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ARTÍCULOS

## HIGH-FREQUENCY ELECTRIC CURRENT FOR DRYING OF WOOD HISTORICAL PERSPECTIVES

*Helmuth Res*

*In memoriam of Dr. Walter G. KAUMAN*

### ABSTRACT

Among the many interesting topics in the field of Wood Science and Technology is a fascinating story about research and development on drying wood products with high-frequency electric current. Historically, it can be traced back over decades.

Heat transfer to and evaporation of moisture from wood may be accomplished with high frequency electric current depending on its dielectric properties. Because wood is generally heterogeneous, these properties vary not only with the frequency of the current and the field orientation, but also with the moisture content, temperature, and density of wood. Considering these parameters and the specific heat of the material, estimates of power absorption can be made.

In an attempt to develop this technology, research covered many products from paper and veneer, lumber and heavy timbers. Much emphasis, however, has been placed on wood species and/or products with larger dimensions that are difficult or impossible to dry when using conventional drying methods. The advantages of employing dielectric heating were found to be rapid and fairly uniform heat transfer, often to solidly stacked timbers, very high drying rates, and avoidance of various drying defects including any significant case-hardening and oxidative discoloration of the wood.

During the last two decades, the development focused mainly on drying lumber in vacuum kilns using dielectric heating, often termed high-frequency/vacuum drying. It has been justified economically on the basis of increased throughput and higher quality. Existing industrial installations provide a positive picture for higher value products. The economics should improve with advances in available equipment, better basic understanding and more practical experience with industrial units now operating. Also, the combination of high-frequency/vacuum drying with other systems, such as moisture leveling after primary drying or pre-heating prior to the high-frequency/vacuum step, hold promise for further technological improvement.

**Keywords:** Wood drying. Hf-current

### *Dielectric heating of wood*

For industrial processing with high-frequency (Hf) electric current, two different frequency ranges may be distinguished: radio frequencies (Rf) below 100MHz, using open wire circuits, and microwave frequencies above 500MHz, using wave guides to transfer power to material contained in them. The term dielectric heating refers to both and the effects on materials, such as polarization and conduction, are similar. For industrial processing, international agreement designated the frequencies in Table 1 are related to wavelengths in free space. However, other frequencies have been used for equipment v

**Table 1.** Frequency bands for industry

	Frequency	Wave length
	MHz	m
<b>Radio frequencies</b>	13.56	22.11
	27.12	11.05
	40.68	7.37
<b>Microwaves</b>	915	0.328
	2450	0.122
	5800	0.052

Heating is influenced by the material structure. A field of high frequency electromagnetic wave is able to polarize charges in insulating materials. This polarization, however, cannot follow the extreme rapid reversals of the dielectric field. The polarization vector  $P$  lags the applied electric field so that the resulting current  $\delta P/\delta t$  has a component in phase in this field, thus, dissipating power within the insulating material. Orientation polarization is caused by permanent dipoles contained in polar dielectrics that reorient under the influence of a changing electric field. Induced polarization stems either from the displacement of electrons around the nuclei or from the relative displacement of atomic nuclei themselves. Further, interfacial polarization arises from space charges built up in interfaces between heterogeneous components.

The average dipole moment of a displaced dipole is the product of the charge  $q$  and the charge separation  $x_i$ ,  $\mu = q x_i$ . Together all dipole moments within a volume  $\Delta v$  containing  $N$  dipoles amount to the charge density of the polarization field  $P$ :

$$P = \sum_{i=1}^N \frac{qx_i}{\delta_v} \quad (1)$$

The electric charge density vector  $D$  may express the total charge of the interface between the dielectric and the surrounding medium. The difference between the two vectors accounts for the remaining charges of the system. Thus,

$$D = \epsilon_0 E + P = \epsilon_0 \epsilon' E \quad (2)$$

Where  $\epsilon_0$  is the dielectric constant of free space,  $E$  the externally applied electric field, and  $\epsilon'$  the relative dielectric constant, often just termed the dielectric constant. The previous equation yields  $(\epsilon' - 1) \epsilon_0 E$  and the ratio of the bound to the free charges is referred to as electric susceptibility

$$X = P / \epsilon_0 E = (\epsilon' - 1) \quad (3)$$

Because the polarization field  $P$  contains individual dipole moments  $P = \mu N'$  and the local field  $E'$  applies to the individual dipole, the dipole moment  $\mu$  is a simple function of the field:

$$\mu = \alpha_r E' \quad (4)$$

### Dielectric Properties

In heating wood by high frequency current, losses due to electronic and atomic polarization can be neglected. The complex dielectric constant  $\epsilon^*$  that becomes effective for high frequency heating includes the imaginary part  $\epsilon''_{eff}$  as loss factor:

$$\epsilon^* = \epsilon' - j\epsilon''_{eff}. \quad (6)$$

The effective loss tangent, the ratio of the effective loss factor to the dielectric constant, is a material property reflecting the effects of applied electric field vectors and direct current conductivity. It stands for the high frequency electric energy dissipated in the material and subsequently transformed into thermal energy:

$$\tan\delta_{eff} = \epsilon''_{eff} / \epsilon'. \quad (7)$$

The dissipation of energy in the frequency range from 10MHz to 3GHz is influenced mainly by two different mechanisms: dipolar and interfacial relaxation. If significant amounts of conductive phases are present, as may be the case with water-saturated wood, the conductivity  $\sigma$  and the angular frequency  $\omega$  have to be considered also. Interfacial polarization can then be expressed:

$$\epsilon''_{dc} = \sigma / \omega \epsilon_0. \quad (8)$$

Losses due to a conductive phase in a heterogeneous dielectric combine with dipolar losses to amount to the effective loss factor  $\epsilon''_{eff}$ .

For proper equipment design and efficient processing of materials, their dielectric properties must be known. However, both components of the complex dielectric constant or permittivity  $\epsilon^*$ , namely  $\epsilon'$  and  $\epsilon''_{eff}$ , are frequency and temperature dependent. Von Hippel (1954) researched the dielectric properties of a wide range of inorganic and organic materials in the frequency and temperature ranges from  $10^3$  to  $10^{10}$ Hz and  $-12$  to  $200^\circ\text{C}$  respectively. Tinga and Nelson (1973) followed with a focus on biological substances. Hearmon and Burcham (1954) James and Hamill (1965) as well as James (1975) concentrated specifically on wood and its products and finally Torgovnikov (1993) brought together a large body of knowledge about dielectric properties of wood and wood-based materials.

Obviously, the presence of water, which is polar and exhibits strong dipole moments, increases for any material the effective loss factor and makes it a good candidate for processing with high frequency energy. Because application of dielectric heat causes changes in moisture contents, the variation of  $\epsilon''_{eff}$  and in particular  $\epsilon''_{eff}$  with moisture content is important. Bound water is tightly held and less rotationally free than the free water present in various cavities. Thus, the latter makes higher dielectric losses possible.

For practical purposes, the influences of the anisotropy of wood, the fiber orientation in respect to the electric field, must be considered also. The optimum field orientation in an applicator may be deduced from the  $\epsilon''_{eff}$  versus moisture content curves as losses are higher for the field orientation parallel to the grain, which is characteristic of wood and paper products (James and Hamill, 1965). Each material possesses different curve forms for different frequency ranges. Further, the slope of the  $\epsilon''_{eff}$  versus moisture content curve is critical to industrial applications where moisture leveling of a material, especially in sheet form, is the main objective (Resch, 1968). Above a critical value of moisture content, wetter parts of a material absorb more power and tend to level off an initially uneven moisture distribution.

look up tables, exemplified by those of Torgovnikov (1993), may be constructed and used for specific calculations.

### ***Volumetric Heating***

The average of power absorbed within a dielectric material can be stated assuming the electric field  $E$  established in the material as constant:

$$P_{avg} = \omega \epsilon_0 \epsilon''_{eff} E^2 v \quad (9)$$

Substituting  $\epsilon_0 = 8.8 \cdot 10^{-12} \text{ F/m}$  and  $\omega = 2 \pi f$ , renders  $P_{avg} = 0.556 \cdot 10^{-10} f \epsilon''_{eff} E^2 v$ .  $P_{avg}$  is expressed in W when  $E$  is in V/m,  $f$  in Hz,  $v$  in  $\text{m}^3$  while electron spin losses are ignored.

Considering the current flow through a lossy capacitor that is connected across a sinusoidal voltage

$$i = i_R + i_C = V/R' + C dV/dt \quad (10)$$

The capacitance for a cross sectional area of the capacitor plates  $A_c$  and their separation  $d$  is

$$C = \epsilon_0 \epsilon' A_c / d \quad (11)$$

Thus, the product of  $f$  and  $\epsilon''_{eff}$  strongly influences the calculation of the power density within a dielectric material explaining why greater power densities can be obtained with microwaves:

$$\text{Power / unit volume, } p = \omega \epsilon_0 \epsilon''_{eff} E^2.$$

The enthalpy of a system at a given pressure, volume, and internal energy  $U$  is given by  $H = U + pV$  and may be shown in differential form:

$$U = dQ_h - p dv \quad (12)$$

The specific heat can be calculated by differentiating with respect to temperature and constant volume

$$c = (\delta U / \delta T)_v = \delta Q_h / \delta T \quad (13)$$

Taking the specific heat of water as 4.19 kJ/kgK, the influence of moisture content of wood can be estimated for the major European species to fall between 1.35 and 2.83 kJ/kgK (Dunlap 1912, Kollmann 1951).

### ***Early developments***

W.R. Whitney of the General Electric Co. in the USA, apparently prior to 1928, conceived the idea to dry wood and similar materials in a high frequency (Hf) electric field and the agent, John G. applied for a British patent in March of the following year (Tiemann 1944). In 1934, Abramson published on experiments, carried out during the previous years, to dry wood by this method. A. Matsumoto (1934) filed for a Japanese patent. Stephen and Holmquest (1936<sup>a</sup>, 1936<sup>b</sup>) followed up with drying studies on lumber and Voigt et al (1940) providing a technological overview. The first patent

In the 1960s, research and development on the Hf-drying accelerated in a number of countries and results were reported by a fair number of researchers (Jagdfeld 1963, Gillwald 1964, Gefahrt 1966, 1967, Dean 1963, Miller 1966, Czepek and Sporkmann 1968, Resch 1966, 1967, 1968, Resch et al. 1968, Pound 1973).

### *Continuous radio-frequency dryer*

At that time, probably the best known tunnel dryer using Rf-current for heating short pieces of European beech had been designed by Brown, Boveri & CIE in 1963 (Czepek, Sporkmann 1968). Located in Southern Germany, it dried mainly beech wood 150mm in length in the production of foot for shoe design. A metal link-chain belt, serving as one electrode, carried the material through an 18m long tunnel. The hot electrodes suspended above could be adjusted in height as to provide an optimum electric field for the changing dielectric properties of the drying wood. The generator worked at 13.56MHz with power adjustable between 2 and 25kW. Its tubes were air cooled through a blower and the warm air ducted into the tunnel to prevent condensation on tunnel walls and transfer some heat to the wood as well. Vents provided for the exhaust of moist air. The wood, that had first been air-dried to just below fiber saturation point, could be dried with hardly any defects to fairly uniform final moisture content of about 9 percent. In fact, most of the pieces contained slightly lower moisture content in the core than in the shell, the opposite to the moisture gradient normally encountered after convection drying. This reflected the different drying mechanism explained later.

### *Radio-frequency/Vacuum drying*

RfV drying technology constitutes a combination of two special methods: heating by high frequency electric current and drying in vacuum where the boiling point of water is decreased with decreasing pressure. Consequently, the movement of water through wood increases leading to shorter drying times than can be achieved at atmospheric pressure. The intensity of the heating depends directly on the moisture content of the wood and the electric field, while the moisture movement depends on the permeability of the wood and the internal pressure gradient. At radio frequencies, the penetration depth influences the dimensions of the electric field that is of the order of meters, thus, making possible the heating of entire stacks of lumber.

The first industrial RfV dryers were built by the Russian Academy of Science in Moscow apparatuses in the 1960s. Some models had dimensions of 8m lengths, 3m heights and 3m widths that accommodated about 10m<sup>3</sup> of lumber. The Rf-generator, located on top of the vacuum chamber, working at a frequency of 13.56MHz and using about 44kW, could produce a maximum of 10kV Hf-current between the electrodes. Internal water vapor condensation was possible on cooled pipes. Its main use was for drying furniture stock from Russian hardwood species (Djakonov and Gorjaev, 1981).

In the USA, a small HfV dryer was built and patented by Koppelman (1976). In its cylinder, lumber was dried between two electrodes with water vapor being condensed originally on the cooled cylinder walls, later in an outside condenser. The advantages of high product quality and short drying times were proven experimentally by Harris et al. (1984) and Trofatter et al. (1986).

### *Microwave drying*

In the 1940s, the advent of the magnetron gave a start to industrial microwave heating for cooking

the order of meters and, unless the loss factor is extremely high, through heating may be assured. In the microwave region, on the other hand, the penetration depths become very small, especially when the material is very wet. Non-uniform temperature distribution is the result when the size of the material to be heated is greater than the penetration depth of the radiation.

It seemed logical to apply the new technology of microwave heating and drying in the field of forest products (Egner and Jagfeld 1964; Resch 1968) especially as continuous processes for thinner materials such as thin lumber (Resch 1966; Mc Alister and Resch 1971), pencil slats (Resch 1967) and veneers (Resch et al. 1970).

The first production-sized, continuous microwave-hot air dryer was built by the Cryodry Corp. and set up at the Yakima plant of the Boise-Cascade Corp. Using 50kW microwave power of 915MHz frequency, it was developed to level the moisture content in softwood veneer that had remained too wet after primary drying. Rollers conveyed veneer sheets to pass through slotted wave-guides that were arranged in meanders. Hot air jets positioned between the wave-guides and rollers impinged on the veneers and carried off evaporating moisture. Drying selectivity obtained was due to a greater microwave absorption in wetter areas, often well-defined wet pockets and streaks. Microwave re-drying prevented over-drying and kept the veneer at equal or better quality than re-drying with hot air (Resch et al. 1970).

### ***Radio-frequency batch dryers***

As an alternative to a continuous microwave dryer for leveling moisture content in re-dry veneers, Speco Inc., in 1982, manufactured an Rf-batch dryer. Reportedly, it was able to bring the moisture contents of 1.22 x 2.44m veneer sheets in a 0.76m high stack into the desired range within 14 minutes. The 300kW generator worked at 13.56Mhz and the temperature of the chamber was maintained by hot air at 150°C. Of course, there were by far fewer moving parts in such a dryer as conveyance to and from the dryer was by forklifts and loading was automatic.

## **R&D and industrial installations during the last decades**

### ***Radio-frequency/vacuum dryers***

In the 1990s, interest was renewed in dielectric heating of wood as part of the drying technology. Using Rf-heating, the combination with vacuum drying emerged as the best option for most applications in the solid wood products industry.

In the USA, Dimension Drying Inc. built an RfV dryer specifically designed to dry red oak furniture parts at Norton Smith Lumber Co. (Smith et al. 1996). It employed an Hf-generator working at 13.56MHz using Siemens tubes with life expectancies between 2000 and 4000 hours. The chamber, having a capacity of roughly 20m<sup>3</sup>, could be evacuated to a pressure level as low as 2.3kPa. At one time, five such dryers were reported operating commercially in the State of New York.

In Canada, the success in drying hardwoods caused interest in the softwood lumber industry. A new RfV chamber with 23m<sup>3</sup> capacity, softwood lumber of various Canadian species was dried at a frequency of 3MHz and a maximum power of 260kW (Avramidis and Zwick 1992; Avramidis et al. 1994, 1996, 1997). Avramidis presented an overview of this technology in 1999 at a workshop in Scotland.

The RfV technology succeeded in drying large lumber sizes that are commonly not dried by

(Avramidis and Zwick 1996). Based on this research, HeatWave Technologies Inc. developed a number of models of commercial RfV dry kilns.

One such RfV-kiln, or rather two units linked together working at 13.56 MHz and a maximum 40kW, have been installed by Forest Grove Lumber Co. in Oregon. This wholesaler markets RfV-dried large Douglas fir timbers under the trade name Tru-Dry asserting high quality, structural integrity, and good appearance. Each unit is 12.2m long and 1.22m wide to accommodate timbers with cross sections ranging from 152x152mm to 254x254mm. To prevent or reduce warp, a top weight of about 113 kg/m<sup>2</sup> is placed on them during drying. Drying time ranges from about 4 to 6 days depending on timber size and moisture content.

The construction of the apparently largest HeatWave unit with 75m<sup>3</sup> capacity and 300kW radio frequency output was announced in 2001 for the main purpose of re-drying Western hemlock and western white fir lumber that had remained too wet during primary hot air convection drying (Elustondo and Avramidis 2001). The scheme is mentioned below in context of combination processes.

In Japan as well, a number of companies constructed Hf-lumber dryers with 13.56MHz frequency generators and capacities ranging from 5 to 40m<sup>3</sup> (Yasujima 2001, Mokushin 2001, Fuji Electronic 2003). While Yasujima decided on the RfV approach using two cylinders as drying chamber and water-cooled vapor condenser respectively, others opted for so-called hybrid kilns combining Rf-heating with hot air convection drying at atmospheric pressure.

In Austria, a commercial RfV-drying chamber, manufactured in Russia on the basis of the design from the Academy of Science in Moscow, had been obtained to investigate the feasibility of this technology for drying major European hard- and softwood species (Resch and Gautsch 2000). This plant with a maximum capacity of 10m<sup>3</sup> and a rather old generator providing a maximum high frequency voltage of 10kW at 13,57MHz was fitted with load cells and condensation traps to determine the rate of drying and was equipped with fiber optics to measure the temperature of the wood. Results were rather promising for beech, birch, and spruce lumber of common sizes that could be dried in 2 to 4 days while oak proved to be much more refractory. In addition, a small, 1.5m long, highly instrumented laboratory RfV-dryer was constructed allowing the continuous measurement of weight, temperature, and pressure in wood samples in the drying chamber (Resch and Hansmann 2002). Among the tests with this equipment, 75mm thick board of *Eucalyptus globulus* could be dried rapidly, in about 290 hours, from about 42% to 11% moisture content without the development of collapse and significant checks. Based on the measurement of internal pressure during drying and residual strain in the wood, it was concluded that the drying mechanism was a combination of pressure flow and diffusion of moisture to the surface. It is that pressure flow which accounts for the high rate of drying as well as the low stress development.

In China, research by Li et al. (2005) proved the RfV concept (using 6.78Mhz) quite applicable for drying plantation poplars containing initially very high amounts of moisture.

### **Microwaves**

To overcome problems of field distribution and power intensity when designing a continuous microwave dryer, multimode applicators have been suggested to advance that technology further toward industrial application (Antti 1992, 1999; Hansson and Antti 2003; Leiker et al. 2004b and 2005). Further improvement of this concept is the additional application of a vacuum to reach even higher drying rates and improving the quality of the dried material (Leiker, Adamska 2004). Two magnetrons working at 2450MHz and up to 3kW each were able to dry 50mm thick beech samples at a rate of about 7%/h.



### *Combination processes*

Hf drying units may be used not only where quality improvement is possible, but also where conventional methods become very slow or inefficient. This is the case when drying wood toward the end of the «falling rate period» prior to reaching the final moisture content. Thus, a combination of drying systems can increase total throughput appreciably thereby reducing space and inventory requirements.

Classic examples were the re-drying of veneer after a primary drying process either using microwave or Rf-current coupled with hot air convection. Conventionally, but rapidly dried material often has a spread in final moisture contents that is too large and not acceptable for further processing. Thus, re-drying is required of the material that had remained too wet. Here, dielectric heating offers important advantages: Dielectric current delivers more heat to wet than to dry areas. This levels the moisture content and helps retain product quality as has been demonstrated with a continuous microwave dryer (Resch et al.1970) and stationary Rf-dryers (Wilson 1989).

A further improvement of this concept is the addition of a vacuum. An RfV- dryer can also be used for re-drying of softwood lumber (Elustondo and Avramidis 2002). HeatWave Technologies installed such a unit at Hampton Lumber Co. in the State of Washington. There, hot air convection kilns dry Western hemlock and White fir structural lumber to a target of average moisture content of 17%. The primary drying step leaves a fairly large portion of boards above 18% as too wet. That portion has to be sorted out by means of a moisture probe and then taken to the RfV-re-dryer. With generators producing 300kW, the moisture content of the lumber is being leveled and reduced to a final moisture target of about 16 to 18%. The advantage of this “dry, sort and dry” approach lies not only in the shorter drying time through the kilns, but also mainly in a reduction of degrade and shrinkage of lumber that otherwise would have been over-dried. That reduction in shrinkage allows for a somewhat smaller target size for sawing and therefore for a reduction in raw material used.

In Asia, studies focused on other alternatives and wood species. Because in conventional drying, especially of refractory woods, the dangers of collapse and checking exist, long drying times are normally mandated. To reduce steep moisture gradients that lead to large drying stresses, intermittent Hf-radiation might be useful. Instead of a steaming treatment, conditioning of Eucalyptus board sections was possible with microwaves at 2450MHz. It proved successful in obtaining stress relaxation to a large extent (Wang 2005).

The combination of microwave radiation and convective hot air heat transfer to Korean red pine timber with a 150 by 150mm cross section proved only partially successful (Lee 2005). This approach of rapid drying reduced the amount of defects compared to those normally occurring with hot air drying but the formation of checks led to the conclusion that further research was needed.

Other combination processes seem possible such as pre-heating by conventional means, such as steam, or steaming of green lumber with all the moisture in it, followed by HfV drying. The steaming would provide the relatively large amount of energy needed in first heating up, leaving only the energy needed for evaporation to the Hf source. In other words, there are still exciting opportunities for research and industrial development in this field.

### *Toward fuller understanding*

the other hand, find proper applications for using microwaves. With the latter, the widespread use of magnetrons for cooking ovens and their stable performance over years proofed to be an incentive. Another stimulant is the energy density that can be attained and permits extremely fast drying rates.

### *Different Drying Mechanism*

Hf heating has been proven to allow rapid heat transfer throughout dielectric materials. This volumetric heating does not depend on heat transfer through the surface and continues through the boiling point of water and beyond. The wet bulb temperature does not limit the wood temperature. Internal evaporation and an increase in pressure occur in the cells moving liquid water and steam to the evaporating surface preferentially to the end grain. Especially during the periods of initial heat-up and constant drying rate, moisture flow responds to absolute pressure differences and the permeability of the wood influences the speed of drying. During the falling rate period, when residual liquid water and water vapor are moving, diffusion becomes an additional mechanism. At low moisture contents, when water is tightly adsorbed, dielectric heating decreases with a decreasing loss factor (Perkin 1980; Zhang et al. 1997; Kobayashi et al. 2001; Kawai et al. 2001).

This drying mechanism results, toward the end at lower moisture levels, in rather flat moisture gradients from the interior to the surface. It permits rapid drying because drying stresses are small or non-existent so that checking of the material is minimized or prevented (Resch and Gautsch 2000; Resch and Hansmann 2002). In a study of pine boards heated with microwaves, Liu et al. (2005) showed higher initial vapor pressure in the cores with a fairly uniform temperature distribution. As drying progressed, the core temperature advanced while pressure levels slowly decreased still with a driving force on the inside. When rapidly heating and drying of poplar wood using microwaves, Yang et al. (2005) found the temperature of outer layers initially somewhat higher than of the core, however, observed soon a reversal of this pattern with moisture migration from the inside out.

The explanations above do not necessarily indicate that everything is understood and kiln schedules are optimized. In the last years, basic studies about Hf-heating were conducted by Makoviny (1999), Resnik et al. (1997), Zhou and Avramidis (1999) on the changing loss factor, Perré and Turner (1999) on the numerical simulation of drying with microwaves; Lee and Hayashi (2000a, 2000b) on HfV drying parameters and wood behavior; to name a few. However, the multitude of factors effecting the outcome of HfV kiln runs, the possibilities to effectively combine HfV drying with other heating and drying methods, and the advantages of on-line measurement systems to assess process parameters of heat transfer, evaporation and condensation require further research and development.

An understanding of the mechanism of moisture movement may also be the basis of future control and scheduling of Hf-drying processes. This, in addition to a desire for basic understanding, explains the emphasis placed by a number of researchers on modeling the effects of microwave radiation on the drying process per se (Turner et al. 1998; Perre and Turner 1999; Zhao and Turner 2000; Jia and Afzali 2005). For continuous HfV-drying of thick lumber, Koumoutsakos et al. 2001a, 2001b, 2002a, 2002b developed a one-dimensional model of flow exclusive of capillary movement.

### *Technical feasibility*

The available literature indicates the technical feasibility of Hf-drying, specifically:

- Refractory woods and timbers of large dimensions can be dried with reduced degrade fresh from saw.

- When uniform heating is accomplished, drying stresses are small or non existent so that checking does hardly develop;
- When drying in vacuum, most of the dried timbers retain their natural light color;
- Drying times required are only a fraction of those needed with conventional methods, however, when drying green from the saw, final moisture equilibrium is not always easily obtained;
- Microwaves permit higher energy densities, however, to a more limited depth; too high an energy input may cause steam expansion checks;
- Wet areas may be preferentially heated in a re-drying process, thus leveling the moisture content.

### *Economic considerations*

For economic considerations of a new process and installation of new equipment, the costs of present drying methods need to be known. Besides capital investment, the costs of energy, labor, maintenance, space, pollution, overhead, et cetera should be compared. While increased throughput is an easily determined advantage, the evaluation of improved material quality is much more difficult and may be influenced by bias and market fluctuations. In the lumber and plywood industries, the actual loss of product quality, the downfall during the drying operation, is often poorly understood and sometimes easily accepted when the amount produced has priority.

The economic analyses of producing hardwood furniture stock with RfV drying (Farkas 1993; Srinivasan et al. 1996) and RfV drying of Canadian softwoods (Avramidis and Zwick 1997) provide a positive picture of the Hf-technology in regard to higher value products. Importantly, the latter study pointed out that capital costs are not based on market prices and include development costs.

### *Changing Generators*

During the last decade, Hf-technology has been improving. Fixed costs of equipment and some of the variable costs have come down, such as the expense for tubes that may not be needed when solid-state technology can be employed. The first Rf-generators were triode oscillators using vacuum tubes that were costly and whose life was a limiting factor. One other drawback was the necessity of readjusting the frequency and the plate voltage from time to time because the dielectric coefficient  $\epsilon'$  and the loss tangent  $\delta$  of the wood change with moisture loss. Rf-amplifiers normally used in telecommunications have appeared more advantageous.

Now, solid-state power amplifiers stand for a new technology. The 50- $\Omega$  systems have a fixed operating frequency with a crystal oscillator amplifying the required power in several stages (Jones 1996). In the first stage, solid-state devices bring the power up to a few kilowatts and then thermionic valve circuits can boost it further. The use of matchboxes assures balanced impedance. A main advantage is the high energy conversion efficiency.

The magnetron remains the preferred microwave power source because of stable frequency output at high energy efficiency and low cost. Depending on the size of materials and their dielectric properties, different applicators may be employed such as single mode resonant cavities, multimode ovens or traveling wave applicators. The limited penetration depth of microwaves somewhat restricts choices.

### *Energy consumption*

or fossil fuel sources. In forest products industries, the cost of electricity is relatively high in comparison to in house process steam produced from manufacturing residues or biomass.

In the case of HfV-drying of red oak furniture squares reported above, the commercial viability seemed to exist for a number of years. The 100mm thick material ranging in initial moisture content between 82% and 89% could be reduced to final moisture contents between 6% and 8% in about 6 to 68 hours. The energy consumption ranged between 7.7 and 12MJ/kg, i.e. 2.14 and 3.33 kWh/kg of water. The higher consumption appeared to be related to low temperatures in the wintertime. The short drying times and the almost defect free material compensated for the costs of electricity.

In the case of the Canadian studies of RfV-drying of 101mm thick softwood, the efficiency appeared to be much higher. From an initially green (fresh from the saw) moisture content to a final of 15%, a consumption of 1.29kWh/kg of water (or 4.64 MJ/kg) was reported, providing for a high efficiency of 70%.

Of course, each process situation requires different considerations. To obtain at least an estimate of electric energy consumption for an HfV dryer, one needs to determine the following energies to

- heat the wood substance to the drying temperature,  $Q_1$
- heat the water contained,  $Q_2$
- vaporize the water to be removed,  $Q_3$
- break the bonds of adsorbed water to be removed,  $Q_4$
- make up heat losses due to radiation and conduction,  $Q_5$
- run the vacuum pump,  $Q_6$
- run the cooling system,  $Q_7$ .

$Q_1$  through  $Q_4$  can be calculated from theory; the others must be estimated empirically. Here included is the energy for transporting the charge.

For instance, assuming a HfV dryer operating at 50°C and at 120mbar with a Hf conversion efficiency of 60%, large dimension softwood timbers with a density of 375kg/m<sup>3</sup> (oven dry basis) are to be dried from an initial moisture content of 60% to a desired final of 18%. An estimate of the energy consumption may be: 5.3MJ/kg of water or 1.47kWh/kg that is about 232 kWh/m<sup>3</sup> of timber.

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