

Modeling the process of water penetration into softwood chips

S.Y. MALKOV, V.A. KUZMIN, V.P. BALTAKHINOV and P. TIKKA

A mathematical model was developed for the process of water penetration into softwood chips under isothermal conditions. The model takes into account several important phenomena, including capillary rise, air dissolution and outward diffusion, and the decrease in the permeability coefficient of wood as a function of the chip saturation degree. Based on this model, a computer simulation program was written to obtain quantitative information about the penetration of water into different chips under different process conditions. The program was found to predict accurately the course and final level of water penetration into the chips under defined conditions. Suggested model can be also used for predicting the penetration of the white liquor into softwood chips. It cannot be used, however, as a general model for predicting the penetration of black liquor.

ADDRESSES OF THE AUTHORS:

S.Y. Malkov and P. Tikka

Laboratory of Pulping Technology, Helsinki University of Technology, Vuorimiehentie 1, PL 6300 Espoo, Finland

V.A. Kuzmin and V.P. Batakhinov

Boreskov Institute of Catalysis, Russian Academy of Science
Pr. Ak. Lavrentieva 5, 630090 Novosibirsk, Russia

INTRODUCTION

The importance of thorough impregnation prior to cooking is widely recognized in the pulping industry. Transport of reactive chemicals takes place via two primary mechanisms, penetration and diffusion, which are entirely different and operate in response to different laws [1]. In practice, a combination of penetration and diffusion occurs when chips of normal moisture content are treated with liquor at elevated temperatures and pressures.

Impregnation of wood chips controls the cooking performance in terms of mass transfer and pulping uniformity [2,3]. It is of vital importance to understand the mechanisms of impregnation and optimize the process conditions. To this end, modeling of the impregnation would be critical for gaining a better understanding of the process. The impregnation model can also be used as a part of the general pulping model. An adequate model would provide a quick and inexpensive tool to be used for process control, development of new cooking scenarios, optimizing process conditions and for training purposes.

Several attempts have been made to model various impregnation processes. Very often the impregnation is considered as a diffusion-reaction process, and complete penetration of chips is assumed [4,5]. Under industrial conditions, however, this assumption can be far from reality; some entrapped air can be expected to be present within the impregnated chips. For this reason, it is important to take into account not only diffusion but also the bulk flow of liquid or penetration when modeling the impregnation process. Some of the suggested models [6,7] deal with the penetration problem by expressing the penetration degree as a negative exponential of the time variable. It can be argued, however, that the “black box” models are too simple and do not provide a clear picture of the process. Kimpe [8] and Zorin [9] have chosen a more fundamental approach. Their impregnation models account for liquor flow into the chips and include the phenomena of capillary rise and air dissolution into the penetrating liquor. To gain a better understanding of the impregnation process and to predict the effect of various factors on its efficiency, it may be advantageous to develop an independent model of liquid penetration into wood chips based on fundamental laws and available experimental data.

This article deals with the development of a “gray box” model of the process of water penetration into softwood chips. The model describes the process based on fundamental laws combined with some empirical correlations, and provides quantitative information on the course of the penetration process under defined isothermal conditions below the boiling point of water. One objective was to make a relatively simple model allowing fast simulation runs. The preconditions for model development and simplifying assumptions used are discussed in the article. In addition, application of the model for predicting the penetration of some cooking liquors is evaluated.

EXPERIMENTAL

Pine (*Pinus silvestris*) was used as a raw material for the experiments. Hand-made chips with different dimensions were separately prepared from the sapwood and heartwood portions of a pine log. The length of the chips corresponded to the longitudinal direction of the stem, the width and thickness to tangential and radial directions, respectively. The chips did not contain bark or knots. The moisture content and basic density of sapwood and heartwood chips were determined with standard methods SCAN-CM 39:94 and SCAN-CM 43:89 (Table I).

Table I. Properties of pine chips.

	<i>Heartwood</i>	<i>Sapwood</i>
Basic density, g/cm ³	0.415	0.430
Moisture content, %	21	56

A number of experiments on water penetration into pine sapwood and heartwood chips were performed to get specific information on the penetration process and to examine the effect of different conditions on its efficiency. Experiments were performed with a specially designed laboratory impregnator at Helsinki University of Technology. A perforated basket containing the chip sample was connected to the heart of the experimental system - weight sensor, which allowed continuous measurements of the chip sample weight throughout the experiment (Fig. 1). Weight sensor's operation was based on level measurement, which was done through the strain-sensitive element. The vessel was equipped with several valves for inlet and outlet streams. Temperature was maintained by using a conventional jacket system. Two temperature indicators were used to monitor the temperature profiles in the lower and upper parts of the impregnator.

Fig. 2 shows an example of the weight sensor reading profile throughout the penetration experiment. The five experimental phases can be defined as:

- 1- *Initial moment:* Sensor reading is zero.
- 2- *Sample introduction:* Sensor indicates the weight of the chip sample.
- 3- *Liquid introduction:* Sensor reading becomes negative due to buoyancy effect of the immersed basket and chip sample.
- 4- *Pressure applied:* Sensor reading becomes less negative due to the effect of pressure.
- 5- *Penetration phase:* Sensor reading changes, indicating the increase in weight of the chip sample due to the penetration of liquid.

When the exact volumes of the basket and chip sample, density of the penetrating liquid, and the correlation between the weight sensor reading (WSR) and pressure are known, the reference value (REF) can be calculated. Reference value can be defined as a hypothetical weight sensor reading, in case if no liquid has penetrated into the chips. The weight of the chip sample was continuously monitored as a difference between the weight sensor reading and reference value (Fig. 2). The penetration degree of wood chips from the theoretical maximum, i.e. the fraction of the voids within the chips filled by liquid, was then calculated at certain time intervals.

Table II. Properties of liquors used in penetration experiments at 25 °C.

<i>Properties</i>	<i>White liquor</i>	<i>Black liquor</i>	
Effective alkali, g/l (as NaOH)	120	10	10
Dry solids content, %	20	11	21
Density, g/cm ³	1.17	1.06	1.12
Surface tension, mN/m	55	32	32
Dynamic viscosity, mPa s	1.95	1.45	2.50

A set of experiments with heartwood pine chips was carried out in order to test the model and evaluate its applicability for predicting the penetration of cooking liquors. The dynamics of liquid penetration can be examined easier with heartwood chips because of their low initial moisture content. Also, the mixing between initial moisture and penetrating liquor can be neglected, because most of the initial moisture is situated within the cell walls. Heartwood pine chips had the following exact dimensions: length - 25 mm, width - 15 mm, and thickness - 8 mm. Chip samples were subjected to penetration by water as well as white and black liquors at several levels of process temperature and pressure. Cooking liquors were delivered from the Metsä Botnia's Rauma Mill, Finland. Their properties were measured

within the temperature range used in the experiments, i.e. 20 - 90 °C. Table II shows the properties of white and black liquors at 25 °C.

MODEL DEVELOPMENT

Assumptions

Modeling of a process such as water penetration into wood chips is a difficult task. First of all, the wood substrate is a very non-homogeneous three-phase system. Also, different mechanisms may prevail when the water flows into the anisotropic wood chip from different directions. Second, the penetration process is most likely accompanied by numerous complicated phenomena, including non-linearity of the bulk flow, capillary condensation of vapor and surface tension in the air-liquid menisci, gas dissolution and diffusion, migration of bound water through the cell walls, swelling of wood and other chemical interactions between wood and water. Making certain assumptions may, however, significantly simplify the modeling. To this end, several assumptions were made based on available information and data obtained from experiments.

- *Wood is a homogeneous porous medium.*
- *The density of wood substance is constant and equals 1.50 g/cm³.*

Of course, the first assumption is far from reality. It is well known that the structure of wood is complex and heterogeneous. The density of wood substance is practically independent of the type of wood, at least for wood in dry state, and can be approximated at a constant level within the range of 1.46 - 1.53 g/cm³ [10]. Variations in wood substance density may result from differences in the proportion, densities, or arrangement of the basic cell-wall substances [11].

- *Movement of water into wood chips takes place via the bulk flow under the pressure gradient. Diffusion of bound water and water vapor is not considered.*

Water initially present within the wood chips can be considered to be in three different states: water present inside the capillaries with the properties of bulk water - free water, water present within the micro-pores and amorphous regions of the cell wall that is in a certain state of interaction with wood components - bound water, and water vapor. Theoretically, movement of water into wood chips may take place via several mechanisms, including bulk flow of water under the pressure gradient, vapor diffusion through the air present within the chip, and bound water diffusion through the cell walls. Diffusion mechanisms of bound water and vapor may play an important role when considering the penetration into dry wood chips. However, for wood chips with moisture content above the fiber saturation point, the bulk flow of water will be the dominant mechanism.

- *Penetrating water is homogeneous and incompressible.*
- *There is no difference in density between bound and free water within the chip.*

Numerous measurements of cell wall density by the displacement technique with water and non-polar solvents resulted in different density values [12]. Together with the presence of micro-voids, which could not be filled by the non-polar solvent, the compression of bound water was assumed to be one of the factors explaining the differences between measurements [13,14]. Calculation of the density of bound water based on the results of Weatherwax and Tarkow [14] would give the value of 1.014 g/cm³, which is just 1-2 % higher than the density of free water. Still, the physical properties of bound water are not fully understood.

- *Most of the penetration of water into a softwood chip takes place through the longitudinal direction. Radial flow may account for some penetration. However, flow through the tangential direction can be ignored.*

The longitudinal flow of liquid takes place via tracheids and interconnecting bordered pits, and is 50-200 times faster than flow in the other two directions [1,15]. Tangential flow in softwoods is controlled by the bordered pits situated on the radial walls of tracheids [16], while the flow in the radial direction is controlled by ray cells [16-18]. The permeability of softwoods in radial direction is considered to be greater than in tangential direction [16,18]. This common knowledge was verified by a set of penetration experiments with pine chips of different length, width and thickness. The results also lead to the conclusion that most of the water penetration into pine chips takes place through the longitudinal direction. Radial flow may account for a small part of the total penetration, while the flow in tangential direction can be neglected.

- *Water flow into wood is laminar and linear.*

It is generally expected that true turbulent flow is unlikely to occur in any of the capillaries in most wood species [19]. Non-linear flow due to kinetic energy losses may occur in wood, particularly where fluids enter a pit opening [20,21]. In most cases, however, liquid flow inside the wood capillaries is viscous.

- *Chemical interactions and swelling of the wood chips are ignored. No losses of wood substance occur during liquid penetration.*

However, these assumptions are also far from reality. Hydrogen bonding is believed to play a major role in the wood swelling mechanism and liquids with strong hydrogen bonding potential, such as water, would be expected to swell wood to a great extent [22]. Higher temperature is expected to increase the swelling rate of wood in water. Some losses of wood substance may occur due to hydrolysis, when the wood chips are treated with water [23]. However, with low temperatures (below 100 °C) and short treatment times, losses of wood substance can be ignored.

- *Entrapped air escapes from wood voids during the penetration process via dissolution into surrounding liquid and diffusion.*

In a capillary system with certain geometry, part of the air can be pushed out from the chip voids by the penetrating liquid. This may take place during the early phases of the process, when liquid comes into contact with the chip. Meanwhile, the most probable mechanism accounting for escape of air during penetration is dissolution into surrounding liquid and outward diffusion. This can also be considered as a one-dimensional process, taking place through longitudinal direction.

In addition, the whole process of water penetration is considered to be isothermal. So, the amount of air present within the chip at the beginning of penetration is estimated based on ideal gas law under conditions corresponding to the penetration temperature.

One-dimensional approach

Because most of the water flow into softwood chips takes place in longitudinal direction, modeling of the penetration, as a one-dimensional process, may be enough for its quantitative description. Considering the cutting pattern of wood chips and assuming the symmetry of the chip, the half-length of the chip, L_x , can be used in modeling the longitudinal penetration (Fig. 3). The objective of modeling is to calculate the fraction of the void volume penetrated by water, $x(t)$, as a function of time. Moisture initially present within the chip occupies a certain fraction of the void volume, which can be estimated from the known properties of wood chips. It is assumed that this fraction is evenly

distributed throughout the chip volume.

It is known that the flow of an incompressible liquid through a porous medium is described by the equation consisting of viscous and inertial components [24]:

$$\frac{\Delta P}{L} = \alpha \mu U + \beta \rho U^2 \quad (1)$$

where

ΔP is drop in pressure gradient,
 L length of the medium,
 U velocity of liquid movement,
 μ dynamic viscosity of liquid,
 ρ density of liquid,
 α viscous resistance coefficient,
 β inertial resistance coefficient.

For purely viscous flows, the inertial component is close to zero and can be neglected [24]. Then, by applying the penetration case presented in Fig. 2 and assuming that $\alpha = K_x^{-1}$, Eq. (1) can be expressed in the form of Eq. (2):

$$\Delta P = \frac{\mu}{K_x} L_x^2 x \frac{dx}{dt} \quad (2)$$

where

μ is dynamic viscosity of water,
 K_x permeability coefficient of wood chip (longitudinal direction),
 L_x half-length of the chip,
 x fraction of void volume penetrated by water.

The formula (Eq. (2)) can be used for calculating the fraction of the chip voids penetrated by water, $x(t)$, as a function of time and known parameters.

Pressure differential

The pressure differential can be considered as the difference between the sum of external pressure, P_{ex} , hydrostatic pressure, P_h , and capillary pressure, P_c , and the pressure of the gaseous mixture within the chip voids. If the presence of some minor gases is neglected, the total pressure of the gaseous mixture can be considered as the sum of partial pressures of air, P_a , and water vapor, P_v (Eq. (3)).

$$\Delta P = (P_{ex} + P_h + P_c) - (P_a + P_v) \quad (3)$$

The effect of capillary pressure on the water flow into wood chips is not very clear. Studies of wood drying have shown that the moisture content of the wood has a drastic effect on capillary pressure [25,26]. Spolek and Plumb [26] suggested the equation for predicting the capillary pressure, P_c [bar], in softwoods as a function of the wood saturation degree (Eq. (4)). However, this relationship may be inappropriate for the penetration process. For heartwood chips with an initial saturation degree of 0.15, for example, the calculated capillary pressure is about 4 bar. As a result, a significant capillary rise would be expected after the chips come into contact with water.

$$P_c = 1.24 * 10^5 \left(\frac{V_{water}}{V_{voids}} \right)^{-0.61} \quad [26] \quad (4)$$

However, experiments without over-pressure showed that water penetrates the pine chips only to some extent at the very beginning of the process. Then, during short period of time, an hour or less, the degree of penetration does not change significantly. Assuming the capillary pressure to be a driving force and pressure equilibrium to take place after the initial penetration, the value of the capillary pressure was estimated from experimental data. For sapwood and heartwood pine chips penetrated by cold water, these values were between 0.07 and 0.1 bar.

$$P_c = \frac{2 \gamma \cos \theta}{r} \quad (5)$$

Based on Jurin's Law (Eq. (5)), the capillary pressure is defined as a function of surface tension, γ , contact angle, θ , and capillary radius, r [12]. Of course, the geometry of the capillaries varies significantly within a single softwood chip, resulting in different values for capillary pressure. It can be assumed, however, that the penetration into pine chips would primarily take place through the lumens of the tracheids with a typical radius of 10-15 μm [12,27]. Based on the surface tension of water (73 dyne/cm at 20 °C) and a contact angle of 30° [28], the capillary pressure will be in the range of 0.08 - 0.13 bar, which is very close to that estimated from the experiments. For this reason, it was decided to use Jurin's Law for describing the influence of capillary pressure on the water penetration process.

$$\Delta P = \left(P_{ex} + P_h + \frac{2 \gamma \cos \theta}{r} \right) - (P_a(t) + P_v) \quad (6)$$

In this case, the pressure differential can be calculated from Eq. (6) based on the parameters that are known or can be estimated from the literature. However, the partial pressure of entrapped air within the chip voids is changing continuously during forced penetration under isothermal conditions: Compression of the gas by penetrating water causes the pressure to increase. At the same time, a slight decrease in pressure takes place due to the dissolution of air into the surrounding liquid. After reaching the compression level, further movement of water would only be possible due to the dissolution of entrapped air into the surrounding water and diffusion towards the chip surfaces.

$$n(t) = A D \int_0^t \frac{\partial C(y,t)}{\partial y} \partial t \Big|_{y=0} \quad (7)$$

where

- $n(t)$ is amount of air escaped from the gas phase through the unit area,
- A parameter that determines the area of phase border,
- D diffusion coefficient of dissolved air in water,
- y distance from the water-gas interface,
- t time from the beginning of penetration,
- $C(y,t)$ air concentration in water as a function of time and coordinate.

The amount of the air, $n(t)$, dissolved through the unit area of liquid-air interfaces present within the chip can be estimated from Eq. (7). The concentration of air, $C(y,t)$, as a function of coordinate and time can be found based on the Fick's law for diffusion and Henry's law for gas solubility (Eq. (8)).

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial y^2} \quad (8)$$

Boundary conditions :

$$\begin{cases} t=0 & C = C_0 & y \geq 0 \\ t > 0 & C(0,t) = \frac{P_a(t)}{HM} & y = 0 \end{cases}$$

where

- C is air concentration in liquid as a function of time and coordinate,
- D diffusion coefficient of dissolved air in liquid,
- H Henry's constant,
- M molecular weight of liquid (water),
- $P_a(t)$ partial pressure of air inside the wood chip as a function of time.

Assuming that air is an ideal gas and obeys the ideal gas law of state, it is possible to estimate the amount of air trapped inside the wood voids at the beginning of the penetration process. Knowing the initial amount of air and being able to calculate the amount of air dissolved into the liquid phase give us the possibility to estimate the partial pressure of entrapped air, $P_a(t)$, at any moment of the penetration process. Zero approximation of the partial pressure of air is determined from the initial amount of air.

Permeability coefficient of wood chips

In Darcy's law for liquids, the specific permeability of the medium is considered as a function of the porous structure of the medium. In this work, however, the permeability coefficient of wood chip, K_x , is considered as a parameter that describes not only the geometry and structure of the wood capillaries, but also other limitations to the flow of liquid.

A special data set obtained from the experiments with water penetration (25 °C) into pine heartwood chips was used to estimate the permeability coefficient of the chips during the course of the penetration process. The results indicate (Fig. 4) that the permeability coefficient is directly proportional to the external pressure and inversely proportional to the degree of penetration in the second power.

The influence of pressure on the permeability coefficient can be explained by the following phenomena. Surface tension in the liquid-air menisci within the narrow pores and capillaries, which are formed due to capillary condensation of vapor [29], may prevent the penetration of water. A high enough pressure differential may be needed to overcome the surface tension in the liquid-air menisci at the narrow pit membrane openings. So, the higher the pressure applied, the greater the number of pores and openings available for liquid passage. In addition, the applied pressure may affect the capillary structure of wood chips. Due to the plasticity of wood, higher pressures may cause stretching and bulging of the pit membranes, thus making the pit membrane openings larger [30]. The effect of the penetration degree on the permeability coefficient is probably caused by the same phenomena. During the course of penetration, the pressure of compressed air increases and the pressure differential drops. As a result of the lower gradient, the surface tension at some narrow openings cannot be overcome. As a result, fewer pores and openings are available for liquid passage, meaning lower permeability coefficient. The empirical dependence shown in Fig. 4 is used in the model.

It is interesting to refer to George Bramhall's paper [31]. Author proposed the model that also accounted for flow limitations within the heartwood specimens, namely blockage of tracheids by aspirated pits. The Darcy's equation was modified by insertion of the empirical component in form of

negative exponential dependency [31]. Pit aspiration within the heartwood tracheids is an important factor affecting the efficiency of penetration. In current model, it is assumed to be included in the permeability coefficient of wood chip. Theoretically, the effect of pit aspiration could depend on the external pressure as well as the penetration degree: Some of the aspirated pits could become more permeable under high-enough pressure differential. Consequently, this would influence the permeability coefficient of wood chip.

Method of solution

The proposed mathematical model is related to the stiff differential equations that require a special numerical method of solution. The backward differentiation formulas (BDF) were popularized by Gear [32], and are highly effective in solving stiff problems. This method was chosen as a method of numerical solution and acknowledged in all respects.

Two-dimensional penetration

Though longitudinal flow is dominant in softwoods, radial flow may still account for a small part of the total penetration. Consequently, it was decided to include the radial flow in the model. In practice, flows of liquid through the lumens of longitudinal tracheids and via the ray cells cannot be separated due to the presence of interconnecting pits. In this work, however, the radial penetration into a softwood chip is assumed to be independent of the longitudinal one (Fig. 5). The total amount of penetrated water at a certain moment is considered as the sum of liquid that has penetrated through the longitudinal direction, $x(t)$, and radial direction, $z(t)$. The radial permeability coefficient of the wood chip, K_z , is related to the longitudinal coefficient, K_x , through the parameter, η , which can be defined in the range of 50 – 200 [15].

MODEL EVALUATION

Penetration of water

A comparison of the results of model simulations with the data from the experiments with pine sapwood chips indicated that the model closely predicted the penetration of water under different levels of process pressure and temperature. However, the sapwood chips with high moisture content have an initial penetration degree of 75 - 80 %. It may be impractical to use the sapwood data for testing the penetration model under high pressures. On the other hand, the data collected from liquid penetration into heartwood chips with low initial moisture content may provide better information for evaluating the model.

Fig. 6 shows the experimental data and simulation curves for water penetration into pine heartwood chips. Three penetration cases with different pressures are considered. With the defined permeability coefficient of $1.6 \cdot 10^{-16} \text{ m}^2$, the model enables simulating the penetration of cold water very well. Fig. 7 compares the experimental data and simulation curves for water penetration at two levels of process temperature: 25 and 60 °C. As can be seen, the simulation of warm water penetration (60 °C) with the defined permeability coefficient of $1.6 \cdot 10^{-16} \text{ m}^2$ does not describe the experimental data well. Increasing the value of permeability coefficient to $2.8 \cdot 10^{-16} \text{ m}^2$ results in an excellent fit between the experimental and simulation data. At higher temperature, this effect is more pronounced, indicating the clear influence of the process temperature on the permeability coefficient of the chips.

Higher temperature, for example, may influence the permeability coefficient of chips by lowering the surface tension in the water-air menisci at the narrow pit membrane openings. As a result, more pores and openings will be used by penetrating liquid under the same pressure gradient. Temperature may also affect the capillary structure of heartwood chips by softening the resin compounds present at the pit openings, thus increasing the effective dimensions of pores [30]. Most likely, temperature affects other interactions between the penetrating water and wood, which can also cause changes within the capillary structure of the wood chip. To account for these phenomena, the empirical dependence of the permeability coefficient on process temperature can be derived based on the available experimental data and then used in the model.

Penetration of cooking liquors

Corresponding values of the measured properties of white and black liquors, including density, surface tension, and dynamic viscosity, were used in model simulations. The idea was to examine if the change in the basic liquid properties was enough to describe the flow of liquor into chips with the current version of the model. As in case of water, the model closely predicted penetration of white liquor into pine sapwood chips.

Fig. 8 shows the experimental data and simulation curves for white liquor penetration into pine heartwood chips at two levels of temperature: 25 and 60 °C. The simulation of white liquor penetration was carried out with the same defined permeability coefficient of $1.6 \cdot 10^{-16} \text{ m}^2$. The simulation of cold liquor penetration (25 °C) is in good agreement with experimental data, when considering the first twenty minutes of the process. After this, the “real” penetration proceeded faster than the simulated one. It is possible that part of the oxygen present in the entrapped air is consumed in reactions with sodium sulfide. Thus, higher-than-expected pressure gradients can be achieved in the final stages of the process. Also, the chemicals present in the penetrating white liquor may affect the chip structure. The current version of the model does not take these phenomena into account.

As can be seen, the defined permeability coefficient of $1.6 \cdot 10^{-16} \text{ m}^2$ is too low to simulate the penetration of warm (60 °C) white liquor. Increasing the permeability coefficient to $3.8 \cdot 10^{-16} \text{ m}^2$ produces a good fit between the experimental and simulation data (Fig. 8). Here, the effect of temperature on the permeability coefficient of the chip is quite clear. The rate of chemical reactions between the wood constituents and reactive chemicals present in the white liquor is strongly dependent on the temperature, so a higher permeability coefficient is to be expected when the chips are penetrated by white liquor at higher temperature. In addition, swelling of wood phenomenon may play a significant role during the penetration of alkaline liquid, such as white liquor, at higher temperatures. It can be concluded, however, that the suggested model of water penetration can be used for estimating the white liquor penetration. Again, the empirical relationship between the permeability coefficient and temperature of white liquor should be derived and introduced into the model.

Fig. 9 compares the experimental data and simulation curves for black liquor penetration into pine heartwood chips at two levels of process temperature. The defined permeability coefficient used in simulations was the same, $1.6 \cdot 10^{-16} \text{ m}^2$. As can be seen, there is a significant divergence between the experimental and simulation curves. In this case, the model predicts much faster penetration than the experimentally observed. Adjusting the permeability coefficient to $0.5 \cdot 10^{-16} \text{ m}^2$ enabled predicting the latest stages of black liquor penetration at 25 °C. However, the early stage of the process could not be closely predicted by adjusting the model parameters.

The penetration of black liquor at 60 °C was closely simulated with the permeability coefficient of $1.0 \cdot 10^{-16} \text{ m}^2$. This permeability coefficient is considerably lower than the ones expected for water and white liquor penetration. The interaction between the large organic molecules present in the black liquor and wood constituents may have a negative effect on the permeability of the chips.

It is not clear why the model is unable to simulate the black liquor penetration at low temperature. One hypothesis can be that at low temperature black liquor may exhibit a non-Newtonian behavior at the beginning of the penetration process, which cannot be described by the model. Non-Newtonian behavior is usually expected in highly viscous black liquors at high dry solids content of over 50 % [33]. Based on the calculations suggested for estimating the non-Newtonian flows [33], the flow of black liquor with a dry solids content of 11 % should be Newtonian. However, the black liquors behavior at lower dry-solids contents certainly requires more clarification. Testing the penetration of black liquor with 21 % dry solids, for example, indicated that the model could not even be used to simulate warm penetration (60 °C). Based on the obtained results, it was concluded that the suggested model could not be used as a general model for predicting the penetration of black liquor.

It is important to note that when modeling the penetration of cooking liquors into wood chips with moisture content above fiber saturation point, the mixing between the penetrating liquor and the initial water has to be taken into account. Internal mixing would affect the properties of the liquid phase, and therefore the penetration degree.

SUMMARY

A mathematical model was developed for the process of water penetration into softwood chips under isothermal conditions below the boiling point of water. The model takes into account several important phenomena, including capillary rise, air dissolution and outward diffusion, and the decrease in the permeability coefficient of wood as a function of the chip saturation degree. Based on this model, a computer simulation program was written to obtain quantitative information about the penetration of water into different chips under different process conditions. The program was found to predict accurately the course and final level of water penetration into the chips. However, simulating the process of water penetration at different temperatures requires the use of different permeability coefficients. To account for this effect of temperature, the empirical dependence of the permeability coefficient on the temperature has to be derived and introduced into the model.

The model can be used to predict the penetration of the white liquor into softwood chips. However, the effect of chemical interactions between the reactive chemicals present in the white liquor and wood constituents on the permeability of wood chips needs to be taken into account. For this purpose, another empirical dependence of the permeability coefficient on the temperature and, for example, effective alkali can be used. The suggested model cannot be used, however, as a general model for predicting the penetration of black liquor.

ACKNOWLEDGEMENTS

Financial support from the Technology Development Centre of Finland (TEKES) is gratefully acknowledged.

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FIGURES

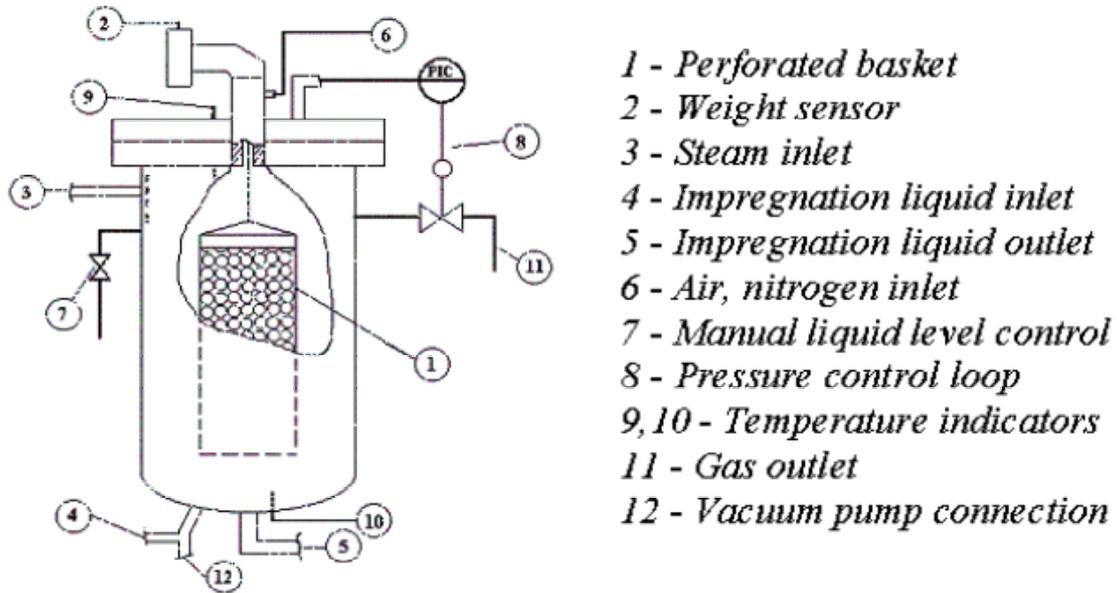


Figure 1. Laboratory impregnator.

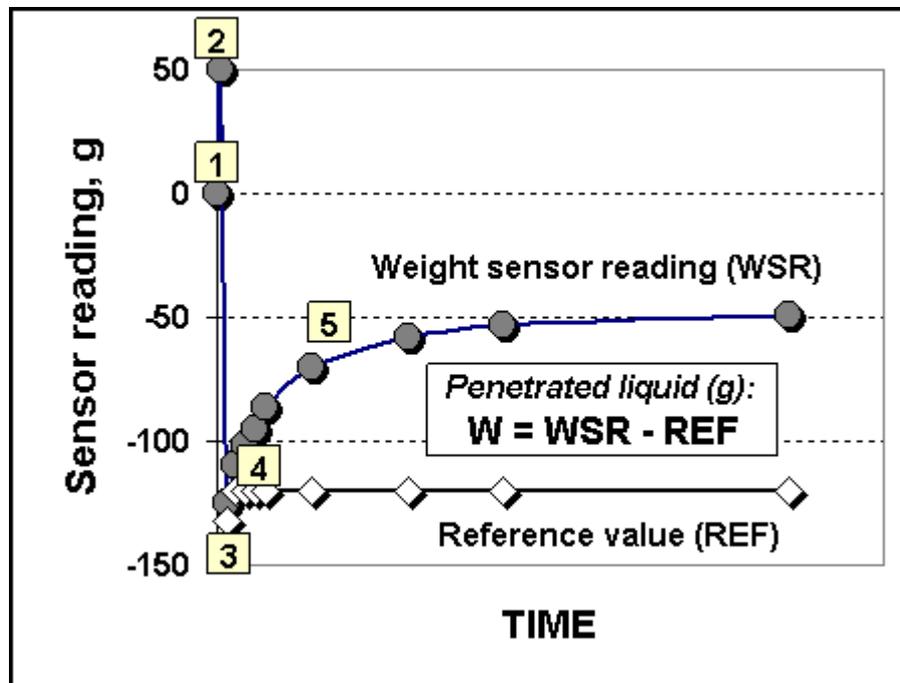


Figure 2. Profile of weight sensor readings.

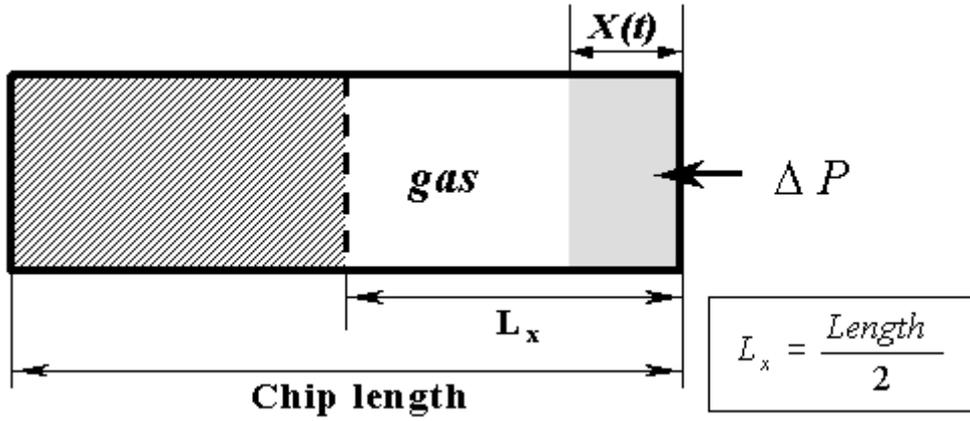


Figure 3. Schematic presentation of longitudinal penetration.

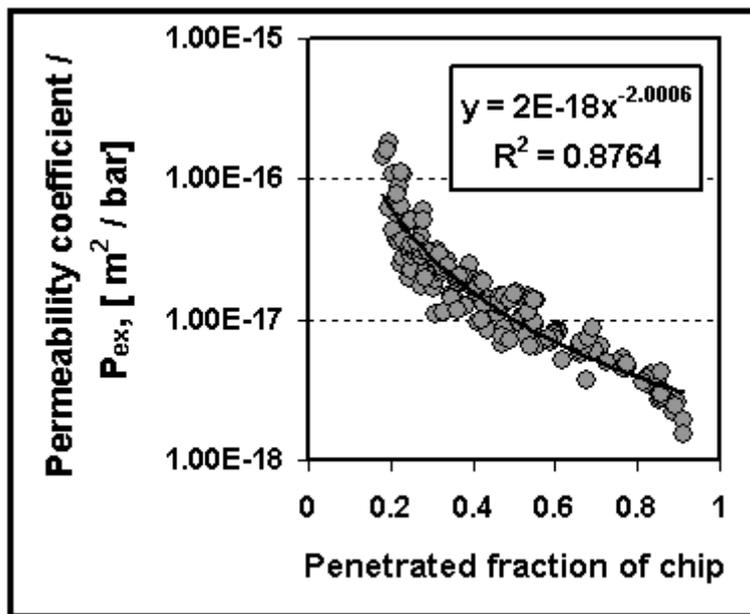


Figure 4. Effect of pressure and penetration degree on permeability coefficient.

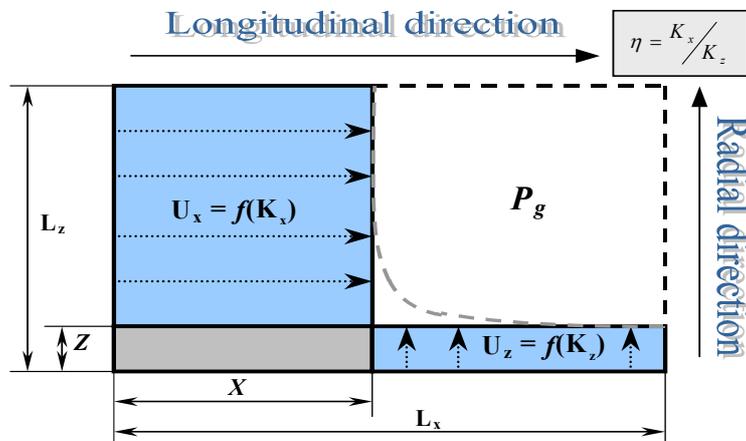


Figure 5. Two-dimensional penetration.

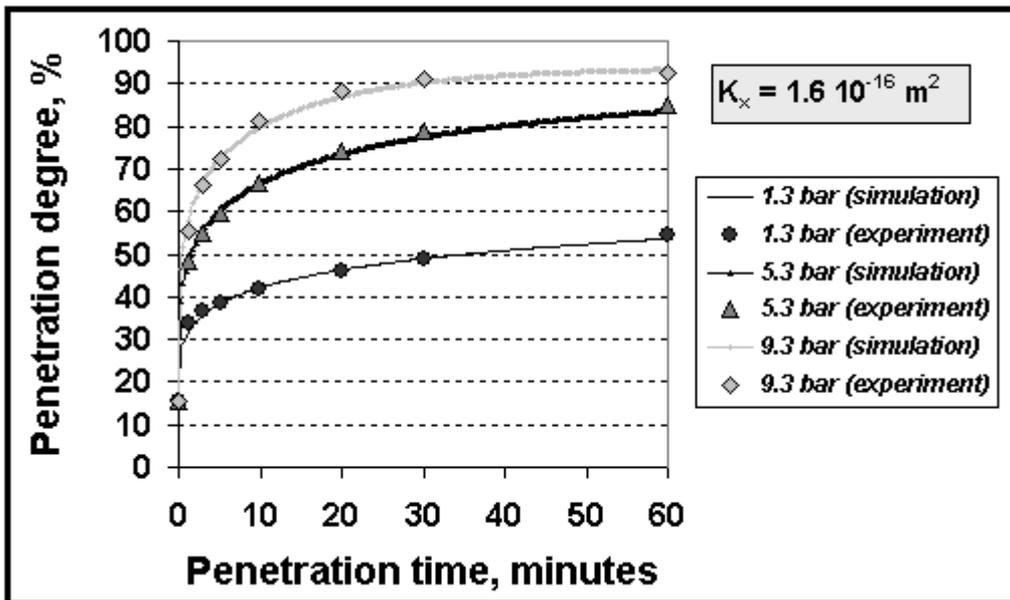


Figure 6. Effect of applied pressure on water penetration into pine heartwood chips; Process temperature 25 °C.

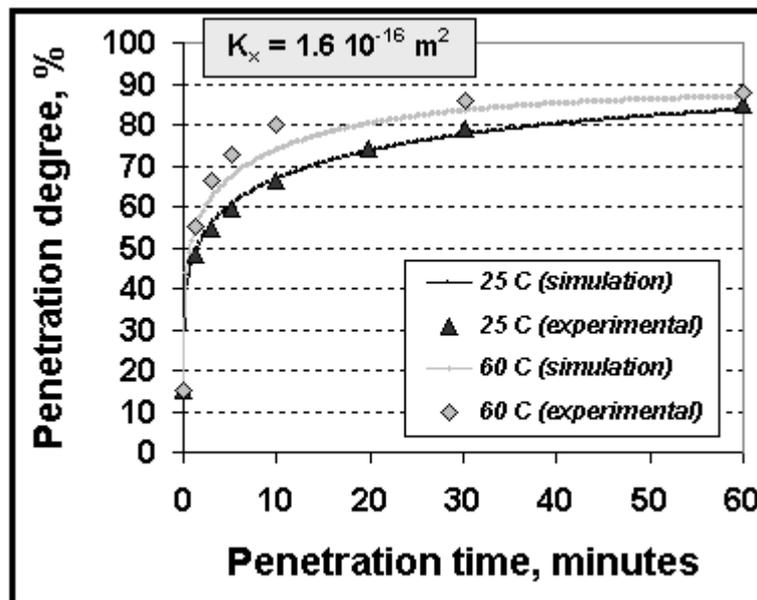


Figure 7. Effect of temperature on water penetration into pine heartwood chips; Over-pressure 5.3 bar.

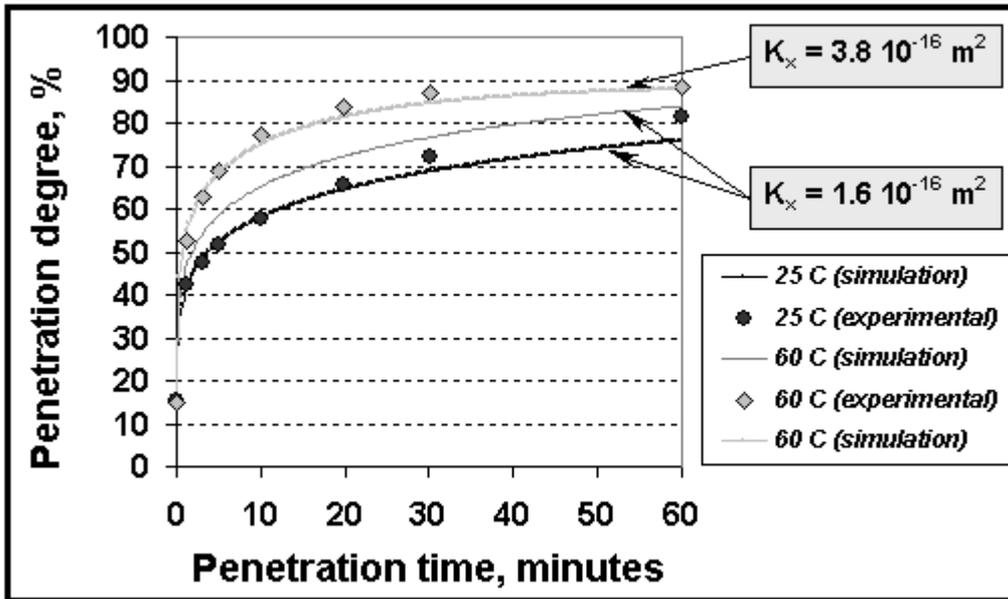


Figure 8. Effect of temperature on white liquor penetration into pine heartwood chips; Over-pressure 5.3 bar.

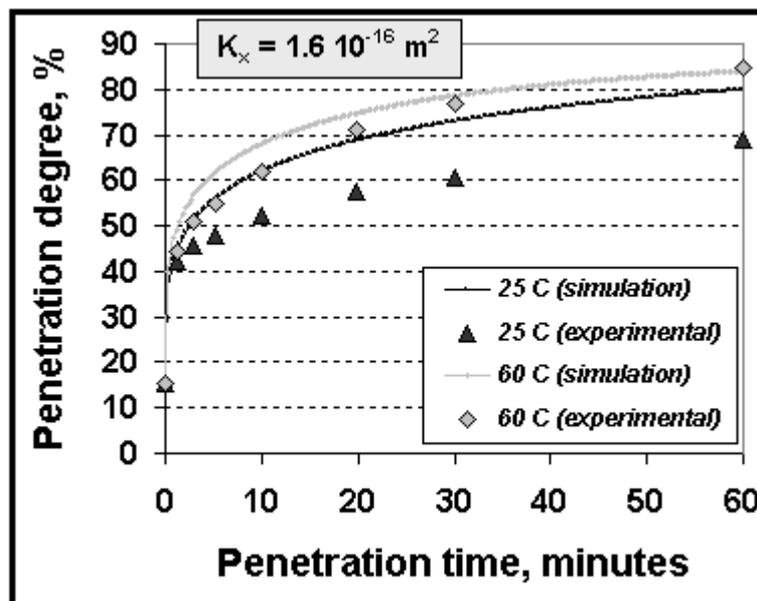


Figure 9. Effect of temperature on black liquor penetration into pine heartwood chips; Over-pressure 5.3 bar; Black liquor dry solids 11 %.