a convective vacuum kiln. In Drying of wood. Marcel Dekker Inc.; 2000.
43. Neumann R, Mielke A, Gios P. Moisture transport in wood during convective vacuum drying Zur Feuchtebewegung im Holz wiihrend der konvektiven Vakuumtrocknung. European Journal of Wood and Wood Products. 1993;51(3):156–62.
44. Yamsaengsung R, Sattho T. Superheated steam vacuum drying of rubberwood. Dry Technol. 2008;26(6):798–805.
45. Pang S, Dakin M. Drying rate and temperature profile for superheated steam vacuum drying and moist air drying of softwood lumber. Dry Technol. 1999;17(6):1135–47.

46. Möttönen V, Luostarinen K. Variation in density and shrinkage of birch (*Betula pendula* Roth) timber from plantations and naturally regenerated forests. For Prod J. 2006;56(1):34–9.
47. Redman AL, McGavin RL. Accelerated drying of plantation grown *Eucalyptus cloeziana* and *Eucalyptus pellita* sawn timber. For Prod J. 2010;60(4):339.
48. Defo M, Fortin Y, Cloutier A. Modeling superheated steam vacuum drying of wood. Dry Technol. 2004;22(10):2231–53.
49. Ananias RA, Vallejos S, Salinas C. Estudio de la Cinetica del Secado Convencional y Bajo Vacio del Pino Radiata. Maderas. Ciencia y tecnología. 2005;7:37–47.
50. Elustondo D, Oliveira L, Avramidis S. Evaluation of three semi-empirical models for superheated steam vacuum drying of timbers. Dry Technol. 2003;21(5):875–93.
51. Resch H. High-frequency electric current for drying of wood—historical perspectives. Maderas. Ciencia y tecnología. 2006;8(2): 67–82.
52. Leiker M, Adamska MA. Energy efficiency and drying rates during vacuum microwave drying of wood. European Journal of Wood and Wood Products. 2004;62(3):203–8.
53. Avramidis S, Liu F. Drying characteristics of thick lumber in a laboratory radiofrequency vacuum dryer. Dry Technol. 1994;12(8):1963–81.
54. Liu F, Avramidis S, Zwick RL. Drying thick western hemlock in a laboratory radio-frequency/vacuum dryer with constant and variable electrode voltage. For Prod J. 1994;44(6):71–5.
55. Hui X, Ying-chun C. Factors affecting relative humidity during wood vacuum drying. J For Res. 2009;20(2):165–7.
56. Cai Y, Hayashi K. New monitoring concept of moisture content distribution in wood during RF/vacuum drying. J Wood Sci. 2007;53(1):1–4.
57. Yang L et al. Real-time moisture content measurement of wood under radio-frequency/vacuum (RF/V) drying. Dry Technol. 2014;32(14):1675–82.
58. Koumoutsakos A, Avramidis S, Hatzikiriakos SG. Fundamental phenomena in wood RFV drying with 50-ohm amplifier technology. Maderas. Ciencia y tecnología. 2002;4(1):15–25.
59. Koumoutsakos AD, Avramidis S, Hatzikiriakos SG. Radio frequency vacuum dyring of wood. III. Two-dimensional model, optimization, and validation. Dry Technol. 2003;21(8):1399–410.
60.• Jia X, Zhao J, Cai Y. Radio frequency vacuum drying of timber: mathematical model and numerical analysis. Bioresources. 2015;10(3):5440–59. **This paper explains the development of mathematical modeling of radio-frequency vacuum drying (RFV). The authors use conservation equations and analyze the heat and mass transfer mechanisms of RFV drying, and explain the model development with great detail and clarity**.
61. Elustondo D, Avramidis S, Shida S. Predicting thermal efficiency in timber radio frequency vacuum drying. Dry Technol. 2004;22(4):795–807.
62. Elustondo D, Avramidis S. Simulated comparative analysis of sorting strategies for RFV drying. Wood Fiber Sci. 2003;35(1): 49–55.
63. Elustondo D, Avramidis S, Oliveira L. Industrial evaluation of re-dry strategy for softwood lumber. Maderas. Ciencia y tecnología. 2005;7(2):65–78.
64. Elustondo D, Avramidis S, Zwick R. The demonstration of increased lumber value using optimized lumber sorting and radio frequency vacuum drying. For Prod J. 2005;55(1):76–83.
65. Harris RA, Taras MA, Schroeder JG. Sound quality upholstered frame part yields from lumber and green cuttings dried by a radio-frequency/vacuum system and by conventional kiln-drying. For Prod J. 1984;34(7–8):19–21.
66. Choi J-H, Lee N-H. Effect of end-taping and removal of sapwood on radial distribution of moisture content and tangential strains during radio-frequency/vacuum drying of Cedrela sinsensis log cross sections. J Wood Sci. 2004;50(4):315–20.
67. Lee N-H et al. Comparison of moisture distribution along radial direction in a log cross section of heartwood and mixed sapwood and heartwood during radio-frequency/vacuum drying. J Wood Sci. 2004;50(6):484–9.
68. Kang W, Lee NH, Choi JH. A radial distribution of moistures and tangential strains within a larch log cross section during radio-frequency/vacuum drying. Holz als Roh - und Werkstoff. 2004;62(1):59–63.
69. Fang F, Ruddick JNR, Avramidis S. Application of radio-frequency heating to utility poles. Part 1. Radio-frequency/vacuum drying of roundwood. For Prod J. 2001;51(7/8):56.
70. Hansmann C et al. High-frequency energy-asisted vacuum drying of fresh *Eucalyptus globulus*. Dry Technol. 2008;26(5):611–6.
71. Lee N-H, Jung H-S. Comparison of shrinkage, checking, and absorbed energy in impact bending of Korean ash squares dried by a radio-frequency/vacuum process and a conventional kiln. For Prod J. 2000;50(2):69.
72. Lamb, F.M. and E.M. Wengert. Techniques and procedures for the quality drying of oak lumber. In 41st Meeting Western Dry Kiln Clubs. 1990.
73. Harris RA, Taras MA. Comparison of moisture content distribution, stress distribution, and shrinkage of red oak lumber dried by a radio-frequency vacuum drying process and a conventional kiln. For Prod J. 1984;34(1):44–54.
74. Trofatter G et al. Comparison of moisture content variation in red oak lumber dried by a radiofrequency vacuum process and a conventional kiln. For Prod J. 1986;36(5):25–8.
75. Li X-J, Zhang B-G, Li W-J. Microwave-vacuum drying of wood: model formulation and verification. Dry Technol. 2008;26(11): 1382–7.
76. Seyfarth, R., R. Seyfarth, and N. Mollekopf. Continuous drying of lumber in a microwave vacuum kiln. In 8th IUFRO International Conference on Wood Drying. Brasov, Romania; 2003.
77. Leiker M, Adamska MA, Gütter R, Mollekopf N. Vacuum microwave drying of beech: property profiles and energy efficiency. In: International Conference of COST Action E15 Wood Drying. Athens, Greece. Athens, Greece: European Co-operation in the Field of Scientific and Technical Research; 2004. p. 10.
78. Jung, H.S., J.H. Lee, and N.H. Lee. Vacuum-press drying of thick softwood lumbers. In Drying of wood. Marcel Dekker Inc. 2000.
79. Li C, Lee N-H. Effect of compressive load on the dimensional changes of the Japanese larch dried in a radio-frequency/vacuum drier. J Wood Sci. 2008;54(6):451–5.
80. Li C, Lee N-H. Effect of compressive load on shrinkage of larch blocks during radio-frequency vacuum heating. Wood Fiber Sci. 2004;36(1):9–16.
81. Li C, Lee N. The effect of compressive load on the moisture content of oak blocks during radio-frequency/vacuum drying. For Prod J. 2008;58(4):34.
82. Jiang JL, Lu JX. Dynamic viscoelasticity of wood after various drying processes. Dry Technol. 2008;26(5):537–43.
83. Yang L et al. Effects of different drying treatments on preservation of organic compounds in Dalbergia bariensis wood. Bioresources. 2015;10(4):7092–104.
84. Perre P, Mosnier S, Turner IW. Vacuum drying of wood with radiative heating: I. Experimental Procedure AIChE Journal. 2004;50(1):97–107.
85. Turner IW, Perre P. Vacuum drying of wood with radiative heating: II. Comparison between theory and experiment. AICHE J. 2004;50(1):108–18.
86. Lopatin, V.V., M.A. Goreshnev, and F.G. Sekisov, Moisture transport in birch lumber at low radio-frequency and contact vacuum drying. 2014.

87. He Z et al. Effects of ultrasound on mass transfer within the boundary layer during wood vacuum drying. Bioresources. 2015;10(3):5267–77.
88. He Z et al. Effect of ultrasound pretreatment on wood prior to vacuum drying. Maderas Ciencia y tecnología. 2014;16:395–402.
89. He ZB et al. Ultrasound-assisted vacuum drying of wood: effects on drying time and product quality. Bioresources. 2013;8(1):855–63.
90. He Z et al. Effect of ultrasound pretreatment on vacuum drying of Chinese catalpa wood. Dry Technol. 2012;30(15):1750–5.
91. Lee N-H, Hayashi K. Effect of end-covering and low pressure steam explosion treatment on drying rate and checking during radio-frequency/vacuum drying of Japanese cedar log cross sections. For Prod J. 2000;50(2):73–8.
92. Lee N-H, Luo J-Y. Effect of steam explosion treatments on drying rates and moisture distributions during radio-frequency/vacuum drying of larch pillar combined with a longitudinal kerf. J Wood Sci. 2002;48(4):270–6.
93. Lee N-H et al. Effect of pretreatment with high temperature and low humidity on drying time and prevention of checking during radio-frequency/vacuum drying of Japanese cedar pillar. J Wood Sci. 2010;56(1):19–24.
94. Avramidis S, Liu F, Neilson BJ. Radio-frequency/vacuum drying of softwoods: drying of thick western redcedar with constant electrode voltage. For Prod J. 1994;44(1):41–7.
95. Kang H-y. Effect of drying methods on the discoloration of three major domestic softwood species in Korea. Forestry Studies in China. 2006;8(3):48–50.
96. Sandoval-Torres S et al. Colour changes in oakwood during vacuum drying by contact: studies on antioxydant potency and infrared spectras in surfaces. Wood Research. 2009;54(1):45–58.
97. Luostarinen K. Relationship of selected cell characteristics and colour of silver birch wood after two different drying processes. Wood Material Science & Engineering. 2006;1(1):21–8.
98. Hiltunen E, Alvila L, Pakkanen TT. Characterization of Brauns' lignin from fresh and vacuum-dried birch (*Betula pendula*) wood. Wood Sci Technol. 2006;40(7):575–84.
99. Möttönen V, Luostarinen K. Discolouration of sawn birch (*Betula pendula*) timber from plantation forests during drying: effect of growing site, felling season and storage of logs on discolouration. Balt For. 2004;10(2):31–8.
100. Hermawan A, Fujimoto N, Sakagami H. A study of vacuum-drying characteristics of Sugi boxed-heart timber. Dry Technol. 2013;31(5):587–94.
101. Thiam M, Milota MR, Leichti RJ. Effect of high-temperature drying on bending and shear strengths of western hemlock lumber. For Prod J. 2002;52(4):64.
102. Blanchet P, Kaboorani AK, Bustos C. Understanding the effects of drying methods on wood mechanical properties at ultra and cellular levels. Wood Fiber Sci. 2016;48(2):1–12.
103. Ouertani S et al. Vacuum contact drying kinetics of Jack pine wood and its influence on mechanical properties: industrial applications. Heat Mass Transf. 2015;51(7):1029–39.
104. Harris, R. and A.W. Lee, Properties of white pine lumber dried by radio-frequency/vacuum process and conventional kiln process. Wood and fiber science (USA), 1985.
105. FAO. Energy conservation in the mechanical forest industries. Vol. xii. Rome: Food and Agriculture Organization of the United Nations; 1990. p. 118.
106. Beakler B et al. Quantification of the VOCs released during kiln-drying red oak and white oak lumber. For Prod J. 2007;57(11):27–32.
107. Ressel JS. State-of-the-art report on vacuum drying of timber. In: Haslett AN, Laytner F, editors. 4th IUFRO International Conference on Wood Drying. Rotorua, New zealand: Forest Research Institute ; 1994.255-255
108. Moldrup S, Moldrup B. Drying of timber under vacuum in an atmosphere of super-heated steam. In: Vanek M, editor. 3rd IUFRO International Conference on Wood Drying. Vienna, Austria: International Union of Forestry Research Organizations - IUFRO; 1992. p. 235–8.
109. Avramidis S, Zwick RL. Commercial-scale RF/V drying of softwood lumber. Part 3. Energy consumption and economics. For Prod J. 1997;47(1):48–56.
110. Avramidis S, Zwick RL. Radio frequency/vacuum drying of B.C. softwoods; preliminary experiments. In 43rd Western Dry Kiln Association Meeting. Reno, NV: Western Dry Kiln Association; 1992.
111. Rice RW, Erich MS. Estimated VOC losses during the drying of six eastern hardwood species. For Prod J. 2006;56(10):48–51.
112. Milota M, Mosher P. Emissions of hazardous air pollutants from lumber drying. For Prod J. 2008;58(7/8):50–5.
113. Bicho PA et al. Characterization and treatment of condensates generated from softwoods that have been radio-frequency/vacuum kiln dried. For Prod J. 1996;46(10):51–6.
114. McDonald AG et al. Characterisation of the condensate generated from vacuum-drying of radiata pine wood. European Journal of Wood and Wood Products. 1999;57(4):251–8.
115. Boyd, D., Drying wood faster under vacuum at low temperatures, in 10th Hardwood Symposium Proceedings: Fighting Recession with Research, F.P. Society, Editor. Forest Products Society. 1982, p. 110–112.
116. Innes T, Redman A. Improvement of hardwood drying schedules. In Manufacturing and products, vol. 114. Melbourne, Victoria: Forest and Wood Products Research and Development Corporation; 2005.