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Tracking and Simulation of Dry Shell Formation in a Wood Drying Process by X-ray Spectroscopy

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Abstract

In this research, dry shell formation and receding of evaporation front through the thickness of beech and spruce boards were investigated during drying, using x-ray spectroscopy. Four surfaces of the boards were coated by epoxy resin to limit moisture flux just through the board thickness. The boards were dried with a convectional drying method under the temperature of 60°C and relative humidity of 70%. The scanning process performed every hour during drying until the dry shell reached the core layer of the boards. The results revealed that the dry shell was formed faster in the beech board in comparison with the spruce one; however, in spruce board it reached the core layer faster. In addition, the dry shell formation pattern was found to be different between the boards and as a result of faster bulk flow of free water a steady-state condition was observed during the early stage of drying of the spruce board. In general, it can be concluded that the controlling factor in the dry shell development to the core layer is water vapor diffusion coefficient of the boards rather than their permeability.

Key words: Dry shell, X-ray spectroscopy, Bulk flow, Diffusion coefficient

Introduction

Dry shell is a thin layer (1 mm and less in thickness), with lower moisture content than Fiber Saturation Point (FSP), that forms immediately after the beginning of drying process near the wood surface due to evaporation front receding (Keey et al. 2000). Bulk flow of free water has stopped in this layer and only moisture transition process performs with bond water and water vapor mechanism, while under the layer, bulk flow of free water is present (Fig. 1).

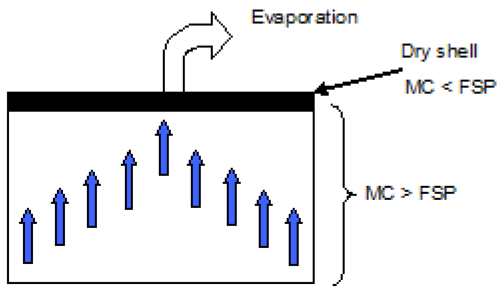

Fig. 1. Scheme of dry shell formation in board during drying.

The importance of studying the dry shell formation in a wood drying process is listed bellow:

1. Modeling and analysis of free water bulk flow and water vapor diffusion above the FSP range
2. Modeling of heat transfer process within the wood in free water phase
3. The Determination of time for dry shell to reach the core layer and therefore opportune substitution of the kiln dry bulb temperature according to drying schedule to prevent wood from drying defects, specially honey combing (internal checks)

Research on dry shell formation in wood drying process is almost a new subject in this field. In fact, since the non-destructive technique such as x-ray spectroscopy was used instead of destructive methods like slicing to survey the moisture gradient in boards during drying, the study on receding of evaporation front and dry shell formation was started. Due to the necessity of installation for these non-destructive equipments, operating in a wood drying kiln and other limitations because of high investments, a few researches have been done on dry shell formation phenomenon in the world (Remond et al. 2005, Rosenkilde et al. 2004, Wiberg 2000). According to Remond et al. (2005) results, one of the reasons for formation of the reverse pattern of temperature gradient in the board thickness during drying is the dry shell formation on its surface that acts as an insulation layer. Because of free water confinement in this layer, the temperature in core layer grows up toward surface temperature. Thermal conductivity of wood is also an effective factor to form this layer. Receding of dry shell through the thickness of boards can be studied using non-destructive methods during drying. Rosenkilde et al. (2004), Rosenkilde and Glover (2004) by using of magnetic resonance imaging showed that the dry shell form on the wood surface and this layer control the drying speed until that the average moisture of wood decline to FSP. Wiberg et al. (2000) and Wiberg and Moren (1999) by using X-ray CT scanning studied the receding of dry shell in the three species of *Pinus sylvatica*, *Picea abies* and *Betula pubescens* under the dry temperatures of 50, 60, 70 and 80 ^{0C}. Between these species, evaporation front receding in *Betula pubescens* was faster than *Picea abies*. They also concluded that the dry shell receding velocity in these three species until reaching the moisture content to the average moisture content of the FSP has the increasing rate and even more when kiln dry bulb increases. Remond et al. (2005) modeled the dry shell formation in the wood drying process and finally derived an equation to calculate the dry shell thickness.

In this paper, aiming at achieving the controller and effective factors on the development pattern of the dry shell, X-ray spectroscopy was used for tracking the dry shell receding in beech and spruce boards, so that by using development pattern of dry shell in these species and simulation of bulk flow of free water based on occurrence of this phenomenon, be able to perform suitable analysis for mechanism of moisture transfer in above moisture range of FSP. Also, a practical purpose for this research is to present a proper time for substitution of kiln dry bulb stage based on duration of reaching the dry shell to the core layer of the board.

Materials and Methods

Picea abies (softwood), *Fagus sylvatica* (hardwood) were used in this research. In the early of spring, two trees were cut from Engref jungle, near the Nancy of France, and immediately after the conversion process, for preventing moisture reduction, green boards were put in several plastic nylon and transferred to the springhouse site.

Sample Preparation

From each of that species, three flat boards with dimensions of 80*40*25 mm (L*T*R) were cut. For limiting the moisture flux through a direction (through the board thickness direction), four surfaces of the boards were coated by two layer of epoxy resin (fig. 2).

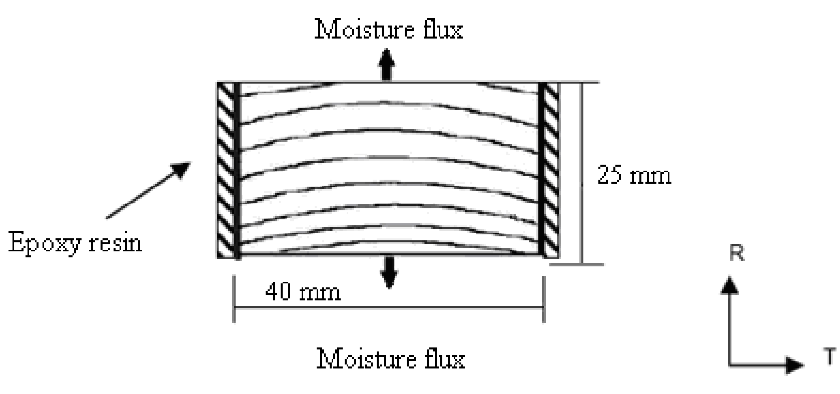

Fig. 2. Samples preparing method for study of dry shell receding during drying

Drying method of boards

The boards were dried with a convectional drying method, under the temperature of 60 ^{0}C and relative humidity of 70% (equal to equilibrium moisture content of 12%). The kiln was multipurpose and equipped with the X-ray source for scanning of boards. For determination the routine moisture content of kiln stock, all of the boards weighted by strain gauge once every 5 minutes automatically during drying until the final moisture content reached to about 12%.

X-ray spectroscopy

The equipments using in scanning method through board's thickness has shown in figure 3.

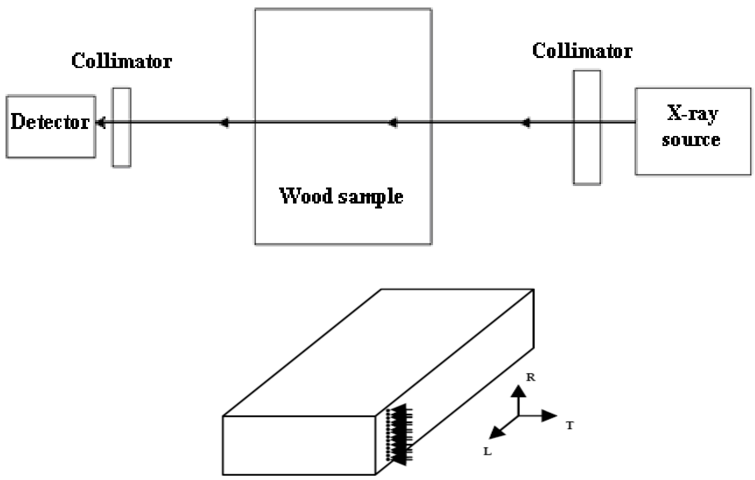

Fig. 3. Putting type of scan equipments and scanning method by X-ray through the board's thickness.

For tracking the dry shell receding through the thickness of the boards, the scanning was conducted once every an hour from the beginning. It was done in 14 points in thickness until the dry shell reached to the core layer of the boards.

On one side of the kiln, a source of X-ray was used for the ray emitting and on the other side, a detector for measuring the photons and recognizing the radiations that pass through the wood samples. There are two collimator with dimension of 1 millimeter near the X-ray source to prevent X-ray distribution and a detector for concentration of radiated rays. Measuring method of the moisture content using X-ray spectroscopy is the indirect method, by measuring the sample density (based on the number of photons that absorbed by samples) that consist of cell wall substance and the wood moisture, subsequently knowing the dry density of sample, we are able to measure its routine moisture content during drying. Thus, at the end of the drying process and after putting out the boards from kiln, some layers were cut and then the dry density gradient was determined by drying method in the stove through the board's thickness.

Results and discussion

The dry shell receding through the board's thickness

The results showed that the dry shell in the beech board form faster in comparison whit the spruce one. The dry shell with 1 mm in thickness was formed after 4 and 6 hours in beech and spruce boards respectively. Also, in spruce boards it was seen that the dry shell reached to the core layer faster than the beech one (fig. 4).

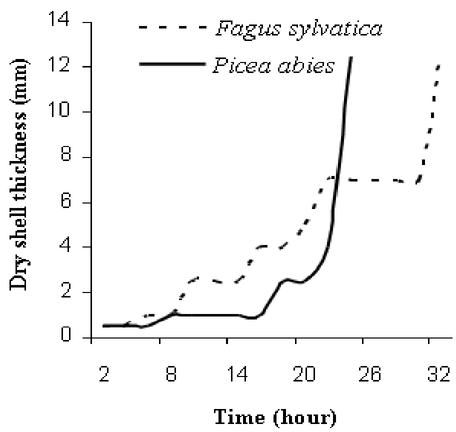

Fig. 4. The dry shell receding through the board's thickness of beech and spruce with passing the time during drying.

In the spruce after 24 hours and in the beech after 34 hours the dry shell reached to the core layer of the boards. In addition, the pattern of the dry shell formation was found to be different between the boards. In the first 16 hours of drying, it was observed steady-state condition in the dry shell thickness in the spruce board, while in case of beech board, the thickness of the dry shell has gradually increased from the beginning of drying process (fig. 4). The reason is due to faster bulk flow (capillary flow) of free water in the spruce board than beech one, which results the free water reaches the board surface faster which prevents the increasing of the dry shell thickness. Also, the pattern of the dry shell formation showed that the abrupt increase in the thickness of the dry shell that causes dry shell reaches to the core layer of the board. This is occurs after 21 hours in the beech board and after 16 hours in spruce, that signifies the complete stop of the bulk flow of free water in two types of the boards. The results of this research were agreed with the results of Keey et al. (2000), Wiberg (2000) and Wiberg and Moren (1999).

The dry shell development through the board's thickness under three moisture ranges

We can study the dry shell development through the thickness of the beech and the spruce boards under three moisture ranges (fig. 5).

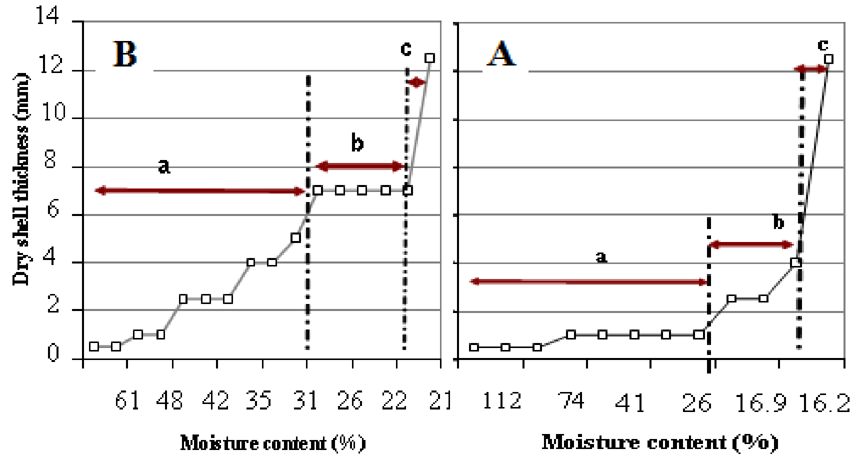

Fig. 5. The dry shell development through the board's thickness under three moisture ranges, A: spruce and B: beech

It was observed a steady-state condition through the thickness of the dry shell from the green moisture content to the average moisture content of 17% in the spruce board and the thickness of the dry shell remained approximately constant in about 1 mm. From the average moisture content of 17% to 16% the thickness gradually increased and reached from 1 mm to 4 mm. In the final stage, the abrupt increase occurred in the dry shell thickness, in the moisture range of bellow the 1%, it reached from 4 mm up to 12.5 mm. The final stage was occurred very quickly. The figure 5 shows the dry shell development in relation to the time. The dry shell development was different in the beech board, in a way that the dry shell thickness from the green to average moisture content of 26% gradually increased and reached 7 mm. In the second stage, in moisture range of 26% to 21%, the steady-state status was seen through the dry shell thickness and almost remained constant in about 7 mm. In the final stage which happened very quickly, in the moisture range of lower than 1%, the dry shell thickness increased from 7 mm to 12.5 mm. As it is shown in figure 6 and 7, the crossing site of drying rate curve and the thickness development of the dry shell curve is lower than the FSP in the beech and spruce board, and the dry shell thickness (considering the FSP be 30%) is lower than 2mm for spruce board and about 6 mm for the beech one.

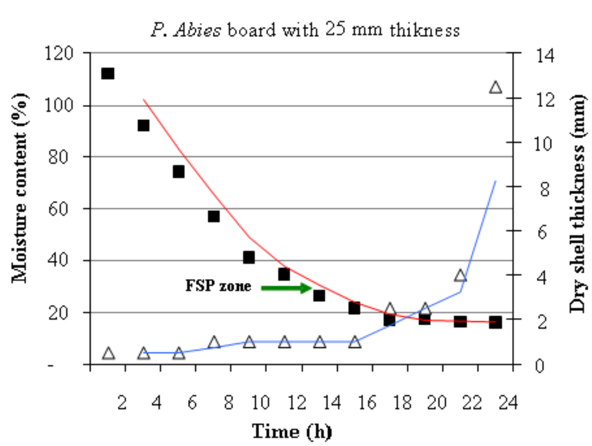

Fig. 6. Drying curve and dry shell development in the spruce board.

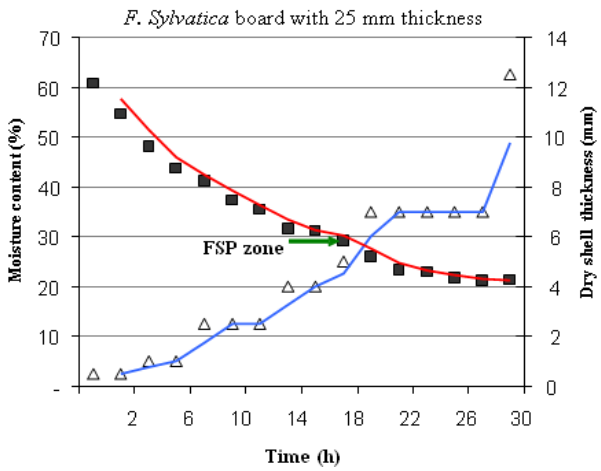

Fig. 7. Drying curve and dry shell development in the beech board.

On the other hand, when the average moisture of board reaches to the FSP, the dry shell specially in the spruce board has yet a considerable distance from core, so the substitution of dry bulb stage in this phase results in the wood drying defects, like honey combing.

The simulation of moisture flux in the boards by using the dry shell formation phenomenon during drying

Moisture transfer mechanism through the boards above the FSP was simulated by tracking the dry shell receding to the core layer of boards. The results are shown in figure 8.

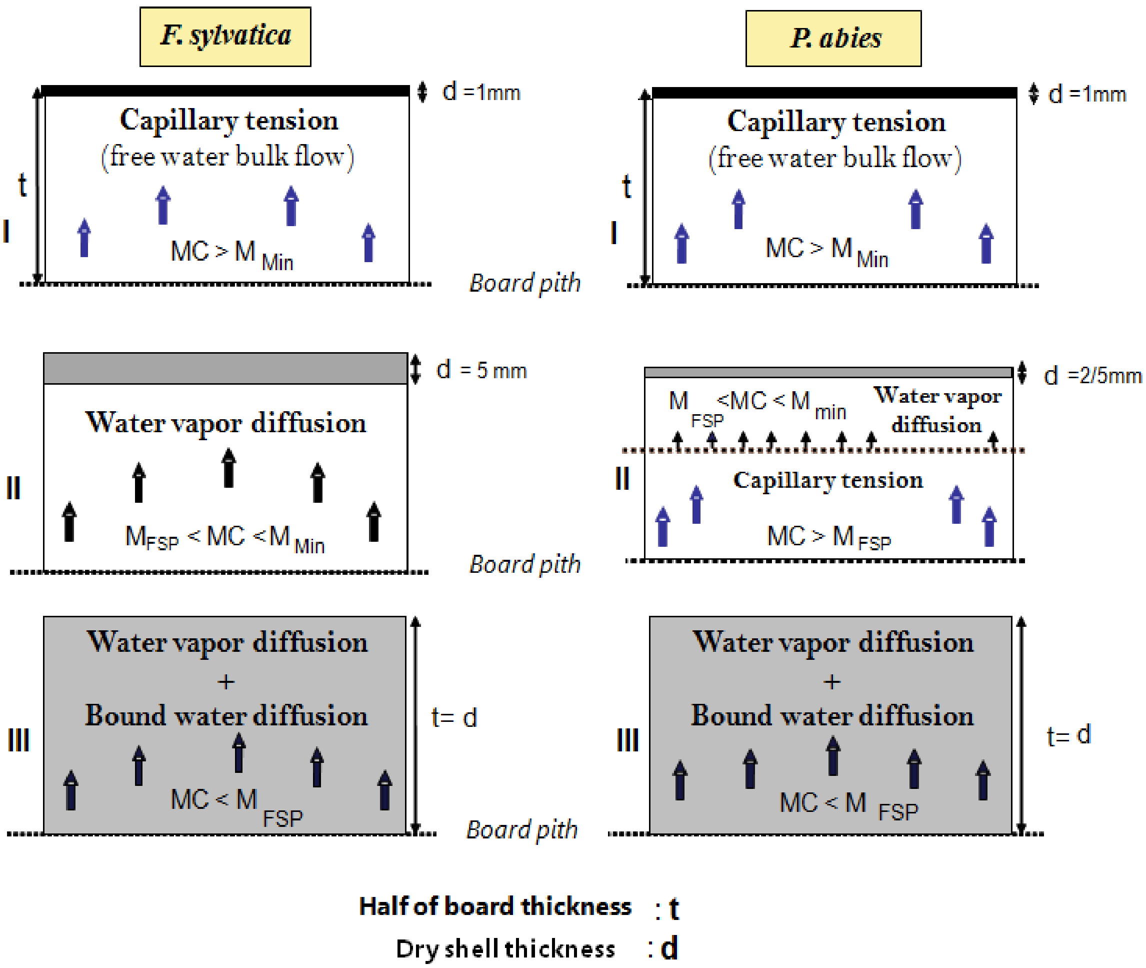

Fig. 8. The simulation of moisture flux in the beech and spruce boards by using the dry shell formation phenomenon in three stages of I, II and III during drying. $M_{min:}$ Minimum of moisture content that needs for occurrence of bulk flow of free water, MC: Routine moisture content of wood, M_{FSP}: Moisture content of fiber saturation point.

The simulation of moisture flux in each board was performed in three stages. In the first stage, the dry shell formed in the board's surface with 1mm in thickness. In this dry shell, the bulk flow of free water has stopped completely and moisture transfer carries out with bond water and water vapor diffusion mechanism only; while, the bulk flow of free water occurs under this layer. In fact, the average moisture of board in this stage is higher than minimum moisture that needs for bulk flow of free water ($MC > M_{min}$). This stage lasted about 10 hours in both types of the boards. In the next stage, the bulk flow of free water was stopped completely in the beech wood, and the moisture of boards is lower than minimum moisture that needs for bulk flow of free water, but, it is higher than FSP, therefore, moisture transfer is just with water vapor diffusion phenomenon (in this stage the dry shell thickness is 5 mm). In the second stage, the thickness of dry shell reached 2.5 mm in the spruce board, but the bulk flow of free water did not stop completely and on the contrary moisture transfer in this stage is carrying out whit two mechanisms, bulk flow and diffusion. The second stage lasted 8 hours in spruce board and 32 hours in beech. So it can be concluded that the controlling factor in the dry shell development to the core layer is diffusion coefficient (indicating the moisture diffusion velocity) rather than their permeability (indicating bulk flow velocity). In the third stage, the dry shell reach to the core layer in both types of boards; and moisture transfer perform by two mechanisms, bond water and water vapor diffusion in the whole structure of boards. The spruce and beech boards reached after 24 and 48 hours to this stage respectively.

Conclusion

The results showed that the dry shell with 1 mm in thickness forms on the surface of board right after putting the samples in the kiln. In both beech and spruce boards, not only the velocity of reaching the dry shell to core layer differed, but also the pattern of the dry shell formation showed a significant difference between the boards. The mentioned differences are because of faster flow of free water and also higher water vapor diffusion coefficient in spruce. The slow bulk flow of free water in beech board results in faster and thicker formation of dry shell, on contrary, due to quick bulk flow of free water in spruce board, the dry shell thickness during 16 hours from start of drying, remains in 1 mm. An important conclusion is that, however, the dry shell form faster in the beech but in comparison with the spruce reaches to the core layer of boards in a longer time, and the final phase of the dry shell development in the spruce boards (the stage that moisture transfer carries out with water vapor diffusion phenomenon) occurs much faster and with a sudden increasing toward beech boards. So, it can be concluded that the controlling factor in the primary formation of the dry shell is permeability and bulk flow of free water in the wood, but the determinant factor in the reaching of this shell to the core layer of board is water vapor diffusion coefficient rather than the permeability. Considering that the dry shell in both types of boards reached in the average moisture content below the FSP to the core layer (in the beech board in the average moisture content of 21% and in the average moisture content of 16% for spruce one), therefore, it is suggested that for preventing the wood drying defects, specially internal cracks (honey combing), the shifting time of kiln dry bulb performs in lower average moisture content of FSP instead of average FSP based on wood drying schedule.

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