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Understanding Vacuum Drying Technologies for Commercial Lumber

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Abstract

Vacuum drying is an economical alternative to conventional drying for many species under a variety of environmental and economic conditions. Vacuum drying can reduce drying time and be more energy efficient compared with conventional steam drying. But there are many factors to consider when comparing the two technologies. This report describes the principles and practices of vacuum drying and discusses its advantages and disadvantages. Among other concerns, final moisture content variation and residual stress have been significant issues of concern with vacuum drying. Standard vacuum drying schedules by species and thickness are lacking for the various vacuum drying technologies; therefore, proper training and applied research are still needed to develop standard practices for vacuum drying.

Keywords: vacuum drying; wood color; drying time; drying temperature

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Understanding Vacuum Drying Technologies for Commercial Lumber

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Introduction

The use of vacuum drying technology for lumber has recently gained attention because of the introduction of lower-cost vacuum kilns for smaller wood product manufacturers and hobbyists. Typically, vacuum kilns require a high initial investment and have the potential for high repair and maintenance costs due to corrosion if stainless steel is not used. Over time, these costs may be offset by lower operational costs due to shorter drying times compared with conventional steam kilns. Ideal applications for vacuum kilns include high-value wood species, hard-to-dry species, timbers, large sections of logs and lumber (including live-edge slabs and wooden rounds), decorative or thick veneer, and small-scale woodworking operations. Given that vacuum drying occurs in a closed system that does not require venting and uses lower drying temperatures, this type of technology is considered a more energy efficient option than conventional steam kilns (Espinoza and Bond 2016, Ressel 1994). Recent research has shown that vacuum kilns contribute to just-in-time production by having fast drying times, thereby reducing green lumber inventories (Brenes-Angulo and others 2015). Just-in-time practices are an important strategy for both small-scale and large-scale wood products manufacturers.

Drying Process

There are three basic requirements for wood drying: an energy source, a mechanism to transfer heat to the wood, and a method to remove water from the wood. With conventional steam heated kilns, the heat source (steam) is passed through heat exchangers to heat the air inside the kiln. Fans circulate this warm air through the kiln, transferring the heat to the lumber by convection. As the lumber releases moisture, the warm moist air is vented out from the kiln.

In vacuum drying, heat is applied while the wood is kept under less-than-atmospheric pressure. The heat source, which defines the type of vacuum drying system, consists of one of four types of heating methods (Espinoza and Bond 2016):

1. Conduction by direct contact (hot platen or electric blanket): heat is transferred to the wood through contact with the hot surface (Fig. 1). The blue hoses shown in Figure 1 circulate hot water through aluminum platens in direct contact with each layer of lumber. This paper will highlight the use of this system.
2. Convection using cycles of hot air (cyclic systems): wood is heated by convection using a heating phase at normal atmospheric pressure and then a vacuum phase in which the pressure is reduced until the wood temperature begins to drop. This cycle is repeated until the lumber is dried. Recall that convection is the transfer of heat by the circulation of a heated gas such as air. In a vacuum, there is no air (or the amount of air is greatly reduced); therefore, heat cannot be transferred through convection during the vacuum phase.

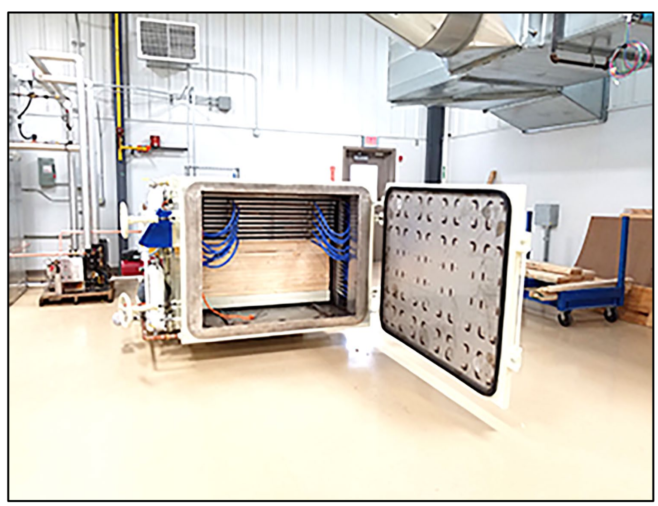

Figure 1. Vacuum kiln with heating by conduction using direct contact with water-heated aluminum platens. Note the wood spacers on the bottom half of the kiln, which are used to fill the kiln to capacity if the lumber volume is too small.

3. Convection using super-heated steam: super-heated steam is used under low pressure conditions and is forced through the layers of lumber.
4. Radio frequency or dielectric heating: heating is accomplished by using an alternating electromagnetic field causing the polar water molecules in the wood to shift back and forth when changing field directions. These rapid shifts or vibrations cause the wood to heat.

In addition to the heating source, the other main features of a vacuum kiln are a pressure vessel and a vacuum pump. The pressure vessel is the chamber where lumber is stacked and the drying occurs (Fig. 1). The vacuum pump assists in removing water from the wood, because drawing a vacuum in the pressure vessel decreases the boiling point of water, which allows the wood to dry at a lower temperature.

Drying is completed by lowering the ambient pressure in the pressure vessel, thus creating pressure differences inside the wood. The water in the wood is removed by two mechanisms: bulk flow and diffusion. Bulk flow consists of water vapor bulk flow and free water bulk flow. Because water boils or converts to a gas at much lower temperatures inside a vacuum, most of the water converts to water vapor (water vapor bulk flow) and is removed from the wood (Chen 1997), although some moisture loss can be in liquid form in permeable species (free water bulk flow). Water vapor bulk flow moves longitudinally through the wood cell structure, exiting the lumber from the end grain as water vapor (Fig. 2). With some species and lumber sizes, free water bulk flow moves longitudinally through the wood cell structure, exiting the lumber from the end grain as liquid water. Some diffusion drying occurs through the lumber's edges and faces; however, bulk flow is the main mechanism for water movement in vacuum-dried lumber. Vacuum drying is unlike conventional drying, in which very little water vapor bulk flow occurs. In conventional drying, diffusion is the primary drying mechanism.

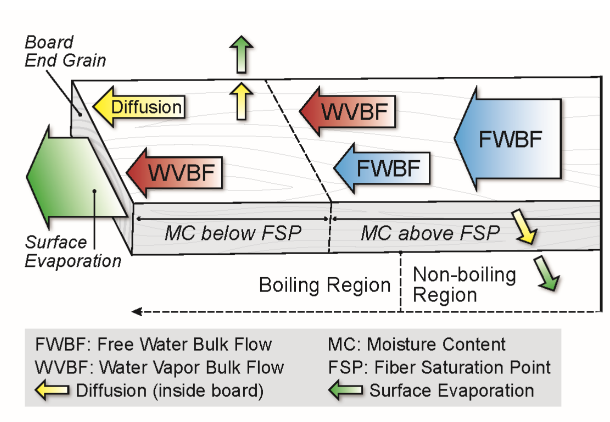

Figure 2. Moisture movement in lumber during vacuum drying (adapted from Chen 1997; used with permission from University of Wisconsin-Madison).

Control Process

Vacuum kiln control systems are different from those of traditional convection steam kilns. Some manufacturers have developed software to assist in this application; however, some kiln operators find that they need to develop their own schedules for their specific systems. Table 1 shows a sample conventional kiln schedule, in this case to be used for drying 1-in.- (25.4-mm-) thick hard maple lumber to bright white color (Denig and others 2000). In this system, an operator controls air speed, temperature, and relative humidity to follow recommended drying schedules, which have been tested and used with consistent results for decades.

In a vacuum kiln, the drying schedule is based on the initial lumber moisture content and is controlled using the core lumber temperature (Fig. 3). Drying control is based on presumed lumber moisture content, implied by internal temperature at a particular level of vacuum.

Depending on the type of vacuum kiln being used, several holes may be drilled into representative boards in the charge. Temperature probes are inserted into these holes to measure and track the lumber core temperature during the drying process. An alternate system estimates core temperature by measuring the temperature of the condensed water that is removed from the lumber.

Figure 3 shows that the water temperature (which heats the aluminum platens) and the core lumber temperature track one another within a few degrees. The slight drop in temperature from water to lumber core represents the energy used to evaporate and remove water from the lumber. Recommended practice is to use traditional kiln samples inside the vacuum kiln to track the moisture content loss of the lumber in the kiln charge.

Advantages of Vacuum Drying

One key advantage to vacuum drying is reduced drying time. The drying time in a vacuum kiln is significantly less than in a conventional steam kiln. For example, a recent study found that a 1-in.-thick hard maple charge was dried in a vacuum kiln in 2 days (58 hours), whereas a paired 1-in.-thick hard maple charge was dried in a conventional

Table 1—Conventional kiln drying schedule T1-C5, used for drying white hard maple

Moisture content (%)	Equilibrium moisture content (%)	Relative humidity (%)	Temperature (°C)	
			Dry-bulb	Wet-bulb
Above 30	11.8	68	37.5	32.0
25 to 30	9.8	58	40.5	32.5
20 to 25	7.6	44	40.5	29.5
15 to 20	4.1	22	46.0	26.5
<15	3.3	17	49.0	24.0

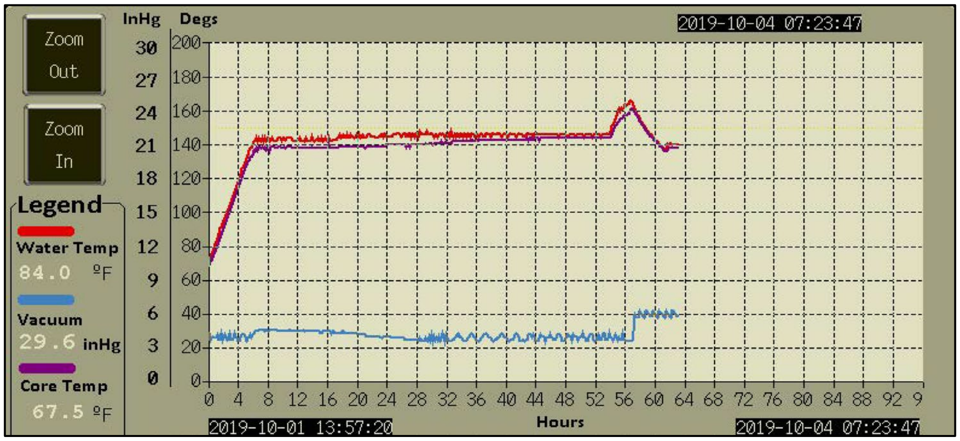

Figure 3. Vacuum kiln drying schedule (VacuPress EASYDry Software 2019, Vacuum Pressing Systems, Brunswick Maine, USA). The upper plots show the temperature in Fahrenheit degrees inside the kiln as a function of hours of operation, and the lower plot shows the pressure in inches of mercury. At 57 hours, there was a spike in temperature, which resulted in an increase in pressure. The slight drop in temperature between water (red) and lumber core (violet) represents the energy used to remove water from the lumber (T°C = (T°F – 32)/1.8; 1 in. of mercury = 3.39 kPa).

steam kiln in 12 days (288 hours) (Lyon and others 2021). This advantage is even more pronounced with thick stock, such as large table slabs or mantle pieces.

A vacuum kiln can also be more energy efficient compared with conventional steam technology. This is partly due to the time efficiency previously described, but vacuum kilns can have significantly lower daily electrical use. In the hard maple study previously mentioned (Lyon and others 2021), estimated average daily electrical use for the vacuum kiln was 166 kWh (597.6 MJ) per day and the estimated average daily electrical use for the conventional steam kiln was 179 kWh (644.4 MJ) per day. At the current rate of $0.11 per kWh, the vacuum kiln dried its charge for approximately $44 and the conventional steam kiln dried its charge for approximately $236. Both the vacuum kiln and conventional steam kiln were powered entirely with electricity, with an electric boiler providing the steam. In most cases, biomass or natural gas is used to generate steam for conventional kilns.

Vacuum kilns use lower drying temperatures, which saves energy and may allow wood to retain more of its original color. The recent study by Lyon and others (2021) found that there was no visual difference in wood color between vacuum drying and conventional steam drying; vacuum drying can produce industry-acceptable white hard maple that is comparable with that produced using a conventional kiln schedule. However, the recent use of low temperature schedules and higher fan speeds in conventional steam kilns can achieve superior color retention.

Another advantage of lower drying temperatures is that wood strength properties are higher because the degrade caused by high temperature drying is avoided. Lower drying temperatures also provide an advantage by reducing drying stresses (Espinoza and Bond 2016). However, the lack of stress reversal systems on commercially available vacuum kilns makes stress removal difficult when it does occur.

In vacuum kilns, organic compounds are extracted and condensed along with the water condensate and need to be treated before being discharged into the water supply (Espinoza and Bond 2016). Vacuum kilns might allow the operator to mix some wood species with similar specific gravities and moisture contents but of varying thicknesses in the same kiln charge. Lastly, because the kilns use hot platens, the dried lumber remains very flat. For example, the Vacupress system (Vacuum Pressing Systems, Inc., Brunswick, Maine, USA) has a flexible rubber membrane that allows atmospheric pressure to push down on the charge of lumber, creating up to 13 lb/in^2 (8.96 MPa) of pressure. This results in a higher yield when resawing into components.

Challenges of Vacuum Drying

Vacuum kilns are fundamentally different than conventional steam kilns. Therefore, wood manufacturers need to rethink how these changes will impact product flow within a business. Loading and unloading, cycle times, and lumber volume must all be considered. First, vacuum kilns are loaded and unloaded differently than conventional kilns. In most systems, stickers are not used and the heating system, heating platens, must be incorporated into the lumber unit, as shown in Figure 4.

For smaller vacuum kilns, the lumber and platens must be loaded and unloaded by hand from a forklift, as shown in Figure 5. For these kilns, lumber layers alternate with

Figure 4. Charge of thick slabs stacked in single layers between heating platens.

Figure 5. Loading 4-in.-thick white oak live-edge slabs into a vacuum kiln. These large slabs require the use of a forklift for the slabs and hand-loading of the aluminum platens between each slab.

Figure 6. Charge of lumber hand-loaded and stickered for drying in a cyclical vacuum kiln.

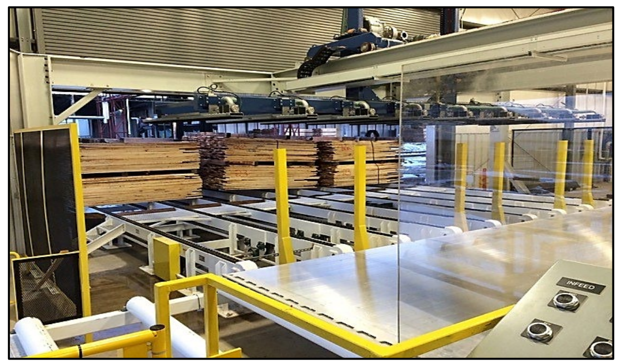

Figure 7. Mechanized, automated loading system at a large-scale drying operation (photo used with permission from Vacutherm, Inc., Barre, Vermont, USA).

aluminum platens through which the hot water circulates to heat the lumber. After drying, the lumber and platens are unstacked by hand. Hand loading and unloading the kiln is time-consuming and can present some safety concerns. Other types of vacuum kilns, such as the cyclical vacuum kiln shown in Figure 6, also require hand loading plus the use of stickers for proper airflow.

Larger operations use a mechanized, automated loading system to build and unbuild the kiln charges (Fig. 7). As the loading system unloads one dry cart, it simultaneously loads a second cart with green lumber using platens from the dry cart. After the new charge is assembled, the cart is pushed into the vacuum chamber for drying.

There are challenges associated with integrating a vacuum kiln into the drying process. The size of the pressure vessel determines capacity and, as with other types of kilns, available sizes are limited by the manufacturer. Some manufacturers produce vacuums kilns that can dry from a few hundred to more than 10,000 board feet (0.7 to 24 m^3) of lumber per charge. A manufacturing plant must take into consideration the challenges of just-in-time material flow. For example, the schedule of a conventional kiln that holds 50,000 board feet (118 m^3) of hard maple lumber takes 10 days and can dry five truckloads in that time. The schedule of a smaller 10,000-board foot (24 m^3) vacuum kiln charge of hard maple lumber takes 2 days and can dry one truckload in that time. Although this ends up to be the same amount of production, the logistics of delivery, kiln loading and unloading, and shipping are different. Production and shipping schedules must be adjusted to accommodate the quicker turnover of smaller loads.

High capital outlay and the potential for high maintenance costs have been a barrier for wood manufacturers to invest in vacuum drying. However, depending on particular circumstances, operational costs might be reduced because of energy efficiency and shorter drying times compared with conventional steam kilns.

Each vacuum kiln system is unique and requires an advanced understanding of the operation. Overall drying variability is a potential concern. Without knowledge of the individual system, there is a chance of over- or under-drying the kiln charge. Over-drying is especially problematic because its effects cannot be undone. This makes it difficult for the user of one system to be able to easily operate another without having in-depth knowledge of how it operates. Compared with conventional drying, there is a lack of available kiln schedules or instructions on how to dry different wood species in vacuum kilns.

Most vacuum drying systems do not allow the operator to add moisture back into the wood at the end of the drying cycle. This process, called conditioning, is an essential part of traditional kiln drying in that it reduces drying stress in lumber. The inability to add a conditioning step in vacuum kilns can produce lumber with residual stress, which makes it difficult to maintain quality when machined into smaller components for use in furniture or flooring. However, a vacuum kiln with a radio-frequency system has been shown to produce stress-free red oak lumber by not allowing the internal wood temperature to go above 100 °F (37.7 °C) for the first 48 hours of the drying process (Harris and Taras 1984). In that system, the drying process took 88 hours to dry the samples from 67% to 7% moisture content. The wood core temperature reached 140 °F (60 °C) during the final stage.

The permeability of wood species is an important consideration when drying in a vacuum kiln. Some species, such as white oak, are generally hard to dry, and it would not be economical to dry them in a vacuum system because of the limited improvement in drying time compared with conventional drying.

Summary

In summary, vacuum drying is gaining interest among wood product manufacturers with its fast drying rates and unique uses compared with conventional drying systems. However, final moisture content variation and residual stress have been significant issues of concern with vacuum drying. Therefore, proper training and applied research are still needed to develop standard practices to assist in reducing drying defects in vacuum drying of commercial lumber.

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Literature Cited

Brenes-Angulo, O.; Bond, B.; Kline, E.; Quesada-Pineda, H. 2015. The impact of vacuum-drying on efficiency of hardwood products manufacturing. BioResources. 10(3): 4588-4598.

Chen, Z. 1997. Primary driving force in wood vacuum drying. Blacksburg, VA: Virginia Polytechnic Institute and State University. 185 p. Ph.D. dissertation.

Denig, J.; Wengert, E.M.; Simpson, W.T. 2000. Drying hardwood lumber. Gen. Tech. Rep. FPL-GTR-118. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 138 p.

Espinoza, O.; Bond, B. 2016. Vacuum drying of wood—state of the art. Current Forestry Reports. 2: 223-235.

Harris, R.A.; Taras, M.A. 1984. 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. Forest Products Journal. 34(1): 44-54.

Lyon, S.; Bowe, S.; Wiemann, M. 2021. Comparing vacuum drying and conventional drying effects on the coloration of hard maple lumber. Res. Pap. FPL-RP-708. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

Ressel, J.S. 1994. State-of-the-art report on vacuum drying of timber. In: Haslett, A.N.; Laytner, F., eds. 4th IUFRO International Conference on Wood Drying. Rotorua, New Zealand: 255-262.