Vacuum Drying of Wood with Radiative Heating: I. Experimental Procedure

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Experimental results for the vacuum drying of wood with radiative heating are presented. In particular, the temperature and pressure measurements at different locations within the board are provided, as are the overall drying curves. The heat source is such that the temperature at the end of the process remains low (≈150°C), and under these conditions, the drying process resembles convective drying with superheated steam. Further important details concerning the internal transfer mechanisms that are induced by this drying process can be pointed out by comparing results for sapwood and heartwood of different species (Picea abies, Abies alba and Fagus silvatica). These extensive experimental data sets will be used in Part II of this work for the purposes of assessing the accuracy and predictive ability of two different drying models and for analyzing the vacuum drying process further at a fundamental level. © 2004 American Institute of Chemical Engineers *AIChE J,* 50: 97–107, 2004
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Introduction

It is now well known that vacuum drying processes can offer reduced drying times and higher end-product quality in comparison with conventional drying operations (Ressel, 1994). Indeed, operating at low pressures reduces the boiling point of water, and such a reduction enables an important overpressure to be generated and maintained within the product throughout drying. More specifically, the only way to take advantage of a significant internal pressure for species that do not support a high temperature level, where collapse and discoloration can arise, is to use a reduced external pressure. This is why the vacuum drying of wood is a research area that is currently receiving significant worldwide attention, especially for high-quality hardwoods that are difficult to dry conventionally, such as oak (Joyet and Meunier, 1996; Resch and Gaustch, 2001) and Australian eucalyptus (Rozsa and Avramindis, 1996; Tran and Rozsa, 1999).

The effect of reducing the external pressure during drying on the transfer phenomena evolving within the porous medium is quite a complex process (Bird et al., 1960; Masson and Malinauskas, 1983; Froment and Bischoff, 1990; Incropera and De Witt, 1990; Perré et al., 1995). In particular, the following two main phenomena have to be noted:

- Increased internal transfers due to the elevated total gaseous pressure gradients within the board; and
- Lowered external exchanges, especially for the heat supplied to the material by the convective flow.

Some lesser known mechanisms can also be reported, for example, the reduction of external transfer is not due to the decrease of thermal conductivity (which, in fact, remains constant), but is due to the effect of pressure on density, and hence on volumetric heat capacity. The main effects of pressure on internal transfer, as free-molecule diffusion and slip flow, are

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Table 1. Typical Values of Samples Used in this Study

Sample	Dry Mass (g)	Initial Moisture Content (%)
Spruce (sapwood)	591	102
Spruce (heartwood)	510	48
Fir (sapwood)	662	160
Fir (heartwood)	611	84
Beech (sapwood)	936	82
Beech (heartwood)	906	79

also physical mechanisms that are worth noting and should be studied further.

The positive impact of the internal pressure gradient within the sample is the primary motivation for vacuum drying. In this case, a reduction of external pressure allows high temperature conditions to be attained for species that do not usually accept high temperature levels. Nevertheless, the difficulty induced by the low pressure on the external energy transfer still remains the problem to be solved and, as a means to overcome this problem, conventional vacuum dryers use a discontinuous process (phases of vacuum drying alternated with phases of convective heating under atmospheric pressure) or drying under vacuum with heated plates positioned between boards (Joly and More Chevalier, 1980). More recently, other strategies have been proposed to supply energy to the product, for example:

- High-vacuum drying, where the pressure level and the gas velocity are higher than in a conventional vacuum dryer, which allows the stack to be heated by convective exchange (Joyet and Meunier, 1996); and
- Radio-frequency heating, which is optimal in terms of process control, delivers the pressure level and the heat supplied to the load independently (Avramidis, 1999).

It should be noted that vacuum dryers have been commercially available for many years and their use is regarded as standard practice in Europe for the economical drying of high-quality hardwoods that otherwise would be difficult to dry (Hilderbrand, 1989). The interested reader can find general descriptions of the industrial vacuum drying process in Ressel (1994), Audebet and Temmar (1997), and Jomaa and Baixeras (1997). All of these authors highlight that due to the enhanced internal moisture migration under vacuum, the rate of drying can be as rapid as that observed for a much higher temperature at atmospheric pressure; however, the higher specific volume of vapor associated with the reduced pressure is a severe limitation for heat transport by convection (see Perré et al. 1995 for further discussion on this issue).

Several industrial solutions have been proposed to overcome this limitation:

- *Continuously operating kilns* that use heated plates. These plates, heated by electrical resistance or circulation of hot water, are placed between each layer of the boards and the heat is supplied by conduction, whereas the vacuum level is used to enhance the internal mass transfers;
- *Discontinuously operating kilns,* where a heating period at atmospheric pressure after about an hour alternates with a drying period at reduced pressure;
- Finally, the most recent *"high-vac" kilns* use a slightly higher pressure level (more than 100 mbar), together with a very high linear air velocity (10 m/s or more), to compensate for the loss of thermal capacity of the air; this method has proved to be very effective.

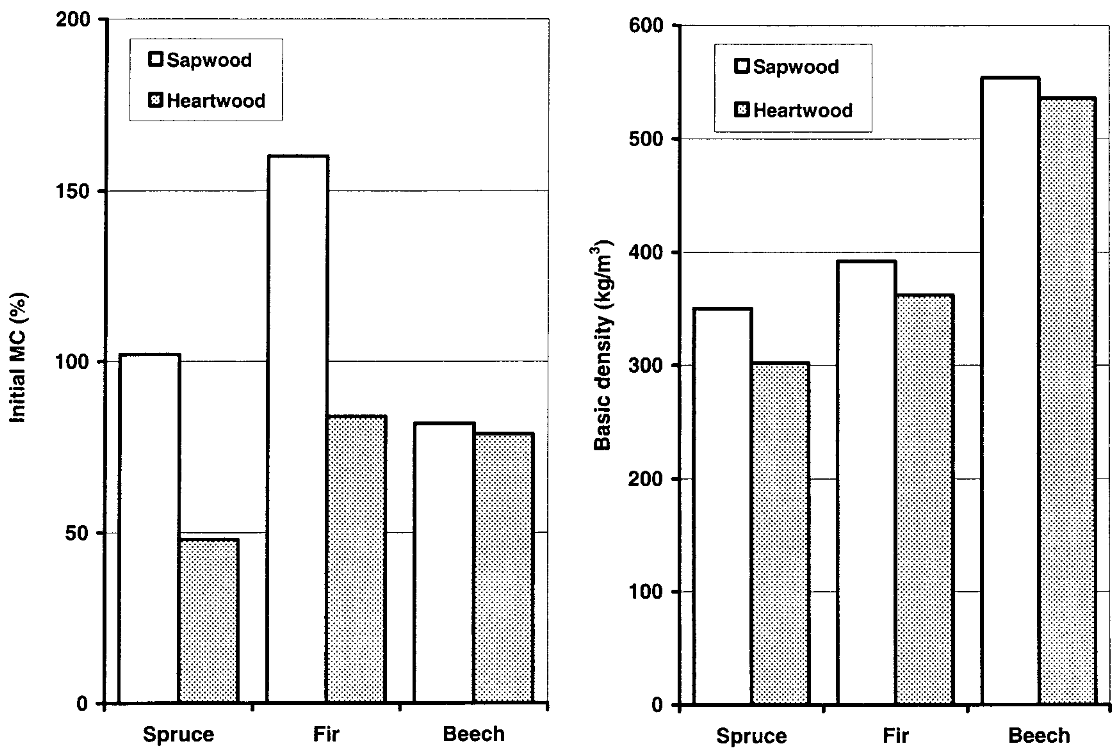

Figure 1. Typical values of initial moisture content and basic density of the boards dried in this study.

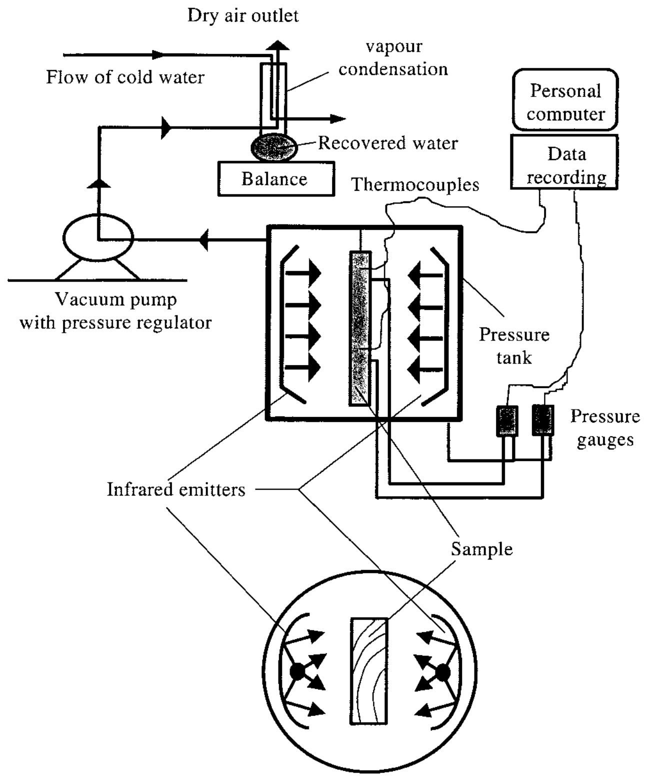

Figure 2. The experimental device.

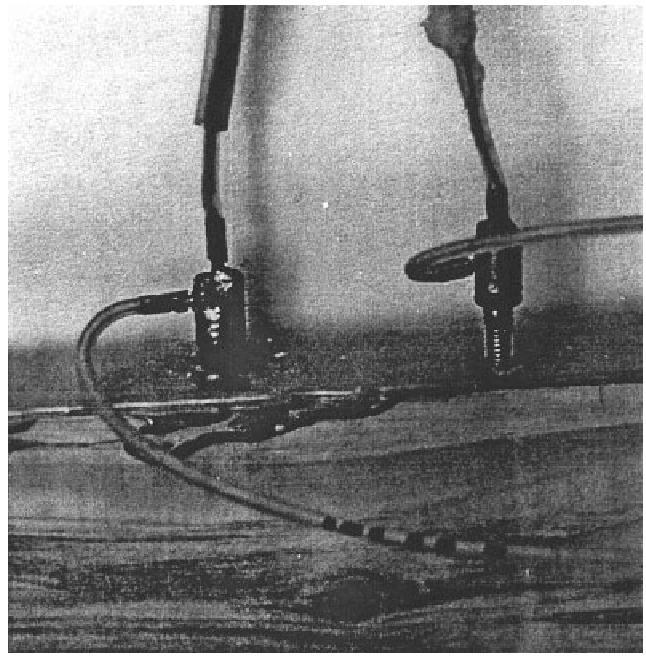

Figure 3. Two sensors placed in the board: note the thread that allows the sensor O-ring to be tidily pressed on the resin coat.

The work proposed here concerns vacuum drying with radiative heating. This method of supplying energy to the product is very commonly used in the paper industry, but seldom used for wood drying. This is due to the geometry of the stacks, which are not readily adapted to this type of heating. However, radiative devices arranged between layers of boards would offer better performance when compared with heated plates. In particular, contrary to heated plates, it would be possible to design the radiative devices in such a way that the path for the moisture remains free at the surface of the boards.

The configuration used in our laboratory experiment allows one single board to be tested at a time. Indeed, as stated earlier, the transfer of knowledge gained by the experimental study undertaken here can be disseminated directly to industry. In particular:

- In the case of continuously operating vacuum kilns, the possibility of supplying energy with radiative emitters instead of heated plates would allow the heat and mass transfer on the main faces of the board to be maintained by convective exchange, which would be a significant improvement to continuous vacuum kilns. Furthermore, the external convective exchange allows the moisture not only to be evacuated from the main faces of the board, but also allows the surface moisture content and temperature to be better controlled, which is of utmost importance for the quality of the dried lumber.
- Innovative on-line kilns with softwood pieces of moderate thickness: these kilns, similar to veneer kilns, can be specially designed. In this case, the radiative heating can be an alternative to microwave heating (Antti and Perré, 1999), where the energy usage is expensive.

In our experimental device, the board under investigation was placed in a pressure tank between two IR emitters with reflectors, where far IR radiation (temperature close to 600 K) was obtained by supplying classic quartz tubes with low voltage. This low temperature of radiation was necessary to have good control over the process by ensuring a significant reduction in supplied power when the surface temperature increased.

The main contribution of Part I of this work is the presentation of extensive experimental data sets for the sapwood and heartwood boards of *Picea abies, Abies alba,* and *Fagus silvatica.* To the knowledge of the authors, such detailed experimental results have not been documented previously in the literature. The innovative part of these experiments is the measurement of internal pressure at different locations within the board. With the aid of other available data (temperatures and drying curve), the latter piece of information is of great

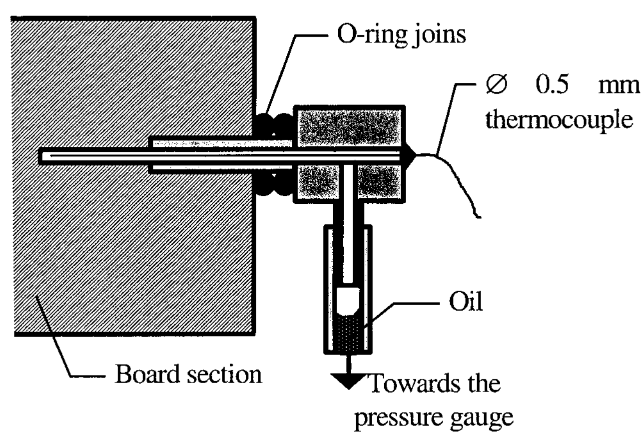

Figure 4. The pressure-temperature sensor.

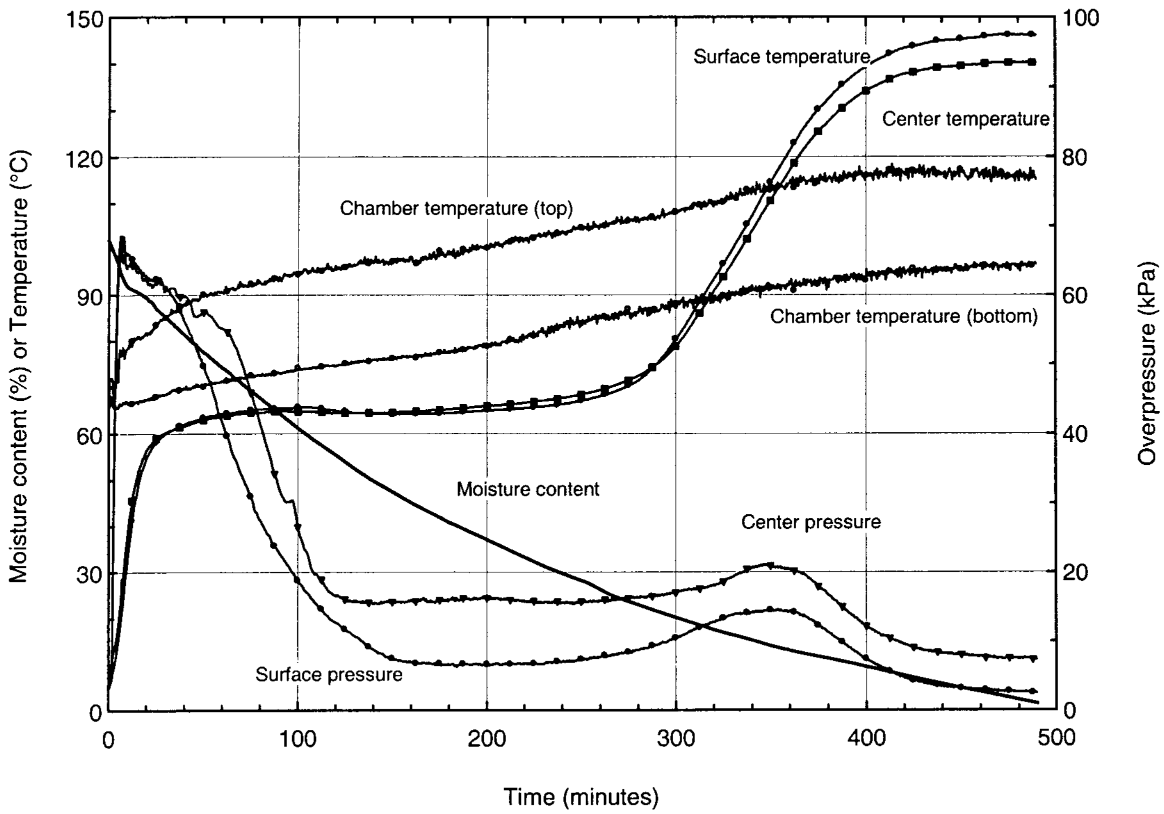

Figure 5. Radiative-vacuum drying of spruce (*Picea abies*), sapwood; Pchamber = 200 mbar (test No. 3).

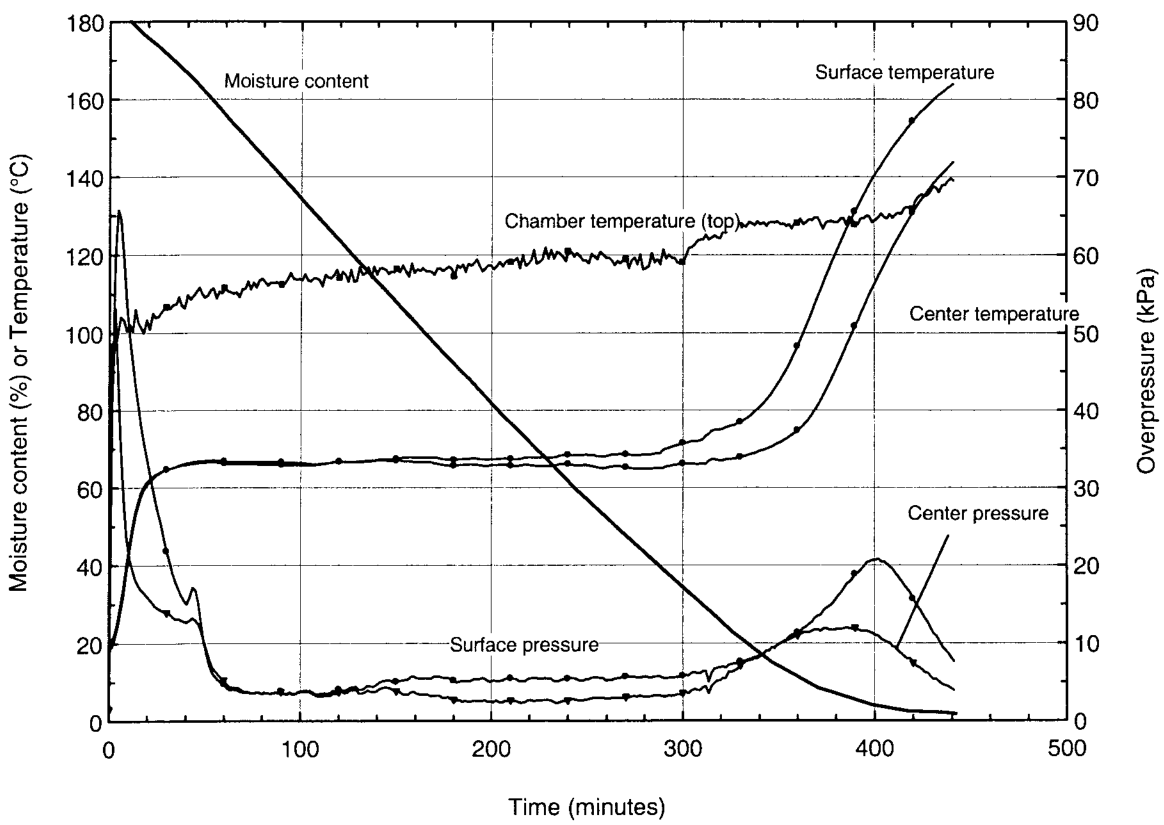

Figure 6. Radiative-vacuum drying of fir (*Abies alba*), sapwood; Pchamber = 200 mbar (test No. 14).

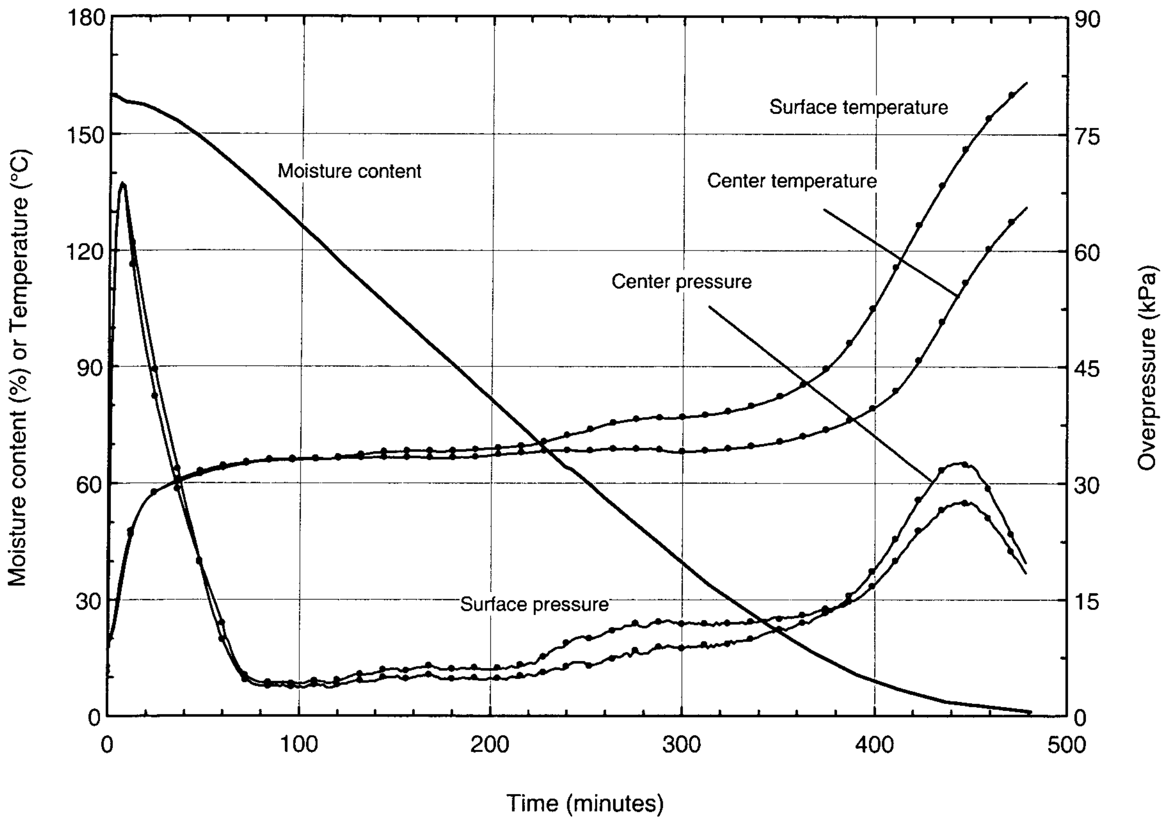

Figure 7. Radiative-vacuum drying of fir (*Abies alba*), sapwood; Pchamber = 200 mbar (test No. 15).

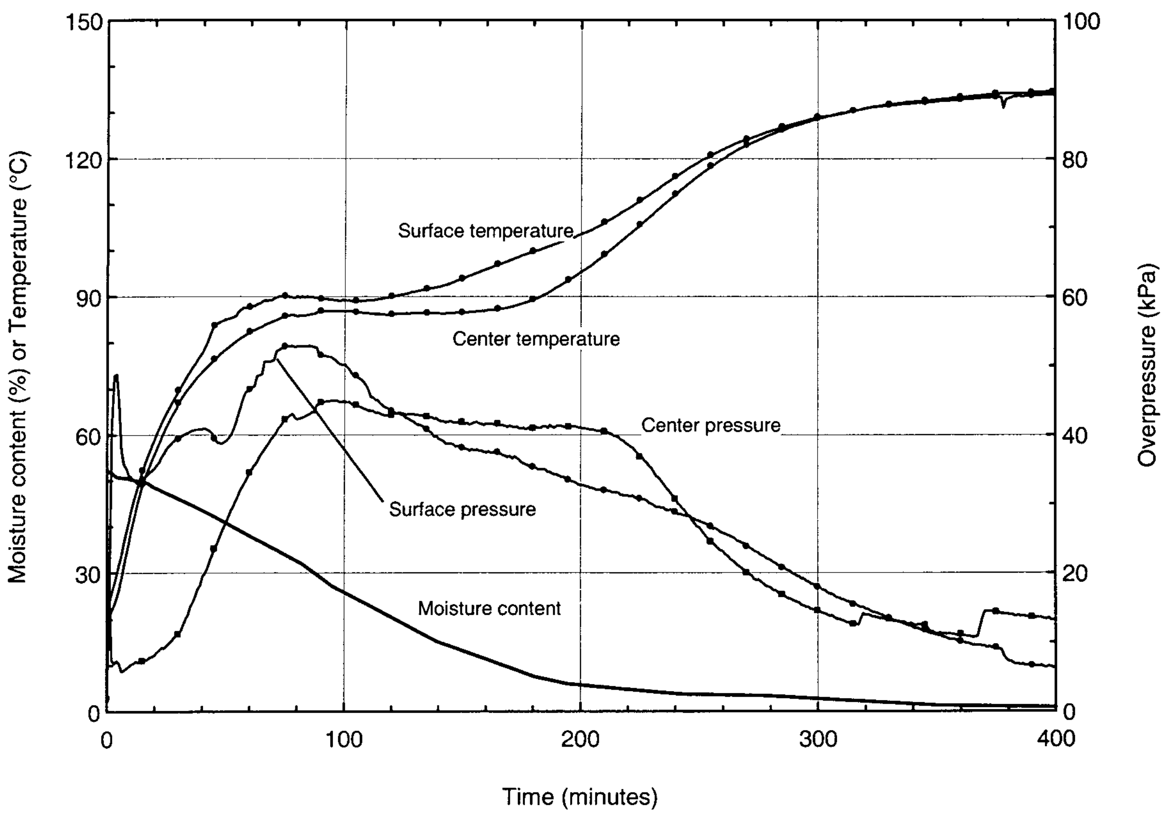

Figure 8. Radiative-vacuum drying of spruce (*Picea abies*), heartwood; Pchamber = 200 mbar (test No. 6).

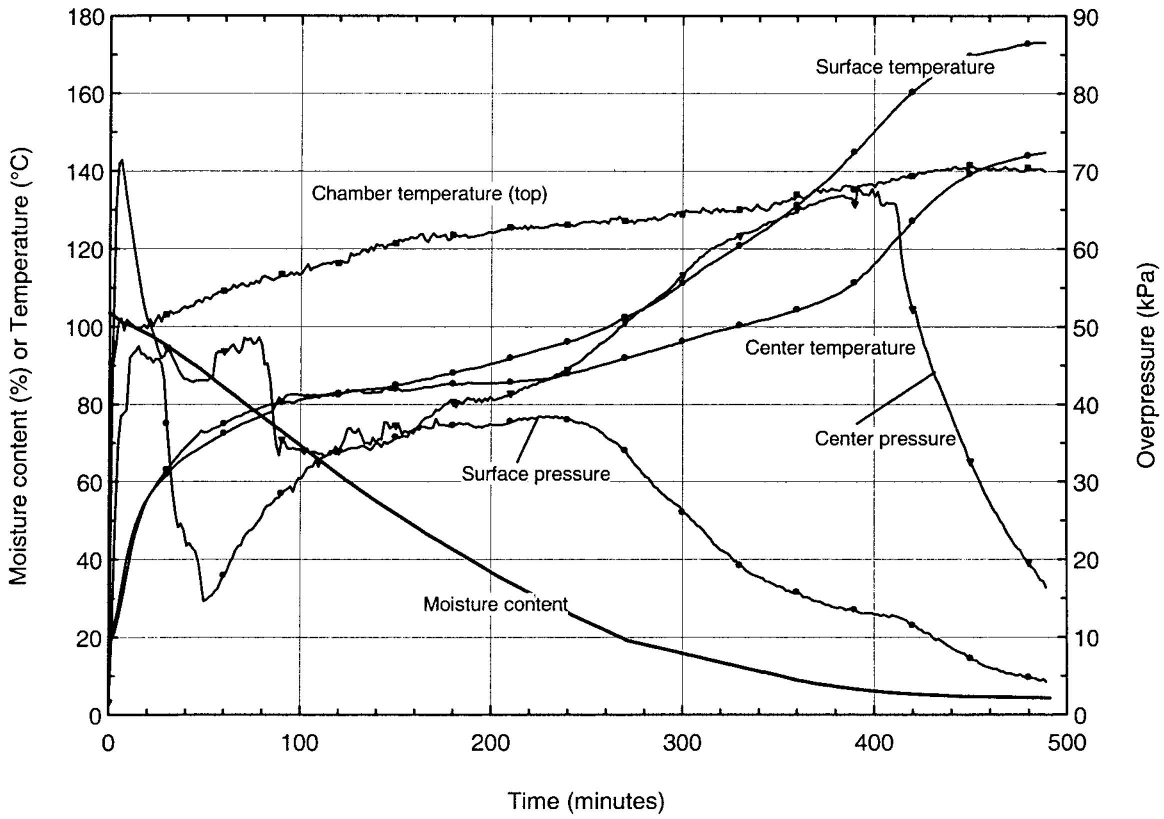

Figure 9. Radiative-vacuum drying of fir (*Abies alba*), heartwood; Pchamber = 200 mbar (test No. 13).

interest for understanding the internal transfer mechanisms arising during the vacuum drying process. Several tests have been carried out on different species and different parts of the log (heartwood and sapwood). These experimental data will be used in Part II to analyze the possibilities offered by two different simulation models.

Wood Specimens

Different species of tree have been used for this study: spruce (*Picea abies*), fir (*Abies alba*), and beech (*Fagus silvatica*). All of the boards ($450 \times 150 \times 25$ mm^3 in L, T, and R directions) were sawn from freshly cut trees. For this study, only one tree has been cut per specie. Flat-sawn boards were chosen intentionally in order to obtain samples consisting almost entirely of sapwood or heartwood. Among the fifteen drying tests performed with the experimental device, only typical results are presented in this article. As previously stated, the main differences in the drying behavior are expected to be found among the species and for boards cut from different positions within the same log. The first evidence of these differences can be observed from Table 1 and Figure 1, which depict representative values of the dry mass and the initial moisture content (MC) measured for the boards. The basic density (oven-dry mass divided by green volume) has been calculated from the dry mass and the green dimensions. Note that the boards have been planed before the drying test to ensure a good geometrical shape in green conditions.

From these values, it should be noted that the basic density is very low for spruce and remains low for fir. Beech, a dense hardwood, exhibits a much higher density. Concerning initial moisture content, one has to note the big difference encountered in softwood species between sapwood and heartwood. Beech appears to be much more even in initial moisture content through the log radius. Typically, heartwood has a lower density because of juvenile wood and the high growth rate in young trees. A low density in the spruce samples was evident because that tree remained cut for a while in the forest before the drying tests were performed.

Experimental Device

The boards were placed in a pressure tank between two IR emitters with reflectors (Figure 2). Far IR radiation (temperature close to 600 K) was obtained by supplying classic quartz tubes with a low voltage. This low temperature of radiation was necessary to have a good control of the process, offering a significant reduction in supplied power when the surface temperature increases. The board was placed vertically in the chamber. The radiative emitters were also placed vertically, and the thermocouples were inserted in the board at different thicknesses, but always very close to midlength, hence, at midheight within the chamber.

A membrane vacuum pump, with moving parts made of Teflon, that is able to pump full water vapor was used during the experiments. This configuration allowed the water at the outlet of the pump to be condensed, thus enabling almost all the moisture removed from the board to be collected and weighed. By taking some precautions, including heating of the tank walls to avoid condensation, it was possible to recover on balance

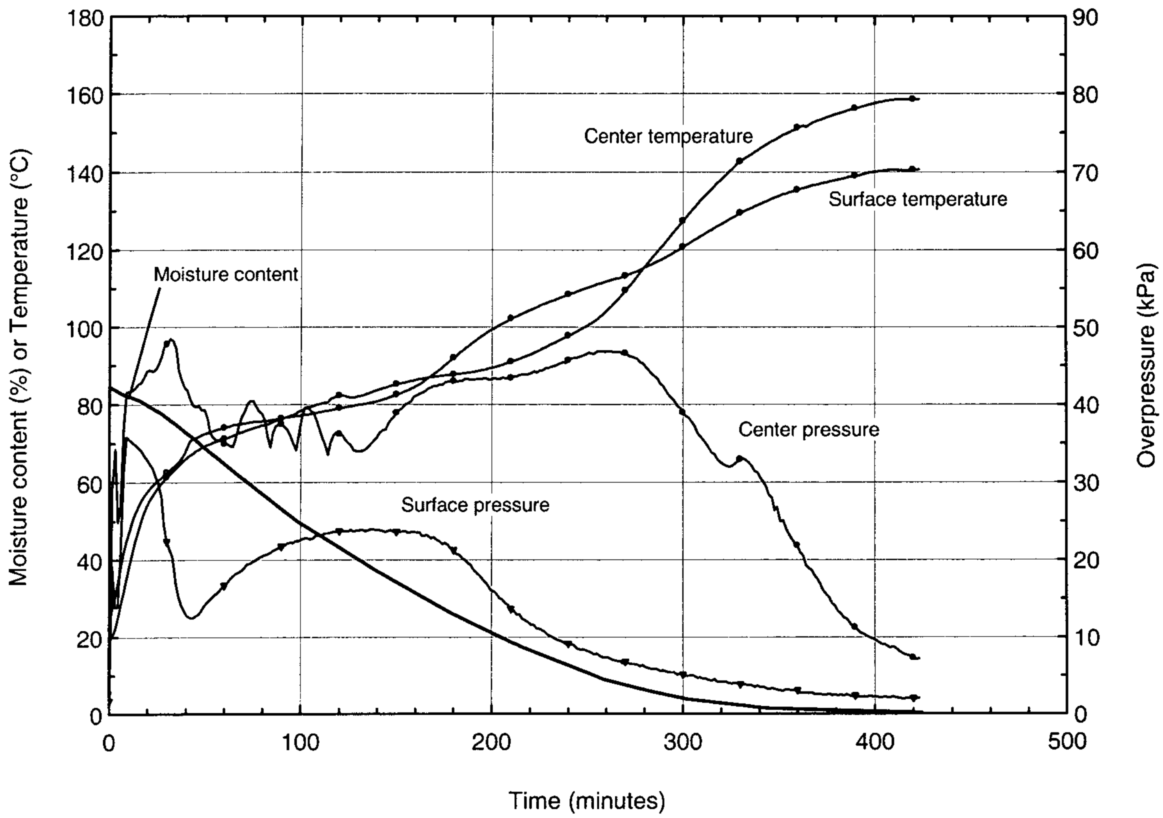

Figure 10. Radiative-vacuum drying of fir (*Abies alba*), heartwood; Pchamber = 200 mbar (test No. 12).

more than 90% of the weight loss of the board. Note that the whole condenser is put on balance, so that water is detected as soon as the vapor appears, without the necessity of waiting for the liquid to flow into the receptacle.

Some results are available in the literature concerning the measurement of internal pressure during drying with internal temperature (Lowery, 1979; Basilico and Martin, 1984; Kamke and Casey, 1988). However, very few results are available with simultaneous measurement of both temperature and pressure at the same location. In the present study, the pressure and temperature measurements use a new version of the sensor developed for convective drying at high temperature (Perré et al., 1993). Pressure and temperature still are measured at the same location, but the addition of a thread and two O-rings sealed against the epoxy resin (Figures 3 and 4) ensures a better airtightness throughout the process. On the other hand, these new sensors are larger (4 mm in diameter instead of 1.1 mm) than the original design and induce more perturbations. In particular, it is no longer possible to put several sensors along the board thickness in the same section. Here two locations were studied, both near the half-length of the board: one at the center (half-thickness) and the other, called "surface," as close as possible to the exchange surface (≈4–5 mm). The connections of the pressure gauge are such that the difference in pressure between the board and the surrounding gas (Figure 2) is measured. In order to reduce the air volume and, above all, to avoid condensation in the pressure gauges, the tubes are filled with oil, from very near to the plank up to the pressure gauge, situated outside the vacuum chamber. Most tests have been performed at a surrounding pressure of 20 kPa (≈ 0.2 P_{atm}). This level reduces the boiling point of water to approximately 60°C. Only one test is presented here at 40 kPa (Beech, test No. 10).

Experimental Results

For all tests, internal pressure values increase rapidly at the beginning of drying due to the pump, which requires 5 to 10 min to reach the required pressure level. In addition, the measurement system is such that the pressure difference (internal pressure minus chamber pressure) is the measured parameter. Consequently, the internal pressure values increase quickly during this period. After this transient period, internal transfer governs the variations and important differences can be observed. Several tests have been chosen to highlight these differences. Some duplicate examples are also presented in order to show how far these observed trends are reproducible.

Figure 5 depicts typical results of a test performed on spruce sapwood. During the first 20 min, the board temperature increases up to the boiling point of water (60°C at 200 mbar), and thereafter a very long plateau can be observed at this temperature. After its fast and large increase, the pressure difference decreases slowly during the period at constant temperature. This phenomenon should be interpreted as a slow departure of the air from the gaseous phase present within the medium. A pressure level that is low and almost constant marks the end of the constant temperature period. Then, due to the surface of the board entering the hygroscopic range, the temperature increases and produces an increase in the internal pressure. The

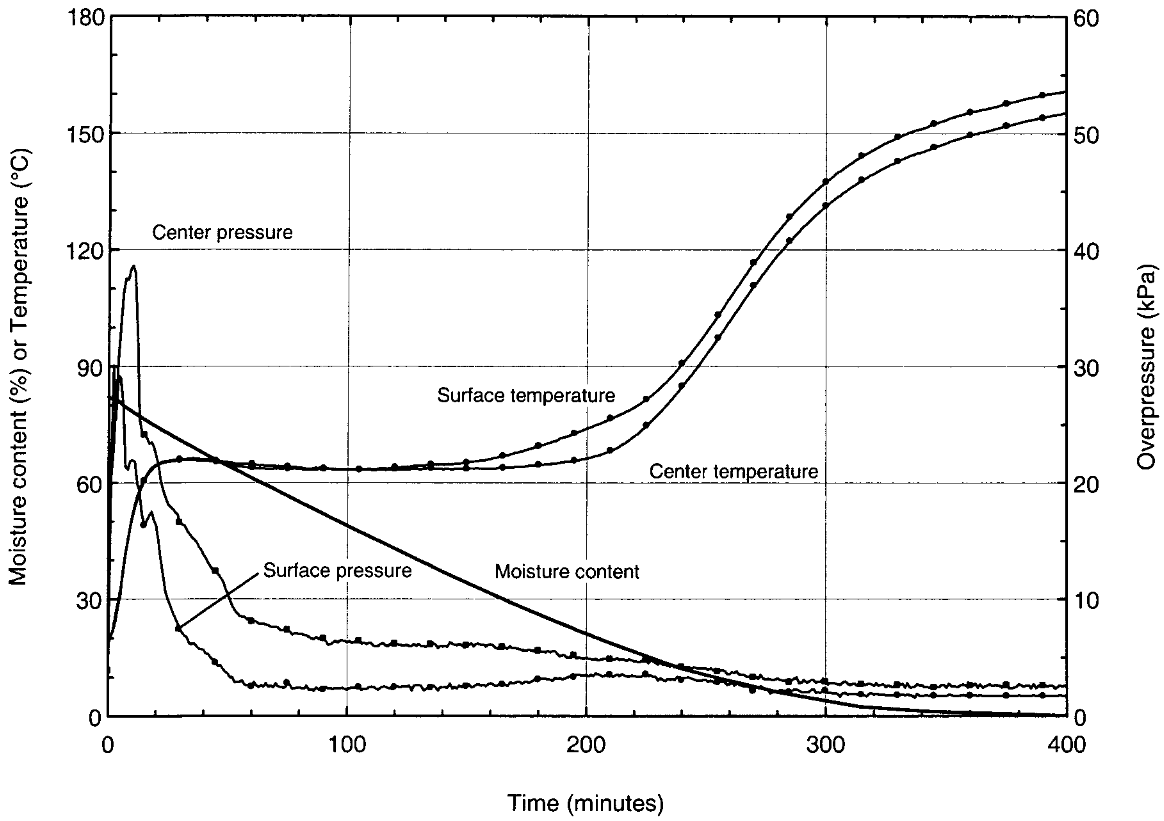

Figure 11. Radiative-vacuum drying of beech (*Fagus sylvatica*), sapwood; Pchamber = 200 mbar (test No. 7).

"surface" pressure rises first and the center value follows very quickly thereafter, with a slightly higher value. All of these phenomena were encountered for convective drying at high temperature and have been reported in previous research work (Perré et al., 1993; Perré and Martin, 1994).

The drying curve depicts an almost constant drying rate up to 140 min, after which the drying slows to 300 min, and then becomes faster after that. This observation indicates that the plateau at the boiling temperature can be divided into two distinct periods:

- A constant drying rate period, with free water available at the board surface
- A decreasing drying period, once free water no longer exists at the surface. During this second period, the board temperature appears to remain at the boiling point. This may be for two reasons. First, what is called "surface temperature" is in fact some millimeters below the surface (typically 4 mm), and second, as long as the dried layer below the surface remains small enough, the temperature increase required to achieve the drying rate flux due to Darcy's flow of vapor is negligible.

For each experiment, two temperature values are collected in the chamber (at the top and bottom sections). The corresponding curves allow the chamber thermal balance to be approximately analyzed. Both the thermal capacity of the entire chamber (container + load) and the thermal flux required to dry the board, which decreases in time, combine to explain the slight increase in the chamber temperature during the test. Obviously, the difference between the upper and lower temperature values is due to natural convection.

Although the sapwood part of the fir tree has a higher initial moisture content value, all of the trends observed for spruce are similar to those observed for fir in Figure 6. The pressure increase at the beginning of drying is very quickly followed by a fast and regular decrease in pressure, which can be the cumulative effect of the higher initial moisture content (less gaseous volume) and the higher value of permeability. For this test, the temperature curves clearly separate the constant temperature period into two parts, one during which the temperature seems to be uniform within the thickness, (while the other exhibits a slight difference between the center and surface, the latter being higher. The real first drying period (where free water is available at the surface) certainly ends somewhere between these two parts. At the end of this "constant temperature" period, the overpressure peak has the same order of magnitude as was evident in Figure 5 (around 20 kPa). Test 15 (Figure 7) has been chosen to highlight how close the experimental results for two different boards can be. By comparing Figures 6 and 7, it is clear that almost no difference can be observed, other than a slightly higher overpressure for test 15 during the second part of the period at constant temperature. This degree of similarity has to be noted as being observed on a material that is often described as being highly variable. The conclusion here is that a careful selection of samples can lead to reproducible results.

Numerous published works have already proven that heartwood behavior during drying is very different from that of sapwood, at least for softwood, mainly because of the existence of bordered pits. It is well known that the heartwood part of softwood has a lower initial MC and, due to bordered pit aspiration and the presence of extractives, has a much lower

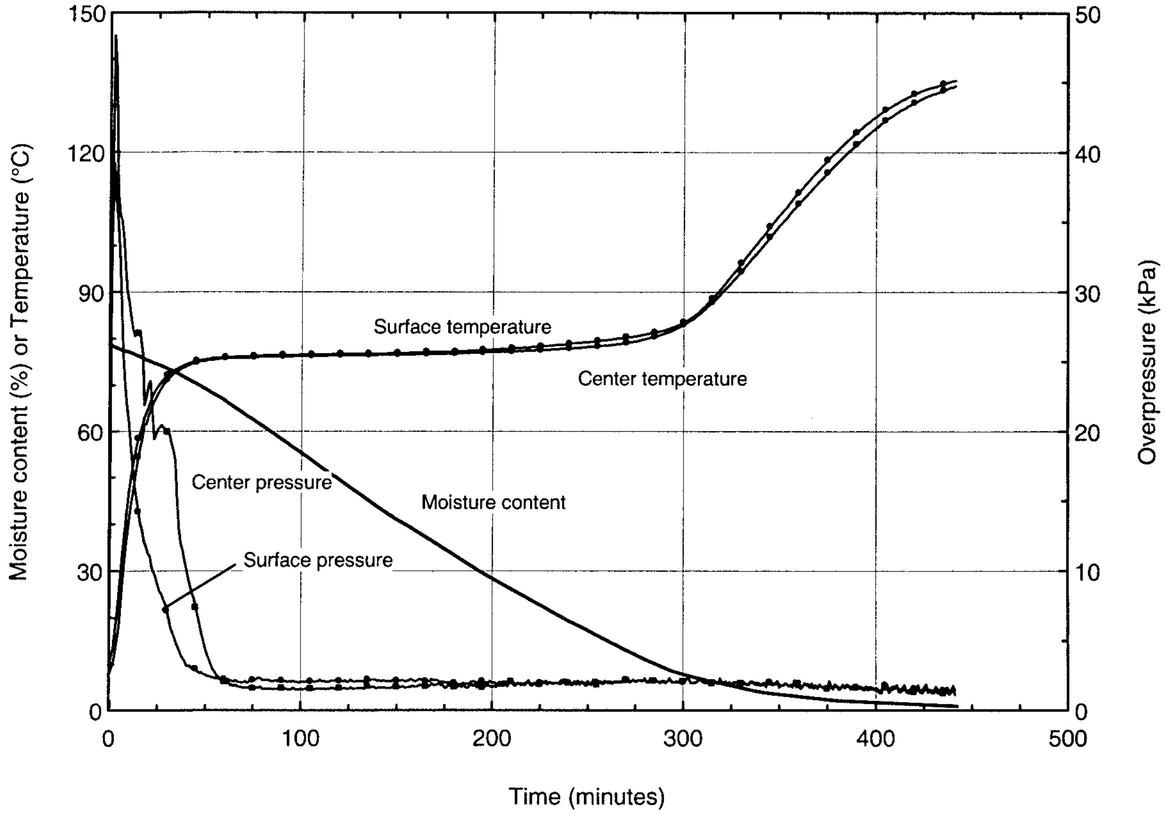

Figure 12. Radiative-vacuum drying of beech (*Fagus sylvatica*), heartwood; Pchamber = 400 mbar (test No. 10).

permeability value. These features explain the results depicted in Figures 8 and 9. These figures show two tests, performed on heartwood boards, for spruce and fir, respectively. Clearly, no first drying period is observed here, temperature increase at the beginning of drying lasts for a long time, and the temperature curves exhibit a quite stable value at around 90°C, which is much higher than the boiling point of water. Due to the low permeability values, together with this large increase in temperature, the overpressure value remains important throughout the entire process. Because the radiant flux is to a large extent determined by external conditions rather than the temperature of the exchange surface, the heat supplied to the board is not much lower than the heat supplied in the case of sapwood. Contrary to classic convective drying, where the drying time is about the same for sapwood as for heartwood (Salin 1989, Perré and Martin 1994), for this configuration of vacuum drying with radiative heating the drying time is shorter for heartwood.

In the case of heartwood, the air migration is very limited due to the low permeability values. Consequently, the values of internal pressure result mainly from the effect of temperature on the air and vapor partial pressures rather than on the effect of gaseous migration. This implies that measurement during drying requires very airtight pressure sensors, and several precautions have been taken for the implementation of these pressure sensors. In addition, it is well known that surface checking occurs during drying. All of these factors can explain why the pressure curves are so erratic, especially during the first two or three hours of drying. However, the observation of a test performed on another heartwood board under the same conditions proves that these variations are, to a large extent, also observed. Note, for example, the same shape of the "surface" pressure variations.

For test No. 12 (Figure 10), note the crossing of the surface and center temperature values at 160 and 280 min. It is very difficult to explain such variations in a homogeneous porous medium with uniform initial moisture content. Only a complex coupling between a nonuniform initial moisture content and nonuniform transfer parameters through the transverse direction would be able to explain this phenomenon.

Tests 7 and 10 concern beech, a sapwood board dried at 200 mbar (Figure 11) and a heartwood board dried at 400 mbar (Figure 12). Beech, which is a diffuse-porous hardwood specie, is well known to be highly permeable. In addition, no thyloses is observed for beech, and the initial moisture content is about the same along the radial direction (see Table 1). All together this implies that there is no significant difference between sapwood and heartwood, which has been confirmed on all tests performed on beech. Compared to the previous species (spruce and fir), a very long first drying phase, a fast decrease in the overpressure after the initial transient period, and almost no overpressure during the second drying period are observed for the beech tests. Comparing the results from tests 7 and 10, it is clear that the effect of board position within the log is not significant. The second difference lies in the chamber pressure level. Using 400 mbar instead of 200 mbar increases the boiling point up to 80°C and the drying process is slightly slower.

In order to have another viewpoint of these different drying behaviors, four IDC identity drying cards (IDC; Perrés, 1994)

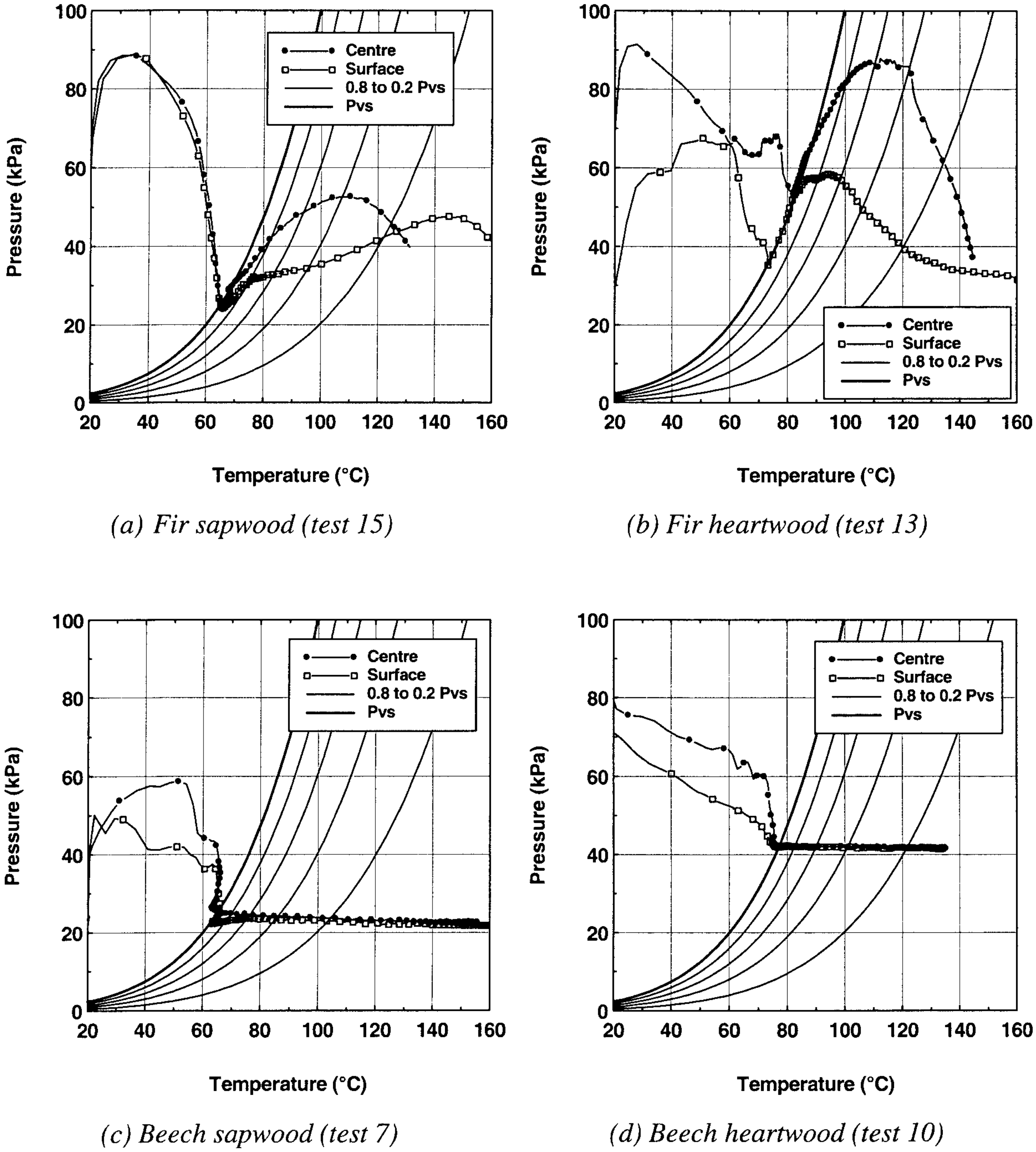

Figure 13. Examples of IDC obtained for vacuum drying with radiative heating. (a) Fir sapwood (test 15); (b) Fir heartwood (test 13); (c) Beech sapwood (test 7); (d) Beech heartwood (test 10).

obtained for fir and beech (Figure 13) are proposed. The IDC consists of plotting, in the temperature-pressure graph, the route of certain points of the product, and to compare this path with the saturated vapor curve. On each curve, markers are drawn at constant drying-time increments, which is a means of recovering the time scale that disappears when this coordinate system is used. Both the center and surface positions are plotted here. In this way, one can see the presence (or absence) of the first drying period (accumulative point at the wet-bulb temperature), the amount of dry air (difference between the curve and the saturated vapor curve), and the differences in permeability between sap- and heartwood (observe the overpressure during the second drying phase, keeping in mind that the heat flux and, therefore, the vapor flux, are almost the same).

Compared to these reference configurations, it is interesting to note that:

- Although differences are not so high between sapwood and heartwood for beech, the sapwood board of this species dries faster, with a plateau at a temperature closer to the boiling point.
- In terms of temperature and pressure, fir and spruce are quite similar for both sapwood and heartwood. Note that the initial moisture content was low for spruce: for this log, sawing

and drying occurred some weeks after the tree was cut (compared to some days for the others).

Conclusion

The experimental results of vacuum drying with radiative heating, which included internal pressure, internal temperature, and drying kinetic measurements, have been presented here for different softwood species. Important variations in the drying behavior have been pointed out for the different species and between sapwood and heartwood of the same specie. All of the reported tests, performed on different species, different parts of the tree, and under different drying conditions (pressure effect) have been useful for furthering the understanding of this drying process and for the purposes of modeling this drying process. This information, together with the recording of the condensation on the chamber walls, and the mass and energy balances arising within the vacuum chamber, provides a valuable source of reference information on vacuum drying of softwood.

In Part II of this work, the relationship between drying behavior and some physical parameters (permeability values and initial moisture content) will be studied using both a comprehensive global drying model that accounts for the complete coupling between the board and chamber, and a semianalytical model that uses several assumptions to arrive at a simplified model that still can capture the overall trends of the vacuum drying process.

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