RADIO FREQUENCY/VACUUM DRYING OF B.C. SOFTWOODS; PRELIMINARY EXPERIMENTS

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ABSTRACT

Five exploratory drying runs were carried out in a commercial size (23 m^3), radiofrequency/vacuum hardwood kiln. The species investigated were Pacific coast hemlock, Douglas-fir and western red cedar of different sizes and grades. Evaluation of the dried lumber showed that the three species can be dried in very short times and low amount of degrade irrespective of thickness with the exception of clear cedar which exhibited severe internal honeycombing; indicating the need to develop proper kiln schedules for this drying process. A thermodynamic and sensitivity analyses were performed which showed that above certain efficiency levels, RF/V drying is economical and fast. That was in particular true with lumber over 8 cm in thickness.

BACKGROUND

Dielectric (or RF) heating is a commercial technology that has been around for over fifty years. Dielectric heating has the unique ability to heat nonconducting materials throughout, with a uniform temperature rise. This can be achieved by taking advantage of the strong dielectric properties of water and its selective heating in hygroscopic materials like wood.

Conventional methods of heating good thermal insulators, depend on heat flow inward from the surface, a process which can take a great deal of time. It is this very point that gives RF heating such an important role in industrial applications; it readily heats materials which are difficult to heat by any other means.

Green lumber is an excellent material for RF heating. Water is a highly dipolar molecule and its dielectric constant is about twenty times larger than that of dry cell wall. As a result, water will heat at a much more rapid rate than wood. Water is therefore selectively heated internally more than the surrounding material. This very fact makes moisture removal when green wood is subjected to an alternating electric field in the radio frequency spectrum, a natural application for dielectric drying. Moreover, levelling out of uneven moisture content distribution in the lumber has also been credited to the RF/V drying method (1,7).

The fundamental principle of RF heating (1 to 100 MHz), is to physically excite the water molecules with electromagnetic radiation (8,11). This will cause dipolar rotation which will lead to a conversion of the electrical field energy to stored random potential energy and then to thermal energy in the material. Additionally, diluted salts in the free lumen water, will dissociate to positive and negative ions that will move towards the direction opposite to their own polarity by the electric field. By colliding with unionized water molecules, kinetic energy will be converted to heat. This phenomenon is called ionic conduction, When both ionic conduction and dipolar rotation occur in an electric field which is alternating millions of times per second, it is obvious that large amounts of heat can be generated (11,12).

RF drying for wood was first introduced in the ex-USSR in 1934 (9). Since then, some RF kiln designs were proposed and few prototypes were built. Some research was carried out with hardwood species like beech and oak (2,4,8,9,10,14) and softwoods like spruce and Douglas-fir (3,5,6). In all studies, considerable reductions in drying times and degrade were reported. Less shrinkage and much better moisture content uniformity along and across the boards were also found, compared to conventional kiln drying. The electromagnetic frequencies ranged between 2 and 13.65 MHz at various RF field powers. Some of the studies were carried out under vacuum. All boards dried had a thickness that ranged between 1 and 2-inches. Lately, 4 3/4" Douglas fir was RF/V dried that resulted in a final product of much better quality compared to conventional drying (13).

The purpose of this communication is to present the results of a preliminary study that was carried out in order to evaluate the drying characteristics of three major British Columbian wood species in a commercial size RF/V kiln. A variety of sizes and dimensions was tested and a thermodynamic and sensitivity analysis was performed.

EXPERIMENTAL

The species used in this study were: Pacific coast hemlock (PCH), which is a commercial species group consisting of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* (Dougl.) Forb.); Douglas-fir (*Pseudotsuga menziesii* (Poir.) Britton); and western red cedar (*Thuja plicata* Donn). A large variety of lumber dimensions and grades, shown in Table 1, were dried.

The drying experiments were carried out in a 23 m^3 stainless steel commercial RF/V kiln for red oak lumber, approximately 3.7 m wide, 2.8 m high and 8.5 m long. Maximum volume of lumber for a typical kiln charge was approximately 21 m^3. The kiln was built to withstand a complete vacuum inside but the normal operating pressure was never below 20 mm Hg. The heating energy was provided by an RF generator which had a controllable power output up to 260 kW at a frequency of 3 Mhz resulting therefore, to a maximum power density of 11.6 kW/m^3.

The lumber was "solid packed" without stickers, packaged with nylon straps and placed between three horizontal 7.3 m long and 3.5 m wide aluminium plates (electrodes). These electrodes were approximately one-sixth of the electric field wavelength at 3 Mhz, with the intention of eliminating any potential standing waves which could result in "cold" spots. One plate was placed in the middle of the lumber pile whereas the other two were placed at the top and the bottom, respectively. The middle plate had a positive charge, whereas the two outer plates were negatively charged (connected to ground). During operation of the RF generator, the respective plate charges alternated at a frequency of 3,000,000 cycles per second (3 Mhz).

Table 1. Grades and dimensions of lumber dried in the RF/V kiln.

RUN	SPECIES	NUMBER OF PACKAGES	GRADES	LUMBER SIZES (cm)
#1	PCH	8	No. 4 Clear & Better	10.5 x 10.5 x 365
#2	PCH	7	No. 4 Clear & Better	10.5 x 10.5 x 365
		1	No. 4 Clear & Better	15.2 x RW x 365
#3	PCH	2	No. 2 Clear	15.2 x RW x 365
		1	No. 2 Shop & Better	4.8 x 15.2 x 610
		1	No. 2 Shop & Better	4.8 x 15.2 x 365
		1	No. 2 Shop & Better	4.8 x 15.2 x 244
		1	No. 2 Shop & Better	4.8 x 15.2 x 244
		1	No. 2 Shop & Better	4.8 x 15.2 x 365
		1	Factory Flitch	10.8 x RW x 610
#4	DF	1	Merch	7.6 x 20 x 365
		3	Merch	7.6 x 20 x 244
		2	Shop & Better	5.1 x RW x 427
		1	Merch	4.8 x 25.4 x 427
		1	Clear	12.7 x RW x 305
#5	WRC	2	Clear	5.1 x 15.2 x 365
		1	Select Tight Knot	4.4 x 20 x 427
		1	Select Tight Knot	4.4 x 20 x 305
		1	No. 4 Clear & Better	5.1 x 15.2 x 335
		1	No. 2 Clear	5.1 x 15.2 x 366
		1	No. 2 Clear	15.2 x RW x 396
		1	No. 2 Clear	5.1 x 15.2 x 488

RW = Random Widths

The tuning of the RF oscillator was carried out manually since no drying schedules existed for the species under investigation. Initially, a low-level input of energy (30% of maximum power), was applied to the charge in order to heat the lumber. Energy input was steadily increased to 50% of maximum maintaining simultaneously maintaining the oscillation frequency constant. Drying was carried out at a 20 to 25 mm Hg pressure inside the vacuum chamber which was controlled by a vacuum pump connected to the kiln. This pressure had to be increased when the moisture content of the lumber dropped below 20% in order to avoid arcing, a phenomenon that develops with this kiln when the air between the kiln center plate (+ charge) and the kiln wall (- charge) ionizes, thus allowing electrical conduction to occur. The moisture coming out of the lumber in a form of vapor, was put with the help of the vacuum pump through a condensing heat exchanger and then collected in liquid form into a common tank. When the tank was filled to capacity, the water was tested for pH and then flushed to sewage and in this way, the drying rate could be monitored.

Initial and final moisture content distributions within the load were obtained from a random statistical sample and at the end of each drying run, moisture content differences between core and shell; and the amount of casehardening were measured with prongs. The core temperature of some of the boards was monitored during RF/V drying with imbedded alcohol thermometers. RF energy absorbed by the wood and the ambient pressure in the kiln were monitored and recorded in each drying run. Defect assessment by grading of each piece of lumber before and after each drying run was carried out by a licensed grader.

A two step thermodynamic model, that was designed to predict drying times, electrical energy consumption, costs for this type of kiln build in Vancouver, B.C. and monthly kiln throughput was developed on a PC spreadsheet. The first step involved the determination of the work required to evacuate the kiln based on the air properties and the assumption that air is an ideal gas. Then, the energy required to evaporate the total volume of water as a function of species, volume and average initial and final moisture contents was calculated. The total energy was broken down to the total sensible heat load for the water and the wood, the energy required for water vaporisation and the activation energy for bound water diffusion. For simplicity, heat losses (conductive, convective and radiative), from the kiln walls to the surrounding environment, were ignored because the internal and external kiln temperatures are typically very similar. Drying times were calculated based on the RF generator's power output and total operating efficiency. The spreadsheet model demonstrated that it was in good agreement (less than 5%), with all observed experimental results for drying times and energy consumptions.

A sensitivity analysis was performed with the spreadsheet model in order to demonstrate the effect of the experimental errors or estimates of the operating parameters on the energy cost calculations of the RF/V process. Energy costs were calculated on a unit basis (ie; \$/Mfbm), since that takes into account "input parameter effects" of both productivity and total energy consumption. The analysis assumed 90% monthly utilisation rate for of RF/V kiln chamber and a 70% hemlock and 30% amabilis fir species mix in PCH.

RESULTS AND DISCUSSION

The load of the first three initial runs, was made up of Pacific coast hemlock, the fourth of Douglas fir and the fifth of western red cedar. The lumber dimensions and grades in each run are given in Table 1. As it is seen, in Run #1, the hemlock/fir mix ratio was 69%/31% and the average green moisture content was 71%. There were eight lumber packages and the total volume dried was 18.87m^3. The average final moisture content was 8% which was far below the targeted 15% and the total drying time was 70 hours. This "long" drying time occured because the RF oscillator was initially "tuned" for red oak and as a result, the efficiency of the operation was very low (coupled with the non-familiarity of local operators with RF/V drying softwoods). Of the 260 kW used for energy input, only an average of 27% was absorbed by the lumber load. The operating efficiency was considerably improved at the end of the schedule, when the load's average moisture content was below 30%. The maximum absorbed energy per volume of wood was 4.1 kW/m^3, about the same as in a commercial red oak RF/V kiln schedule.

The hemlock/fir mix ratio was 69%/31%, with an average green moisture content of 69% in run #2. The lumber was piled in eight packages (Table 1), with a total volume of 21.5m^3. Drying to the target final moisture content took place in 34 hours. The tuning of the RF generator was considerably more successful compared to Run #1. The average efficiency was 46% and the maximum absorbed energy density in the lumber pile was 6.1 kW/m^3. One of the packages in this run (10.5 x RW x 365 cm), contained end-coated lumber (i.e. "red end-sealed"). During drying, some moisture appeared to be "boiling" out of the ends, not as prevalent though as in nonsealed lumber. Evaluation of the end-sealed lumber after drying, showed little or no moisture loss and substantial surface checking.

Eight packages of a total volume of 21.3 m^3 of PCH a hemlock/fir ratio of 80%/20% and an average green moisture content of approximately 97% were dried in run #3. Final moisture content was 17%, reached in 40 hours. The average operating efficiency was 67.2% which meant that only 33% of the electrical energy was wasted. The maximum absorbed energy was 8.3 kW/m^3 which is considered high. In all three PCH runs, the dried lumber had an excellent surface appearance. It was white, bright with no traces of brown stain and a freshly-sawn appearance and texture. In Runs #1 and #2, end and surface checking was nonexistent. Compression wood had noticeably less defects than what is normally encountered in conventional drying. Some honeycombing was observed in Run #2 which was similar in appearance to that observed in high temperature drying. Approximately 10% of the load though, exhibited an unusual kind of bow. That was most likely caused by casehardening in the longitudinal direction probably due to moisture content differences between the end and the middle parts of the lumber. The total degrade varied in Run #3 with the 10 by 15 by 610 cm pieces showing no checking which became worse though in the 20 cm wide pieces. The 15 cm thick pieces exhibited over-drying (below 6%), which resulted in prevalent checking.

The moisture content differences between the shell and the core of the lumber pieces were found to be of interest in the PCH run #1. The average difference was approximately 3%, although some specimens with wide moisture content discrepancies were detected. In addition, almost half of the specimens had a core moisture content below that of the shell. This phenomenon was also reported by Kanagawa (3), in Douglas fir lumber of 12 cm in thickness. For the PCH runs, the average shrinkage ranged between 5.2 and 6.3% and the value total loss which resulted from the grade analysis between green and dried lumber, ranged between 1.7 and 4.5%.

In Run #4, eight Douglas-fir packages of 21m^3 in volume (Table 1) were dried, from an average green moisture content of 38% to a final 8% in 37 hours. The RF generator's tuning, again posed a problem for the first 15 hours of this run. The energy efficiency operated as high as 67% once the generator was correctly tuned to the species dielectric characteristics, with maximum absorbed energy density of 6.4 kW/m^3 occurring at 22% moisture content. This implies that most of the free water was driven out of the wood cell lumens before substantial energy was applied to the lumber. The alcohol thermometers indicated that the wood temperature was about 11°C higher than that expected for the given vacuum pressure of 33 mm Hg. Wood resin may have been a factor associated with the higher wood temperature. The wood temperature continued to rise to 65°C at the end of the schedule and for this reason, the energy input was substantially reduced.

Evaluation of the dried lumber showed resin exudation from the ends with no apparent effect on the drying process. This was contrary to what was observed in Run #2 with the end-sealed lumber. It was also observed during drying that the exudating resins did not completely cover the cross section of the lumber ends, which is possibly the reason why resinous species still allow water vapor to escape the wood in the longitudinal direction. Lower levels of resin exudation in RF/V compared to commercial kiln drying were also reported by Kanagawa (3).

The final moisture content distributions between the lumber pieces, were extremely tight with literally no deviation around the average value of 8%. The color of the dried lumber was noticeably lighter, with a freshly-sawn strawberry blonde color rather than the deep rust color normally associated with air or kiln dried Douglas fir. No end, surface or internal checking was observed after drying and the casehardening was completely absent. Average width and thickness shrinkage for all packages was 5.8% and 6.3%, respectively.

Eight packages of western red cedar of different sizes and grades were dried in run #5. The total lumber volume was 22.5 m^3 with an average initial green moisture content of 49%. The final moisture content was 8% and was reached after 34 hours of drying. The RF generator operated at an average efficiency of 52%, with the achievement of optimized tuning approximately 7 hours into the schedule and maximum absorbed energy density of 5.6 kW/m^3. Operating pressure was maintained initially at 33 mm Hg raised later to 75 mm Hg thus resulting in wood temperatures of 35°C and 77°C, respectively.

No internal honeycombing was revealed after resawing of the Tight Knot packages, contrary to the Clear graded lumber where almost all pieces had extensive honeycombing even though externally they appeared flawless. The high absorbed energy density by a low permeability species such as cedar during a point in schedule where the Clear lumber was still above the fiber saturation point, could have been the reason for the above defect. Evaluation of the dried lumber revealed a product with freshly-sawn appearance that made it hard to conclude whether the green or dried product had a lighter color.

A summary of the results obtained from the thermodynamic analysis for the five runs is shown in Table 2. The data determined for the test runs which were used as input into the thermodynamic model included: initial and final moisture contents, initial and operating temperatures for the wood, average energy input, lumber volume and average RF generator efficiency. The calculated results were compared to the actual experimental data and the percentage error with the time prediction is listed in Table 2. It can be seen that the predictions of the RF/V kiln operation were very accurate with the exception of Runs #4 and #5 where the drying time estimations were off by 4.7 and 6.7%, respectively. A small air leak that was developed by the kiln after Run #3, resulting in higher operating temperatures (anywhere from 11 to 17°C above ambient), is suspected to be the reason for that discrepancy since radiative and convective heat losses from the drier structure to the ambient surroundings, were not taken into consideration. Monthly kiln dried production estimates from the thermodynamic model were based on an RF/V kiln chamber being utilized 90% of the time.

The results of the sensitivity analysis demonstrated how experimental data errors or estimates of operating parameters can greatly affect the energy cost calculations of the RF/V process, are shown in Figures. 1 to 3. In Figure 1, the percent change in electrical energy cost is plotted against the RF generator efficiency. It is seen that the curve behaved in an exponential fashion, implying drastic increases in unit costs at low generator efficiencies (i.e. a decrease from 65 to 60% efficiency will result in an 8% increase in electrical energy costs.) Initial

Table 2. Summary of RF/V drying runs and model comparisons

VARIABLES	RUN #1 (PCH)	RUN #2 (PCH)	RUN #3 (PCH)	RUN #4 (DF)	RUN #5 (WRC)
Average Energy Input (kW)	227	231	183	145	186
Average Efficiency	27%	46%	67%	57%	52%
Max. Energy Absorbed per m^3 of Green Wood (kW/m^3)	4.4	6.1	8.3	5.2	5.6
Max. Energy Absorbed per m^3 in Schedule (kW/m^3)	6.5	6.1	5.9	6.3	5.7
Actual Drying Times (hrs)	70	34	40	37	34
Predicted Drying Times (hrs)	68.1	35.3	41.0	35.2	31.7
Percent Error in Predicted Drying Time	-2.7%	3.8%	2.5%	-4.7%	-6.7%
Unit Electrical Energy Cost (\$/Mfbm)*	90.31	41.59	39.07	26.42	29.27
Monthly Drying Production (Mfbm)	77	170	145	173	197

*Electrical energy costs were calculated based on regular B.C. Hydro rates for an industrial consumer located at Vancouver.

moisture content was also shown to strongly affect the energy cost (Figure 2). The relationship was linear with a unit cost change of 8% for a 5% change in initial moisture content. Since there was a wide variation in initial moisture content within the green PCH population, the sensitivity analysis reinforces the assertion that complex issues face RF/V drying of PCH and the need to possibly carry out initial moisture content and/or species sorting and sorting for pieces with a high sapwood content.

Figure 3, shows the relationship between energy cost and absorbed energy density. It can be seen that the absorbed energy density, plays a critical role in kiln schedule development. Too large a value will result in lumber degrade as was shown in Runs #3 and #5. If the species of interest require a kiln schedule of lower absorbed energy density in order to avoid internal degrade, the drying process becomes uneconomic. The base case for PCH and DF drying is 4.5 kW/m^3, shown to produce discernable results in Runs #1 and #4. Figure 3, shows that unit electrical energy costs are not overly sensitive to the absorbed energy density. This implies that cutting back on energy input with the intention to reduce or eliminate drying degrade, will not have a substantial impact on unit energy costs. A decrease

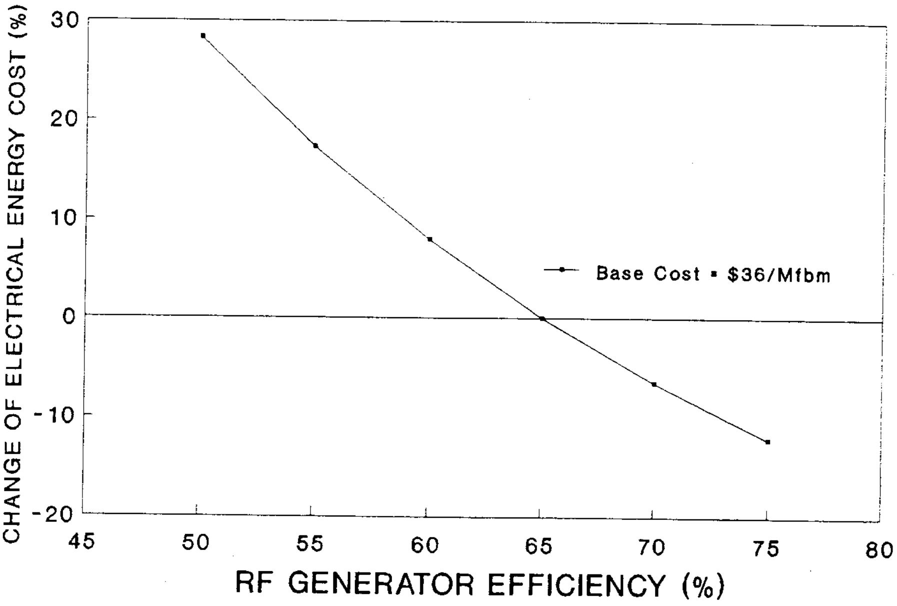

Figure 1. Plot of the change of the electrical energy cost against RF generator efficiency for PCH.

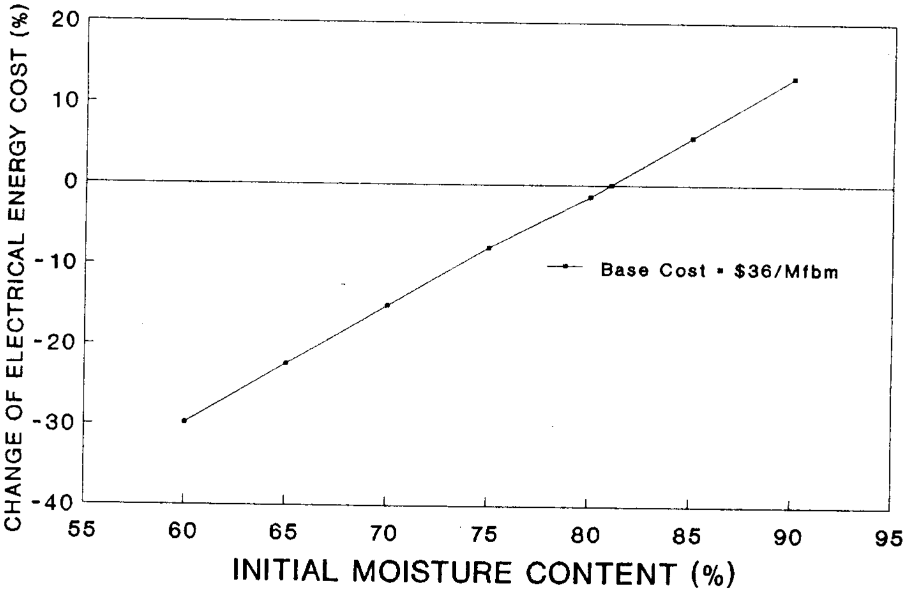

Figure 2. Plot of the change of the electrical energy cost against initial (green) moisture content.

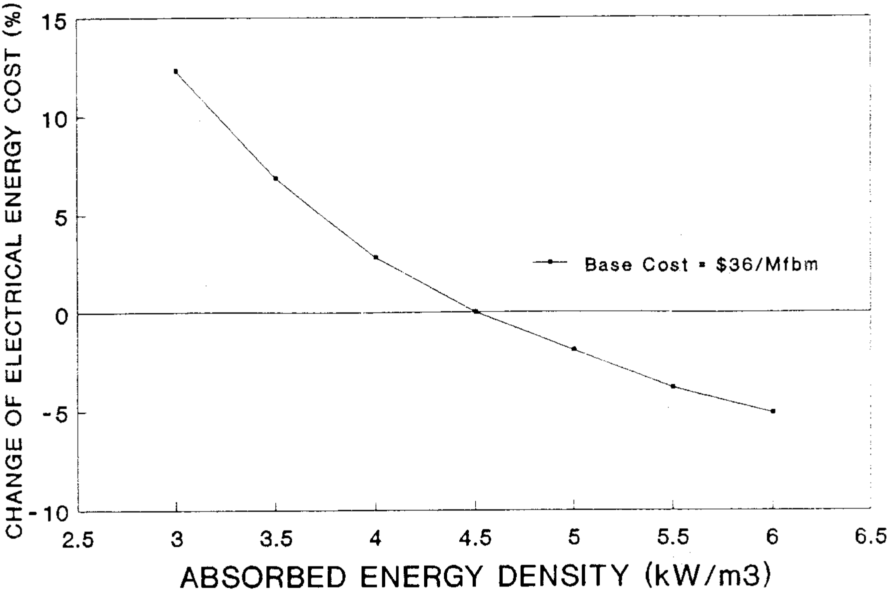

Figure 3. Plot of the change of the electrical energy cost against absorbed energy density.

of absorbed energy input by 22%, will increase unit energy costs by only 7%. However, this relationship is exponential and rapidly increases at values less than 2.5 kW/m^3.

CONCLUSIONS

Radio frequency/vacuum drying of Pacific coast hemlock, Douglas-fir and western red cedar in a commercial size kiln is technically possible and economical, especially when the lumber has a cross-section greater than 8 cm in thickness.

The RF/V kiln trials on Pacific coast hemlock demonstrated that it can provide a product with minimum surface, end and internal checking and case-hardening. The lumber exhibited no discoloration but retains a freshly-sawn appearance and texture. The same surface quality was also observed from Douglas-fir and western red cedar trials.

Minimum resin exudation appeared in Douglas-fir and the dried product quality was flawless even though significant over drying (8%), occurred. Western red cedar exhibited substantial degrade in the Clear grades yet, the Tight Knot product was flawless. The knots were extremely stable and there was very little star-checking. In all runs final moisture content of the core was often lower than that of the shell. It was observed that mixing of thicknesses in the same kiln charge appeared to have a negative effect on the quality of the final product. Thicker boards appeared to dry faster than thin ones.

Thermodynamic and sensitivity analysis showed that drying times can be predicted accurately and that there is a maximum amount of energy that can be absorbed into the wood before internal damage of the lumber occurs particularly when the lumber moisture content is still above the fiber saturation point. Additionally, the sensitivity analysis showed that high financial losses can occur with an improperly tuned RF generator.

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