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Efficiency of chip presteaming – result of heating and air escape processes

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Keywords: Presteaming, Wood chips, Heating efficiency, Air escape, Modelling

SUMMARY:

Efficient removal of air from the wood chips prior to impregnation with cooking liquor is important for achieving pulping uniformity and improving the overall digester performance. Because of its effectiveness, relative simplicity and other advantages, steaming of wood chips became a primary process in pulp industry to fulfil this task. In the present article the process of chip presteaming is examined from viewpoints of chip heating and air escape.

A three-dimensional model was proposed to estimate the efficiency of heating the single chip by saturated steam. Model simulations and experimental results indicated that the time required to heat the single pine chip with steam was very short, only a few minutes. Under industrial conditions, however, longer heating time may be expected due to the heat transfer limitations.

The process of air removal does not proceed as fast as the chip heating process. Based on the experimental data it was shown that the process of air escape fell to the negative exponential dependency. To achieve the air removal degree of 90 % for heartwood pine chips, half an hour of steaming with saturated steam at 105 °C was required, for sapwood pine chips only 5 minutes. The steaming temperature was found to influence the efficiency of air removal, probably by affecting the structure of wood chips. To achieve a high degree of air removal would require very long steaming times, especially with heartwood chips. Complete removal of air, however, may be difficult to achieve, even by applying optimal steaming conditions and long steaming times.

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INTRODUCTION

Utilization of steam during the chip charging stage was suggested in the middle of the 1930s (Svensson 1936). At that time, the main idea behind the use of steam was to achieve uniform packing and to limit the passage of air into the digester. At the beginning of the 1940s, it was shown that presteaming of chips could also improve the impregnation stage in chemical pulping (Haagglund et al. 1940). Because of its effectiveness, relative simplicity and other advantages, steaming of wood chips became a widely used process in the pulp industry. Presteaming of chips is an integral part of continuous kraft cooking processes. Nowadays, modern continuous systems use an atmospheric bin as a primary steaming unit. In some cases, however, a pressurised horizontal steaming vessel is still used. In contrast to continuous systems, modern batch cooking technology does not utilise steaming as effectively: only slight presteaming of the chips is taking place during the chip packing stage. Flash steam recovered from the spent liquors, low-pressure process steam or a combination of them, are used in steaming.

Presteaming of chips can serve several functions. It helps to recover heat when flash steam is used (Gullichsen, Fogelholm 2000). It preheats the wood chips from ambient temperature to 100-120 °C and removes the air between the chips. It also removes the non-condensable gases (NCG), such as air, present in the void volume of the chips. One can argue that the removal of entrained air is the most important function from the viewpoint of digester operation and pulping uniformity. Efficient removal of air from the chips is a prerequisite for achieving rapid and complete penetration of liquor during the impregnation stage (Kraev, Korolkov 1969; Maass 1953; Oulie 1992; Rydholm 1965; Stamm 1953; Woods 1956). More complete penetration, on the other hand, improves pulping uniformity and can help to reduce the cooking time (Gullichsen et al. 1992; Gustafsson et al. 1989). In continuous digesters, it also helps to improve the overall digester performance by minimizing the buoyancy of the chip column (Anon 1998).

Thanks to intensive laboratory research in the area of chip steaming during the past decades, the importance of its use prior to chemical pulping is well understood by pulping specialists. However, application of presteaming at industrial level needs to be developed further, especially in connection with batch technology. More attention has to be paid to the design of industrial systems to ensure proper contact between steam and chips during a sufficient time interval. In addition, some fundamental issues, including the mechanism of air escape from the chips during presteaming, still need to be studied more thoroughly.

The objective of this article is to discuss the process of chip presteaming. For this purpose, presteaming is examined from viewpoint of chip heating and air escape. Some speculations and hypotheses related to the efficiencies of these processes as well as mechanisms were verified from experimental data and numerical calculations.

MATERIALS AND METHODS

Sapwood and heartwood chips were hand-made from 50-year old pine (*Pinus silvestris*). The chips were prepared to the following exact dimensions: length - 25 mm, width - 15 mm, and thickness - 8 mm. The chips did not contain bark or knots. The moisture content and basic density of the chips were determined in accordance with standards: SCAN-CM 39:94 and SCAN-CM 43:89 (***Table 1)***.

Part of the hand-made chips was laminated through applying a thin layer (0.5 mm) of epoxy-paint. Both original and laminated pine heartwood chips were used in experiments to examine the efficiency of chips heating by saturated steam. A small hole (∅ 0.8 mm) was drilled through the middle of a single chip along the length dimension (longitudinal direction of wood). A thin K-type thermocouple (∅ 0.2 mm**)** was introduced to the middle point of the chip and wooden pins were used to close the drilled holes. The temperature at the central point of the chip was continuously measured during chip treatment with saturated steam at 100 °C.

***Table 1**. Properties of pine chips.*

Properties	Heartwood	Sapwood
Basic density, g/cm^3	0.410	0.425
Moisture content, % on o.d. wood	28	130

Penetration experiments with water were carried out to obtain indirect information on the efficiency of air removal during presteaming. Experiments were performed with a specially designed laboratory impregnator at Helsinki University of Technology (Malkov et al. 2001). Small samples of pine heartwood and sapwood chips were presteamed with saturated steam and then pressure-impregnated with warm water (85 °C). A perforated basket containing the chip sample was connected to a weight sensor, which allowed continuous measurements of the chip sample weight throughout the experiment. The penetration degree in relation to the theoretical maximum, i.e. the fraction of the voids within the chips filled by water, was calculated at certain time intervals based on the method and assumptions described elsewhere (Malkov et al. 2001). Initial temperature of the chips was 30 °C. The temperature of saturated steam and the duration of steaming, measured from the first contact between the steam and the chips, were chosen as variable parameters. Penetration trials were conducted at 1.3, 5.3 and 9.3 bar over-pressure.

In addition, one set of experiments was carried out to examine the effect of steaming on the moisture content of the chips. Here, samples of heartwood and sapwood chips were steamed with saturated steam at 105 °C for a certain time interval. After presteaming, the chip samples were quickly placed into plastic bags and their weights were compared to the weights of original chips.

RESULTS AND DISCUSSION

GENERAL MECHANISM OF STEAMING

Under uniform mixing, air and water vapour obey the Gibbs-Dalton law of partial pressures. Each gas occupies the entire volume available as if the other were not present and the pressure exerted by each gas adds to that of the others to produce the total pressure. If all non-condensable gases (NCG) within the chip voids are considered as air, then the total gaseous pressure can be simply described as the sum of partial pressures of water vapour and air:

$$P_{gas} = P_{vapour} + P_{air} \quad \textbf{[1]}$$

As a result of chip presteaming, temperature within the chip voids increases and a pressure gradient is formed. Increased temperature leads to expansion of the air inside the chip voids, accompanied by an increase in the partial pressure of the air. The partial pressure of the water vapour also increases when the temperature rises. Based on experimental data (Zorin et al. 1970), the following equation was suggested to describe the partial pressure of the vapour inside the wood [*Pa*], as a function of temperature [℃] and wood moisture:

$$P_{vapour} = aT^{3.2} \quad \textbf{[2]}$$

Parameter ***a*** has two values, depending on the moisture content of wood. If the moisture content is less than the fibre saturation point (FSP), the factor equals 0.0385; if the moisture content equal to or above the FSP, it equals 0.0405 (Zorin et al. 1970). ***Fig. 1*** shows the relationship between vapour pressure within the wood voids and temperature in accordance with *Eq. [2]*.

The increase in the total gaseous pressure inside the chip voids causes the air-vapour mixture to flow towards the chip surface under the pressure gradient. As a result, the air is expelled from the chip. Theoretically, complete removal of air can be achieved when the partial pressure of the water vapour is equal to the ambient pressure. This may be valid, for example, when heating the chips by steam to a temperature above 100 ºC at atmospheric pressure.

In practice, presteaming has to be considered as a simultaneous process of heat and mass transfer inside and outside of the chip. However, it may be advantageous to consider its efficiency from the viewpoint of chip heating and air escape. This may provide a better understanding of the process itself as well as the conditions needed to achieve a certain task.

HEATING OF THE CHIP

The time needed to heat the chip to the required temperature is an important technological parameter of the steaming process. Only reaching a certain temperature level would give a theoretical possibility for complete air removal from the chips. The efficiency of heating wood chips with steam is affected by a number of factors that can be divided into two groups (***Table 2***). The first group contains the factors related to the wood chip, the second group the factors related to the process. Wood properties such as density, composition, and moisture content determine the heat-conducting properties of the wood chip. The dimensions of the wood chip define the distances for heat transfer. On the other hand, process parameters affect the heating process by determining the rate of heat transferred to the chip surfaces, thus contributing to the efficiency of the entire heating process.

Table 2*. Factors affecting heating of wood chip.*

Factors related to chips	Factors related to process
Wood properties	Steam temperature
Chip dimensions	Steam pressure
Initial chip temperature	Venting of steam

Wood itself is a relatively good insulator (Siau 1984). The low thermal conductivity of wood may account for the considerable time interval required to bring the wooden block to a uniform, elevated temperature by application of heat to its external surfaces. Heating of the chip with saturated steam takes place from all three directions. Most of the heat released from the condensation of steam is consumed in the heating process. Calculations show that the heat losses on the evaporation of the water present inside the chips can be ignored. Let us consider "ideal" steaming, where the heat transfer through the liquid film on the chip surface is instantaneous. For a wood chip of parallelepiped shape, anisotropy with orthogonal symmetry can be assumed, where the heat conductivities are different in three mutually perpendicular directions (axes X, Y, and Z). The heating process of the wood chip can then be modelled based on the fundamental equation for unsteady state conduction in solids and fluids, in which there is no substantial motion (Parson 1989):

$$\rho C_p \frac{\partial \theta}{\partial t} = \lambda_x \frac{\partial^2 \theta}{\partial x^2} + \lambda_y \frac{\partial^2 \theta}{\partial y^2} + \lambda_z \frac{\partial^2 \theta}{\partial z^2}$$

Boundary conditions :

$$\theta \big|_{x=0} = 1; \quad \theta \big|_{y=0} = 1; \quad \theta \big|_{z=0} = 1; \qquad \textbf{[3]}$$

$$\lambda_x \frac{\partial \theta}{\partial x}\bigg|_{x=a/2} = 0; \quad \lambda_y \frac{\partial \theta}{\partial y}\bigg|_{y=b/2} = 0; \quad \lambda_z \frac{\partial \theta}{\partial z}\bigg|_{z=c/2} = 0$$

Initial condition : $\theta \mid_{t=0} = 0$

Here, θ is dimensionless temperature; x, y, z – spatial coordinates; λ_x, λ_y, λ_z – thermal conductivities of wood in a certain direction; a, b, c – chip dimensions; t – time; ρ - density of the wood chip and C_p is the heat capacity of the wood chip. By transforming the system of coordinates, it is possible to reduce the solution of the anisotropic problem to the solution of the corresponding isotropic problem. In this case, an analytical solution can be found (Carslaw, Jaeger 1964).

The basic properties of the experimental chips, density and moisture content, were used to calculate the heat capacity and heat conductivities in accordance with the relationships suggested by MacLean (1941). It was also assumed that thermal conductivity in longitudinal direction is 2.5 times greater than that in transversal direction (Siau 1984). These calculated parameters and dimensions of the chips in the experiments were used in simulations. Data from the experiments with original and laminated heartwood pine chips and the simulation curve are compared in ***Fig. 2***.

It can be seen that the time needed for heating the heartwood chip with steam up to steaming temperature is quite short, about two minutes. The simulation curve is in quite good agreement with the experimental data obtained with the laminated chip. Heating of the original chip seems to proceed faster. This can be explained by the following phenomenon: During steaming of the laminated chip, the heat transfer from condensed steam takes place from the chips surfaces. In the original heartwood chip, part of the steam can diffuse into chip voids and condense inside the chip. Thus, the distances for heat transfer may become shorter. According to the simulations, the heating efficiency for sapwood and heartwood pine chips is almost the same (***Fig. 3***). Although the thermal conductivity of “wet” sapwood is higher, the higher density and specific heat capacity counteract its influence. In practice, however, the heating of heartwood chip may proceed faster due to steam diffusion into chip voids. If the temperature of saturated steam is increased, the efficiency of heating, i.e. the time needed to heat the whole chip to steaming temperature, should not change significantly.

From the results it can be concluded that heating of wood chips of typical dimensions with saturated steam is a fast process, lasting only a few minutes. The results presented by some researchers (Oulie 1992; Zorin et al. 1970) also confirm that the time needed to heat a thin wood chip with steam is very short. It is also claimed that even a frozen chip can be heated quite rapidly by applying proper steaming (Oulie 1992). Under industrial conditions, however, longer heating may be expected because of limited heat transfer in the immobile chip layer. Increased chip dimensions, especially thickness, may also result in significantly longer heating times to achieve steaming temperature. Still, fast heating does not guarantee fast air removal. Part of the air from the chip voids can be removed during the heating stage. However, complete removal of air from the chips would probably require much longer steaming times.

EFFECT OF STEAMING ON CHIP MOISTURE CONTENT

If chip steaming is carried out with sufficiently superheated steam (by at least 40 °C), most of the moisture present within the chip can vaporize within a very short period of time (Salin 1988). However, superheated steam is not used in industrial chip steaming processes because it is not readily available. There are also other reasons that may restrict the use of superheated steam in chip presteaming (Gullichsen, Fogelholm 2000; Howard 1951). When heating chips with saturated steam, only a small part of the water present within the wood voids, less than 0.5 %, will vaporize at the moment when the whole chip has been heated to the ultimate temperature. This can be seen from numerical calculations and is valid for heartwood and sapwood chips. Experimental data indicate (***Fig. 4***) that presteaming with saturated steam results only in a slight increase in the moisture content of both heartwood and sapwood chips, which is in good agreement with the results reported by Aurell *et al*. (1958). Theoretically, moisture may increase as a result of the condensation of steam onto chip surfaces and within the chip voids. However, the possibility of error due to the experimental procedure cannot be ignored.

PROCESS OF AIR ESCAPE

Fig. 5 shows the effect of presteaming on the penetration of water into pine heartwood chips under 5.3 bar over-pressure. A longer steaming time led to a higher penetration degree, indicating that more air was removed from the chips. Data from the water penetration experiments with pine sapwood under 1.3 bar over-pressure are shown in ***Fig. 6***. Similar effect of presteaming on penetration efficiency can be observed. Due to the smaller amount of air initially present within the sapwood chips, the differences in the final penetration degree for steamed chips were not very significant when using the higher penetration pressures (5.3 and 9.3 bar). Based on the design of the impregnation vessel used, the chip dimensions and the size of the chip sample, it can be assumed that the chip heating process was quite rapid, lasting only a couple of minutes. From the results of the experiments with heartwood chips it seems that the process of air removal takes much longer time. In fact, one hour steaming was long enough to remove most of the air from the chips.

If the dissolution of remaining air during water penetration into the chips is ignored, it is possible to make a rough estimation of the efficiency of air removal from the chips during presteaming based on the penetration experiments. ***Figs. 7 and 8*** show the values for remaining air as a function of steaming time for heartwood and sapwood chips. Most of the air is removed during the first two minutes of presteaming, when chip heating takes place. As can be seen, the air escape from the chips during presteaming falls to the negative exponential dependency, $N = N_0 \exp(-k*t)$. This solution can be obtained from *Eq. [4]*, where the rate of air escape from the wood chips during presteaming, dN/dt, is assumed to be proportional to the amount of entrapped air, N. The constant k is a parameter dependent upon the properties of wood chips.

$$\frac{\partial N}{\partial t} = -k\,N \qquad \textbf{[4]}$$

To achieve an air removal degree of 90 % for heartwood chips, 30 minutes of steaming is required, while for sapwood chips only 5-6 minutes. It seems that air removal from sapwood chips is faster than from heartwood chips. The accuracy of the data presented in ***Figs. 7 and 8*** was somehow affected by the dissolution of air. Nonetheless, it can provide reasonable information on the efficiency of air removal from pine chips during presteaming. Kraev and Korolkov have studied the efficiency of air removal from chips during presteaming with direct saturated steam, presenting quite similar results (1969). They have shown that to remove 90 % of initial air from spruce chips 30 minutes of presteaming is required.

Eventually, the following questions arise:
What is the mechanism of air escape from the chip and the factors limiting this process?
Is it possible to achieve complete removal of air and under what conditions?

In pine heartwood chips with low moisture content (28 % on o.d. wood), most of the water can be considered as "bound water" that is situated within the cell walls. A gaseous mixture of air and water vapour occupies the void volume inside the chips. The increase in temperature that takes place during steaming causes the mixture of air and vapour to flow from the chip voids under the pressure gradient. With pine sapwood chips, some free water is present within the cell cavities, and a mixture of water vapour and air occupies the rest of the void volume. Still, the most logical mechanism for air escape is a flow through the gas channels inside the chip under the influence of the pressure gradient. Because of the specific features of the capillary structure of softwoods, a flow of gases can be expected to take place primarily in longitudinal direction. Bearing all this in mind, the mass transfer of air from the wood chip, which involves mechanisms of bulk motion and molecular diffusion, can be described in terms of the following one-dimensional equation (Vjukov et al. 1975):

$$\frac{\partial c}{\partial t} = -\frac{\partial (c,u)}{\partial x} + D_L \frac{\partial^2 c}{\partial x^2} \qquad \textbf{[5]}$$

where

D_L is longitudinal air diffusion coefficient of wood.

Let us consider a case where the wood chip is already heated to its ultimate temperature. Some simplifying assumptions can be made: air is an ideal gas, the gas volume is constant and the process is isothermal. The pressure of the gaseous mixture is the sum of the partial pressures of water vapour and air (*Eq. [1]*), where the partial pressure of water vapour is constant, so the pressure gradient equals to the gradient of the partial pressure of air: $\partial P/\partial x = \partial P_a/\partial x$. The bulk motion of air under the pressure gradient can be described with the help of Darcy's law (Siau 1984), where the flow rate, *u*, is proportional to a specific permeability of wood the chip to gases, K_g, divided by dynamic viscosity, μ:

$$u = -\frac{K_g}{\mu}\frac{\partial P}{\partial x} \qquad \textbf{[6]}$$

By applying these assumptions and considering the unsteady-state case, *Eq. [5]* can be transformed to *Eq. [7]*. The initial condition for solving this equation can be defined as following: $P_{vapour} = 1$, $P\big|_{t=0} = 1 + 373/298$, while the boundary conditions as $P\big|_{x=1} = 1; \partial P/\partial x\big|_{x=0} = 0$. In the future, we are going to model the process of air escape by means of the *Eq. [7]* and compare the results with experimental data.

$$\frac{\partial P}{\partial t} = \left[\frac{K_g}{\mu}\left(\frac{\partial P}{\partial x}\right)^2 + \frac{K_g}{\mu}(P - P_{vapour})\frac{\partial^2 P}{\partial x^2}\right] + D_L \frac{\partial^2 P}{\partial x^2} \qquad \textbf{[7]}$$

Fig. 9 shows the effect of steaming temperature on the subsequent penetration of water into heartwood chips. By increasing the steaming temperature from 105 °C to 120 °C it was possible to achieve a higher final penetration degree. This means that more entrained air was removed from the chip voids during presteaming under higher temperature. It is probably caused by the temperature influence on the permeability of wood chip to gases (air). Higher temperature can, for example, accelerate the dissolution of wood substances at the pit membranes (Nicholas, Thomas 1968).

Can the entrained air be removed completely from the chips by presteaming? It is claimed that a new design of steaming bin enables complete air removal from the chips (Lundgren, Andtbacka 2000). It is quite difficult to believe this, especially considering the retention time of 15 minutes (Lundgren, Andtbacka 2000). Extrapolation of the calculated data (***Fig. 7***) shows that to achieve an air removal degree of 99 % for heartwood chips, almost 90 minutes of steaming is required under the conditions in question. In practice, however, complete removal of air may be difficult to achieve, even by applying optimal steaming conditions and long steaming times (Kraev, Korolkov 1969). Removal of air can be limited by the specific features of the wood capillaries. Some air cannot be removed because the pressure gradient at the end of presteaming is insufficient to overcome the surface tension forces at the liquid-air menisci that block the air passage. In addition, some air can be trapped within capillaries, which are sealed by extractives, or within the blind pores.

From an industrial point of view, complete removal of air from chips prior to impregnation is desirable, but not vitally important. Prolonged presteaming of chips may not be feasible under industrial conditions. The duration of chip presteaming has to be chosen based on the resources and targets in each particular case. Achieving high uniformity of pulping and optimal digester performance would probably require efficient steaming for half an hour or so. This time may vary depending on the type of wood chips used and the parameters of the process itself.

Essentially, there is a great need for a method to directly measure the air removal from wood chips. Such a technique would enable researchers to acquire a more comprehensive understanding of the air escape process during presteaming, and to find answers to some other puzzles.

CONCLUSIONS

The time needed to heat the wood chips to the required temperature is an important technological parameter of the steaming process. Only reaching a certain temperature level would give a theoretical possibility for complete air removal from the chips. A three-dimensional model of the process of heating wood chip by steam was proposed. Model simulations and experimental results indicate that the time required to heat both heartwood and sapwood pine chips with saturated steam is very short, only a few minutes. Under industrial conditions, however, longer heating time may be expected because of limited heat transfer in the immobile chip layer. Increased chip dimensions, especially thickness, may also result in a significantly longer heating time.

The process of air removal does not proceed as fast as the chip heating process. The steaming time was found to have a great effect on the amount of air removed from the chips. Recalculated data from the water penetration experiments indicated that the process of air escape fell to the negative exponential dependency. To achieve an air removal degree of 90 % for heartwood pine chips, 30 minutes of steaming at 105 °C was required, for sapwood chips only 5-6 minutes. The steaming temperature was found to influence the process of air removal, probably by affecting the permeability of wood chips.

To achieve a high degree of air removal very long steaming times would be required, especially with heartwood chips. Complete air removal, however, may be difficult to achieve, even by applying optimal steaming conditions and long steaming times. Under industrial conditions, prolonged chip presteaming may not be feasible. The duration of chip presteaming has to be chosen based on the resources and targets in each particular case.

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FIGURES

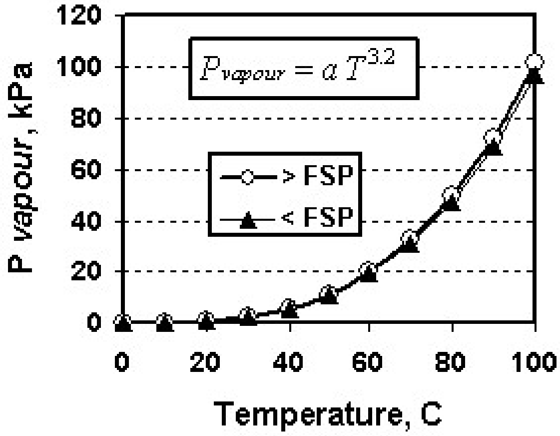

Figure 1. *Vapour pressure inside the chip as a function of temperature and wood moisture.*

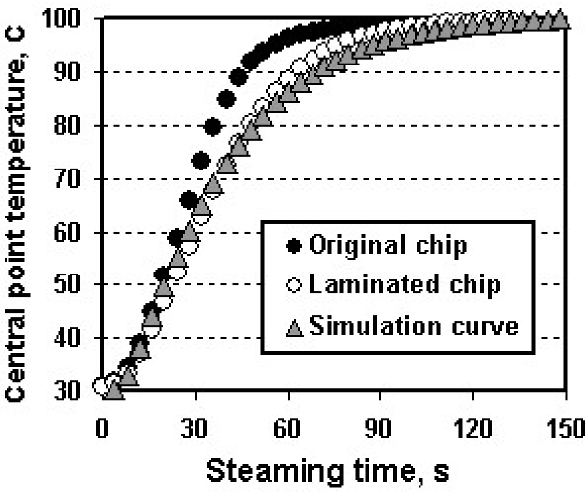

Figure 2. *Heating of pine heartwood chips by saturated steam at 100 ℃.*
(Starting temperature 30 ℃).

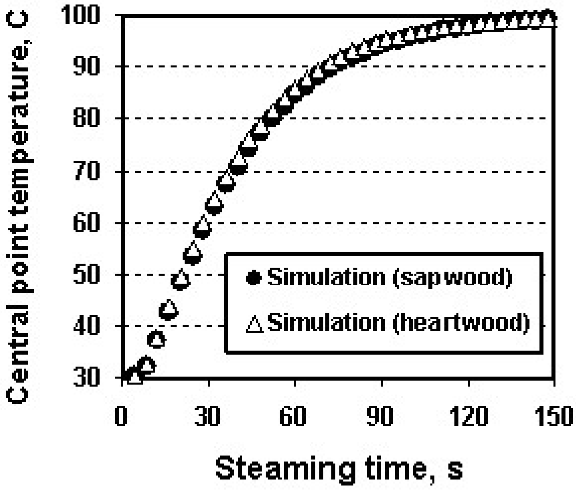

Figure 3. *Heating of pine chips by saturated steam of 100 ℃.*
(Starting temperature 30 °C).

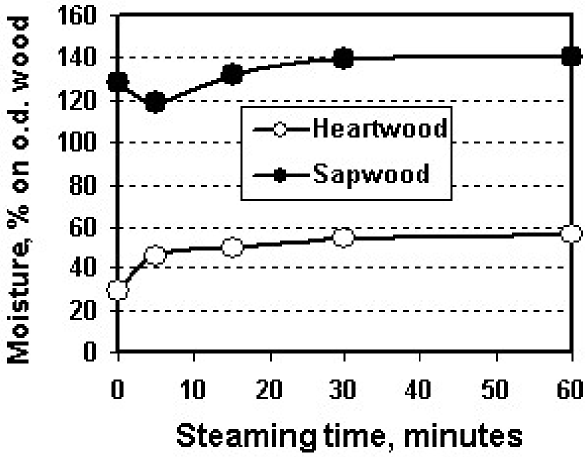

Figure 4. Effect of steaming on moisture content of pine chips. (Steaming temperature 105 °C).

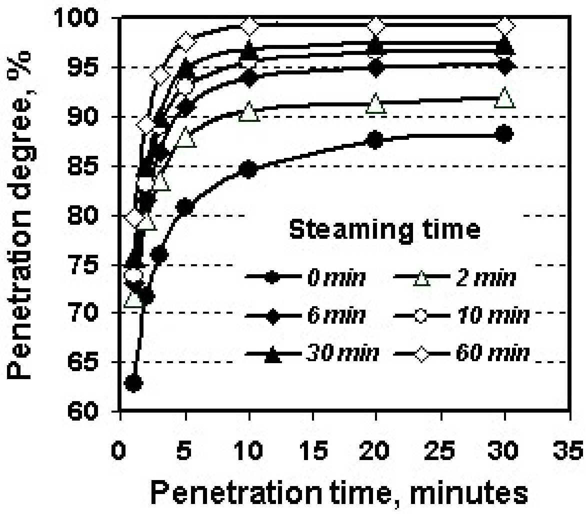

***Figure 5**. Water penetration into heartwood pine chips. (Steaming at 105 °C; conditions: 85 °C, 5.3 bar over-pressure)*

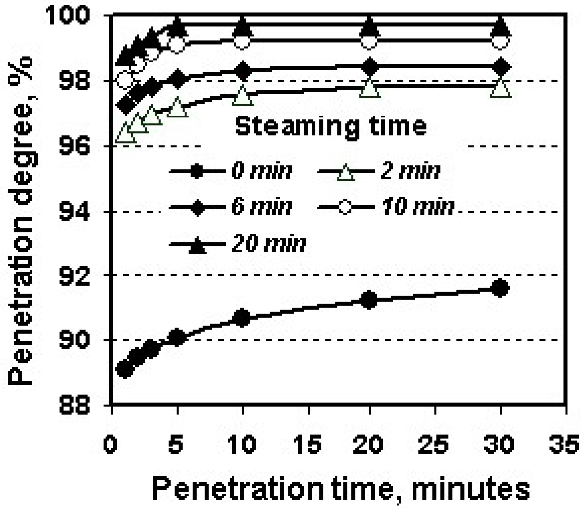

Figure 6. *Water penetration into sapwood pine chips.*
(Steaming at 105 °C; conditions: 85 °C, 1.3 bar over-pressure)

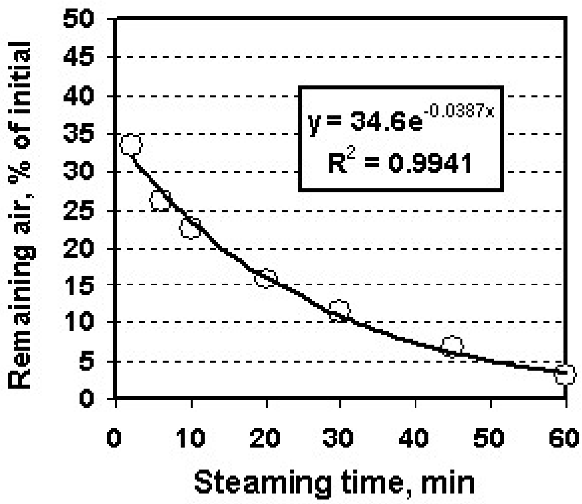

Figure 7. *Effect of steaming (105 °C) on air removal from heartwood chips.*

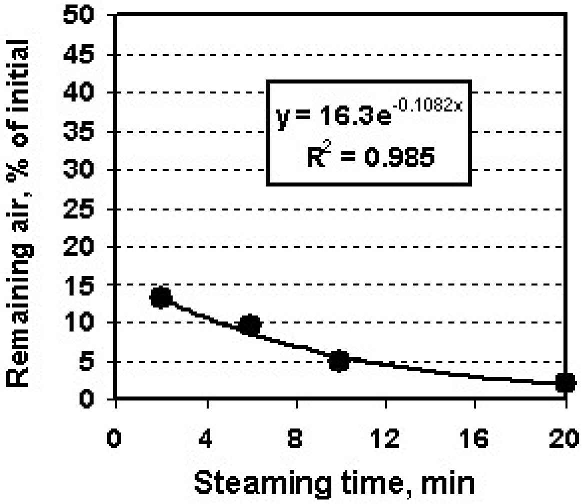

Figure 8. *Effect of steaming (105 ℃) on air removal from sapwood chips.*

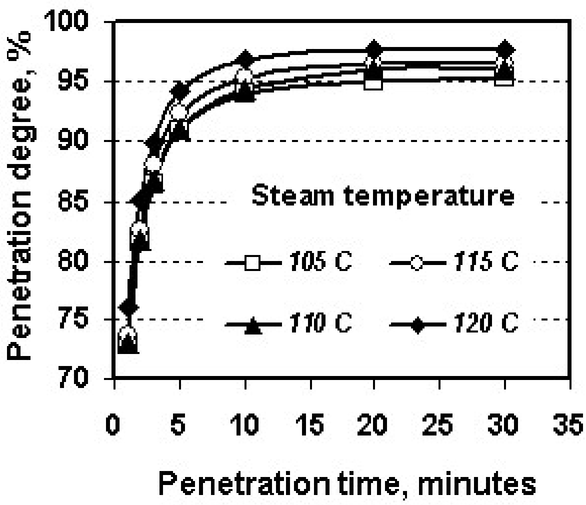

Figure 9. *Effect of steam temperature on water penetration into pine heartwood chips. (Steaming: 6 minutes, conditions: 85 ℃, 5.3 bar over-pressure)*