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Towards complete impregnation of wood chips with aqueous solutions

Part 1: A retrospective and critical evaluation of the penetration process

Keywords:

penetration, wood chips, mechanism, process conditions, presteaming, modelling.

Abstract

This paper evaluates the process of liquid penetration into wood chips from the retrospective viewpoint of industrial development and research and provides a summary of currently available knowledge in this area. During the past few decades, researchers have been dealing mainly with pulping chemistry and the back-end of pulping processes, while less attention has been paid to the front-end of cooking. As a result, the latest developments in chemical pulping have been driven by pulping chemistry, and the importance of front-end phenomena has been ignored. In spite of the existence of several concepts and theories, several aspects still remain unclear and more research is needed to achieve a complete understanding of the process of liquid penetration into wood chips. Special emphasis is given to the need for model of liquid penetration and for new reliable and accurate methods that provide direct continuous data on the process.

The paper also discusses the effect of different factors on the penetration process as well as techniques used to improve the penetration efficiency. More effort has to be directed to research concerning techniques designed to promote liquid penetration, including chip presteaming. Industrial applications of chip presteaming allow some scope for improvement, especially in batch cooking systems. To achieve the ultimate target of effective heating and fast gas removal from the chips, special attention has to be paid to optimisation of steaming parameters such as retention time and the pressure-temperature relationship. Against this background, developing a model of chip presteaming is particularly important.

Tiivistelmä

Tässä artikkelissa tarkastellaan puuhakkeen penetraatioprosessia teollisen kehityksen ja tähänastisen tutkimuksen näkökulmasta sekä luodaan yleiskatsaus nykyisestä tietämyksestä tällä alueella. Viime vuosikymmenien aikana tutkijat ovat käsitelleet lähinnä keiton kemiaa ja keiton loppuvaihetta kiinnittäen vähemmän huomiota keiton alkupään prosessivaiheisiin. Tästä seurauksena viimeisimmät kehitysaskeleet kemiallisessa massanvalmistuksessa ovat tapahtuneet lähinnä keittokemian lähtökohdista jättäen pienemmälle huomiolle keiton alun merkityksen. Nesteiden penetroitumisprosessia hakkeisiin on yritetty selittää monin käsittein ja teorioin, mutta yhä on paljon epäselvää joka kaipaasi lisätutkimusta. Erityisesti painottuu nesteiden penetroitumisen mallinnuksen tärkeys sekä tarve löytää luotettavia ja tarkkoja menetelmiä antamaan tietoa prosessista ja sen muutoksista.

Artikkelissa käsitellään myös eri tekijöiden vaikutusta penetraatioprosessiin. Pääpaino on penetraatiota edistävien menetelmien kuten esihöyrytyksen tutkimuksessa. Teollisissa prosesseissa huomiota tulisi kiinnittää hakkeiden esihöyrytykseen etenkin eräkeittoprosesseissa. Tehokkaan hakkeiden lämmityksen ja nopean ilman poiston saavuttamiseksi tulisi kiinnittää erityishuomiota höyrytysolosuhteiden optimointiin kuten höyrytysaikaan ja paine-lämpötila suhteeseen. Tätä taustaa vasten hakkeiden höyrystä kuvaava mallintaminen on erityisen tärkeää.

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Introduction

It is widely recognized today that effective mass transfer of reactive chemicals into wood chips is of utmost importance for chemical pulping processes. Efficient impregnation enables uniform pulping and reduced cooking time /1,2/. Chemical transport into the chip voids is accomplished by two primary mechanisms. The first mechanism, liquor penetration, refers to the flow of liquor into the air-filled voids of the wood chip, under the pressure gradient. The second mechanism, diffusion, refers to the movement of ions or other soluble matter through water under the influence of the concentration gradient /3/.

The objective of the present paper is to evaluate the penetration process from the retrospective standpoint of industrial development and research and to give a comprehensive summary of the currently available knowledge concerning the penetration of aqueous solutions into wood chips. This paper discusses the mechanism of liquid penetration into the wood matrix, phenomena that take place during this process, the factors affecting it and the techniques used to improve penetration efficiency. In addition, the need and directions for future research in this area are outlined.

Retrospective view

A retrospective view of the development of pulping systems and the front-end of the cooking process is schematically presented in *Fig. 1*. The main features of sulphite and kraft pulping processes were already established at the end of the 19th century. Wood chips were cooked in moving, for example rotating spherical, reactors. A big break-through was the transition to stationary batch digesters during the 1910s. Then, until the 1950s, the development of cooking systems involved mainly increasing the size of digesters and optimising the stages and conditions of the process.

The need for efficient transport of chemicals into the wood chip matrix prior to cooking was already emphasized in the early 1920s /4/. During the 1930s, several research projects were undertaken to study the mechanisms of wood chip impregnation and the techniques to improve this process. At that time, however, the interest was mainly focused on sulphite pulping /5-7/ because of the serious concerns related to the “burnt cook” phenomenon /7,8/. “Burning” during sulphite pulping occurred when the incompletely impregnated chips were heated over critical temperature /7/. As a result of numerous studies, the impregnation stage of the industrial sulphite cooking process was gradually perfected. Chip presteaming and pressure impregnation were used to enhance the penetration of liquor into the chips /8/. However, these advances in technology were seldom applied to the kraft process. It was believed then that, because of the much faster diffusion of alkaline liquors impregnation played a negligible role in soda and kraft processes /7/. Also, the heating-up times of the kraft batch processes were long enough to disguise the effect of diffusion limitations. Wood chips were usually only briefly steamed during the chip charging stage /9/. This can be viewed in relation to enhanced penetration, though the main idea behind this was to achieve uniform packing and to limit the passage of air into the digester.

During the 1950s, following the development of continuous systems that had a shorter impregnation time, the question of efficient impregnation in kraft cooking was brought up, especially in relation to softwood chips. This triggered research aiming at optimising the conditions for penetration and diffusion of kraft liquor into the wood chips, as well as application of certain pre-treatments to enhance these processes. For many years, the horizontal steaming vessel was the only presteaming equipment available in the industry. However, because of unfavourable conditions and short retention times /10/ its efficiency in removing air from the chips was low. Further advances in continuous kraft technology took place during the late 1960s - early 1970s. These included development of two-vessel systems with a separate impregnation vessel and atmospheric chip bins, which had some success in addressing the problem of inefficient penetration.

Continuous cooking remained the mainstream of digester design until the 1980s, when the concept of “modified kraft cooking” was developed in Sweden /11/. The main ideas behind this concept were to even the alkali profile throughout the cook, to increase the concentration of hydrosulphide ions at the beginning of the cook, to lower the dissolved lignin content at the end of the cook and to lower the cooking temperature. Since then, some of the principles of “modified cooking” have been utilized for developing the batch kraft pulping technology, resulting in several new competitive processes /12,13/. The “modified cooking” concept was also applied to continuous technology to develop new processes /14,15/. The last couple of decades have been characterised by a burst of research activity all around the world in the area of pulping chemistry and the latest stages of the process (back-end of cooking). In contrast, the basic phenomena that take place at the front-end of cooking have barely attracted attention among scientists. As a result, the latest developments in kraft cooking have mainly been driven by advances in pulping chemistry, disregarding the front-end issues.

Still, new trends in cooking processes emphasise the need for improving contemporary “front-end” technology: Lower the temperature profile during the cook leading to a lower process pressure, increasing the batch capacity and shortening the batch cycles to achieve the higher pulp production as well as concerns for uniform pulping /1,2/ would all call for more effective penetration and diffusion of reactive chemicals into the wood chips. Nevertheless, the front-end technology has remained practically unchanged during the past few decades (**Fig. 1**). The only advances have been related to the development of atmospheric chip bins.

Research methods used

A number of studies have been carried out in the past to examine the process of liquid penetration into wood. Different techniques and methods have been used to obtain quantitative and qualitative information about this process (**Fig. 2**). Some basic methods included a sinkage test /16,17/, where the time it took for wood blocks to sink in water was measured and an “uptake”-method /17-19/, where the weight of an untreated or oven-dry sample was compared to that of a treated sample. With these methods, it was difficult to achieve reproducible and accurate results, due to a number of drawbacks and specific features of these procedures. Also, special penetration clamps have been used to study the permeability properties of different woods /20-23/. The image analysis technique, including digitising and analysing photographs of sliced frozen chips after impregnation, has also been used for quantitative studies /24/. However, because of interference between diffusion and penetration, only a rough estimation of the penetration degree could be achieved with this method. Most of the methods used provided indirect data on liquid penetration process, while only a few techniques provided direct information. Quartz spiral balances have been used to measure the flow of liquids into a single wood chip on a continuous basis /25-27/ and to study the effect of different process conditions and chip pre-treatments on penetration efficiency. Here, however, the small size of the wood sample did not allow accurate results to be obtained for various chips.

While the above-mentioned methods gave an estimation of the amount of penetrated liquid and the penetration rate, others also provided qualitative information about the ways how liquid penetrates into wood voids. These methods generally included treatment of wood samples with liquid under controlled conditions, followed by a microtoming procedure and analysis /28-32/. These included scanning electron microscopy (SEM) /28,29/, staining and precipitation techniques /20,22,30/ followed by microscopic observations as well as a radioactive tracer technique /31,32/. Most recently, nuclear magnetic resonance (NMR) imaging has been suggested as a non-destructive method for studying the movement and spatial distribution of moisture within wood samples /33-35/.

Research carried out from the 1940s until the 1970s led to the introduction of a number of concepts and theories related to the transport of liquid in wood. This knowledge helps to understand some of the phenomena that take place during the flow of liquid into the wood matrix, the factors affecting the penetration of liquid and ways how to improve it. However, a lot of aspects remain unclear and more research is needed to achieve a complete understanding of the process of liquid penetration. As a

result, there is a need for new reliable and accurate methods that are able to provide direct continuous data on the process of liquid penetration.

General mechanism of penetration

Forced penetration of liquid into the capillaries of the wood chip takes place due to the pressure gradient /36/. Wood chips used in chemical pulping processes are practically never oven-dry or water-saturated. Usually, wood chips represent a three-phase system consisting of solid wood substance, water and some amount of gases, mainly air, present within their voids. In this case, the pressure differential can be considered as the difference between the sum of external, hydrostatic and capillary pressures and the total pressure of the gaseous mixture within the wood voids (Eq.1). Here, the external pressure is the sum of the ambient pressure and the over-pressure applied.

$$\Delta P = (P_{external} + P_{hydrostatic} + P_{capillary}) - P_{gas} \quad (1)$$

When liquid starts to penetrate into a wood chip, the gas present inside the void spaces becomes compressed. Transport of liquid will then be slowed down and eventually stop because of the growing back-pressure. After pressure equilibrium is achieved, further penetration would be possible either due to an increase in the pressure applied or a decrease in the pressure of the gaseous mixture.

$$P_{gas} = P_{air} + P_{vapour} \quad (2)$$

Neglecting the presence of minor gases, the total pressure of the gaseous mixture can be considered as the sum of the partial pressures of air and water vapour (Eq.2). The last one is a function of temperature and can be considered constant under unchanged conditions. In this case, the decrease in gas pressure inside the wood chip would take place only via a reduction in the amount of entrapped air. Theoretically, some air may be pushed out of the chip by the penetrating liquid, which is determined by the geometry of the capillary system. Also, the chemicals present in the penetrating aqueous solution may consume the oxygen contained in the air. However, in practice, the most probable way for remaining air to escape from the chip voids is by dissolution into the surrounding liquid and outward diffusion.

The structure of wood and the fact that the cell walls are hygroscopic complicate the mechanism of liquid penetration into the wood chip. A number of different simultaneous phenomena take place when the liquid penetrates into the wood voids. While some phenomena may have a positive effect on the penetration process, others might cause obstruction of the liquid flow. For example, diffusion of water vapour may play a critical role during penetration into dry wood chips /8,17/. On the other hand, capillary condensation of vapour in pit pores above the penetrating liquids may prevent the escape of trapped air from the fibre cavities with fine pit openings /37/. The influence of bound water, swelling of the cell wall, and surface tension forces at the gas-liquid interfaces within the wood chip on the penetration process is still unclear. In addition, the potential escape of air from the wood voids during penetration is not well understood.

Theoretically, different kinds of liquid flow may occur in a porous medium such as wood /38/. It is generally accepted, however, that the viscous or linear laminar flow is the dominant one, while true turbulent flow is unlikely to occur in wood capillaries /39,40/. Non-linear flow due to kinetic energy losses can also occur in wood, particularly where fluids enter a pit opening /41-43/. Molecular slip flow can be considered insignificant due to the relatively short mean free path of liquid molecules.

$$Q = \frac{K A}{\mu L} \Delta P \quad (3)$$

where

- Q - volumetric flow rate of liquid,
- μ - dynamic viscosity of liquid,
- K - specific permeability of wood chip,
- L - length of the specimen in the flow direction,
- A - cross-sectional area,
- ΔP - pressure differential.

$$Q = \frac{N \pi r^4}{8 \mu L} \Delta P \quad (4)$$

where

- N - number of uniform circular capillaries in parallel,
- r - radius of capillary.

$$h^2 = \frac{r \sigma t}{2 \mu} \quad (5)$$

where

- h - capillary rise,
- σ - surface tension at interface,
- t - time.

Assuming pure viscous flow of liquid inside the wood chips, the penetration process can be estimated with the help of fundamental laws: Darcy's law (Eq.3) or Poiseuille's law (Eq.4) /38/. The effect of the capillary forces may be approximated with Jurin's law /38/ or the formula suggested by Lucas /8/, which describes the capillary rise as a function of the radius of capillary and liquid properties (Eq.5). Keeping in mind that these laws were discovered long before the 20th century, the following question arises: Why has nobody evaluated the penetration efficiency of water and liquors into wood chips just by developing a simple model of the process? With the current progress in pulping technology, mathematical calculation and modelling of the penetration process may play an important role. Adequate models may provide a quick and inexpensive tool that can be used for process control, development of new cooking scenarios, for optimising process conditions and for training purposes.

Factors affecting the penetration

A great deal of knowledge has been obtained regarding the factors that influence the penetration of various liquids into wood chips. These factors can be put into three groups (**Fig. 3**). The first group includes factors related to wood chips, such as the structure of wood capillaries, the chemical composition of wood, the moisture and air contents of the chips, and chip dimensions. The second group includes factors related to the liquid, such as its viscosity, surface tension, composition, air solubility and air saturation degree. Process conditions, such as pressure, temperature and duration of penetration, form the third group of factors.

Factors related to wood chip

Arguably, the most important factor that affects the penetration is the capillary structure of wood chips. The structure of the wood capillaries, which is defined by their types, geometry, distribution and accessibility, is different in softwoods and hardwoods, sapwood and heartwood, earlywood and

latewood, normal wood and reaction wood and also varies between wood species. The porous structure of softwoods and hardwoods and its effect on liquid flow paths were intensively studied during the last century. A review of this matter will not be attempted here, as excellent summaries of this early work have been given by Rydholm /8/ and Siau /38/. Regarding the liquid flow paths within the wood chip, it is important to add that the availability of artificial paths, such as cracks or fractures, can play an important role for penetration. The rate of liquor penetration into commercial chips may be higher than expected due to fissured structure of the chips /2/. It has also been suggested that cracks and fissures could be created inside thick chips by various crashing or compressing methods to improve the penetration of liquor /44,45/.

Since the longitudinal flow is dominant in both hardwoods and softwoods /3,8,17/, the length of the chip should be the most critical dimension for liquid penetration. Some direct /46/ and indirect experimental data /47,48/ confirm that a reduction in chip length results in improved penetration. However, chip thickness is also believed to affect the penetration by providing shorter paths for diffusion of dissolved air /24/.

The permeability of a wood chip is strongly influenced by its moisture and air contents. Cell walls of “dry” wood chips with moisture content below the fibre saturation point may adsorb part of the penetrating liquid and swell to some extent. This liquid up-take by unsaturated cell walls may result in reduced flow resistance and an improved penetration rate. On the other hand, the permeability of some softwoods decreases with an increase in moisture content /49,50/, which is attributed to swelling. Excess moisture in the wood voids may also act as a physical barrier to the mass motion of liquor /51/ and, therefore, negatively affect the penetration efficiency. It is generally agreed that the air present within the wood capillaries is the main obstacle to rapid penetration of liquor /17,23,26/. When penetration is allowed to occur from both sides of the wood chip, the back-pressure of trapped air, which becomes compressed by capillary forces, soon checks the penetration /8/. For this reason, in order to reach a high penetration degree it is more favourable to have chips with a higher moisture content and less air.

The chemical composition of wood chips also has a bearing on the penetration process. Phenomena that take place during penetration, including capillary rise, swelling, and chemical interactions are greatly dependent upon the nature of the wood constituents. A high content of extractives, for example, can negatively affect the penetration of liquid by enhancing pit aspiration and plugging capillaries, reducing the wetting of surfaces and decreasing the effect of capillary rise /52/, forming a colloidal solution /51/, and affecting the swelling rate of wood in liquids /53,54/.

Factors related to liquid

The viscosity of the penetrating liquid and the surface tension at the liquid-gas interface are major characteristics influencing the flow rate in wood and the capillary rise /8,38/. Other factors, such as the solubility of air in the penetrating liquid and the degree of air saturation at the beginning of penetration, determine the efficiency of the final penetration phase. The chemical composition of the penetrating liquid may affect the penetration process in several ways. Reactions between chemicals present in the penetrating liquor and wood constituents may alter the capillary structure of the chip. Also, the chemicals may consume the entrapped oxygen, possibly causing a decrease in the gaseous pressure inside the chip. In addition, the nature of the liquids has a significant influence on the swelling of the wood. Liquids with strong hydrogen bonding potential have an affinity for wood and are likely to produce the greatest swelling effect /53,55/. Still, it is not well understood how the swelling of wood influences the changes within the capillary structure of the wood chip and the liquid penetration process. According to some researches, the slow penetration of sufficiently alkaline cooking liquors, such as kraft liquor, is due to their wood swelling capability /3,50/. Nevertheless, the total amount of penetrated liquid has been found to be higher for liquids with higher swelling capability /56/.

Process conditions

An increase in the temperature of penetrating liquor in the range below boiling point under constant pressure leads to an increase in the penetration rate, which can be attributed to a reduction in liquor viscosity /3,17,25/. On the other hand, the higher liquor temperature may have some negative effects on the penetration, including thermal expansion of the gaseous mixture within the wood chip voids, reduced solubility of air in the liquor, and decreased surface tension. This may be the reason why the increase in temperature in some cases did not have any noticeable effect on the liquid uptake into wood chips /18,46/. The temperature of penetrating liquid may also influence the penetration process by promoting changes within the capillary structure of wood chips /25/ and affecting the swelling process /53,54,57/. The overall effect of temperature on the penetration of liquid into wood chips is strongly dependent on the type of wood chips, the liquid and the pressure applied.

Since the pressure gradient is a driving force for penetration of liquids into wood chips, it is clear that an increase in applied pressure will result in faster penetration /3,25,27/. In most cases, the application of over-pressure is a pre-condition for efficient penetration of liquid into wood chips. High enough pressures are required to overcome the negative effect of surface tension in the liquid-air menisci, which are formed by capillary condensation of vapour /37/. With a number of wood species, the flow rate of water through the wood increases more rapidly with an increase in applied pressure than would be theoretically expected /17/. This has been explained by the effect of pressure on the capillary structure of wood chips. Because of the plasticity of wood, high pressures may cause stretching and bulging of the pit membranes, thus making the pit membrane openings larger /25/. Higher pressure also results in better solubility of air into the liquid, thus allowing more air to be dissolved and a higher penetration degree to be reached. There are some controversial results regarding the effectiveness of the pressure pulsation technique in comparison to constant pressure /25,27/.

The duration of the penetration process is another critical factor that determines the final degree of penetration achieved. Most of the liquid penetration under pressure takes place within a few minutes /23,25/. This initial penetration proceeds until the compression of the gaseous mixture inside the chips is reached. The time required to reach this “compression level” greatly depends on the capillary structure of the wood chips or their permeability /46/. The duration is even more important for the final penetration stage, which is determined by the dissolution of entrapped gas and diffusion /25/.

“Penetration aid” techniques

Much work has been devoted to the development of suitable pre-treatments, in order to improve the penetration of liquids into wood chips. The main objective of these “penetration aid” techniques is to alter the parameters related either to the wood chips or to the liquid, thus affecting the penetration process. Most of the known “penetration aid” techniques can be divided into four groups (**Fig. 4**): methods aiming for air removal, addition of surfactants, “mechanical impact” techniques and biological pre-treatments of chips. The “mechanical impact” group includes techniques that mechanically affect the structure of wood chips, i.e. inducing cracks and fissures. These include thickness screening, chip conditioning and chip optimising. Some new techniques, which aim at improved permeability of pits can also be added to this group, including pre-compression of chips /44/ and laser treatment /58/.

Air removal techniques

It is obvious that the air present within wood capillaries is one of the most detrimental factors affecting the penetration of liquid. Moreover, complete penetration can only be achieved if most of the trapped air is removed prior to penetration. A number of methods have been developed with the primary aim of removing air from the chips /8,26,59-61/.

Evacuation of dry wood chips has been found to be very effective in removal of air /17,23/. The efficiency of evacuation is greatly dependent on the vacuum used. Theoretically, evacuation under fairly low pressure, which causes water to boil and air to expand and escape, makes it possible to achieve complete removal of air. In practice, complete removal of air is difficult to achieve, especially when applying the evacuation technique to wood chips with normal moisture content. Removal of air can be limited by the specific characteristics of the wood capillaries. Some air can be trapped within capillaries, which are sealed by extractives. In addition, the high surface tension which occurs in the narrow capillaries of a partially saturated chip may counteract the pressure gradient formed during evacuation /7/ and limit the removal of entrapped air. Since evacuation is impractical in ordinary digester operation /8/, research on this method has remained at laboratory scale.

Another technique is to replace the air present inside the wood chip by condensable gases, such as sulphur dioxide and ammonia /7,17,23/. Part of the air within the wood chip can be replaced by repeated applications of a gaseous pressure, alternating with relief. During the subsequent penetration of liquid, the gas present within the capillaries will dissolve and cause the liquor to fill up the chip. If the gas used in treatment is easily soluble in cooking liquor, fast penetration can be expected. The results obtained with penetration into wood chips treated by condensable gases are comparable to those achieved with pre-evacuation /7,17,23/. This technique is not in practical use, mainly because there are equally effective but simpler methods.

The most common technique for air removal is presteaming of the wood chips by a flow of steam at atmospheric or super-atmospheric pressure /10,26,61-63/. Thermal expansion due to elevated temperatures causes partial removal of air, up to 25 % of the original /8/. However, the main effect on air removal is due to the increased pressure of water vapour, which causes air to be expelled from the chip /64,65/. Theoretically, complete air removal can be achieved when the partial pressure of water vapour inside the chip is equal to the ambient pressure. In addition to its primary objective of air removal, presteaming seems to improve penetration process by affecting the structure of wood capillaries /66-68/. Important variables related to chip presteaming are steaming temperature, pressure and time. An increase in steam temperature or pressure enhances the penetration rate of liquids /26/. Still, more critical than presteaming temperature is its duration /8,10,26/. Incomplete removal of air during presteaming is not necessarily related to low efficiency in heating, but can be caused by pressure resistance inside the wood capillaries. To achieve efficient steaming, it is very important that the retention time is long enough for air to escape and that the pressure-temperature relationship is correct. Because of its relative simplicity and other advantages, steaming of wood chips prior to impregnation is widely used in the pulping industry. However, the contemporary industrial equipment used for chip presteaming allows some scope for improvement. The ultimate target for these systems is to ensure proper contact between steam and chips during a sufficient time interval, so effective heating and fast diffusion of gas are achieved.

Addition of surfactants

Addition of surface-active agents, surfactants, to the penetrating liquid has been intensively studied in the past few decades. Addition of certain surfactants can result in reduction of the contact angle and increased wettability of the wood chip surfaces /69,70/. Surfactants can also improve the penetration through wetting and emulsifying effects on hydrophobic extractives /52,71,72/. On the other hand, the reduction in surface tension may have a negative influence on the penetration and counteract all positive effects. In fact, the application of surfactants will primarily depend on the capillary structure and composition of the wood chips under consideration. The overall effect of surfactants is still unclear. Some studies indicate that surfactants have little or no effect on penetration efficiency /18,71/. In other cases, addition of surface-active agents to the cooking liquor has resulted in improved pulping performance, which is attributed to more thorough penetration /50,72-74/. Contradictions between various results can be caused by differences between the wood chips used and between surfactants and penetrating liquids. There is still a need for detailed research in this area to achieve a better understanding of the effects of surfactant addition on the penetration of liquids into wood chips and the mechanisms behind it.

Bio-treatments of chips

Several methods have been suggested based on the biological pre-treatments of chips with enzymes or fungi prior to liquid penetration. It has been shown that enzymes containing pectinase, cellulase and hemicellulase attack the pit membranes in both softwoods /75-78/ and hardwoods /78/, causing dissolution of the membrane material. Theoretically, this phenomenon should clearly improve the penetrability of the treated chips. In practice, however, the use of enzymes to enhance the penetration will strongly depend on the mass transfer efficiency of enzymes, which is determined by their molecule size.

Pre-treatment of wood chips with various fungi prior to chemical pulping is a relatively new area of research. It has been suggested that changes within the capillary structure, which take place during pre-treatments, can result in improved liquid penetration /79-83/. Electron microscope studies indicate that treatment by fungi results in softening and swelling of wood cells /79,80/. In addition, many species of fungi have been found to degrade extractives within the wood capillaries and rupture the pit membranes /79,82,83/. To achieve a better understanding of the effect of pre-treatment by fungi on penetration, more experimental data are needed.

Summary

Thanks to the research carried out from the 1940s until the 1970s, a number of concepts and theories related to the transport of liquid in wood are today available, and it is possible to understand some of the phenomena that take place during the flow of liquid into the wood matrix and the effects of various conditions on the process. However, a lot of aspects related to the mechanisms of liquid penetration still remain unclear. In the past few decades, researchers have been focusing on pulping chemistry and the back-end of the pulping processes, while less attention has been paid to front-end phenomena. As a result, the latest developments in chemical pulping have been driven by chemistry, and the importance of the physics at the front-end of cooking has been ignored.

For this reason, more research is needed to achieve a better understanding of front-end phenomena and to improve contemporary front-end cooking technology. Modelling of the penetration of liquid into wood chips would help to gain a better understanding and knowledge of its mechanisms. Modelling a process such as liquid penetration into wood chips is a very difficult task because of the non-homogeneous and complex structure of wood and the numerous phenomena that take place simultaneously. The proposed models of penetration have to be validated against reliable data. To this end, it is important to develop techniques that allow quantitative and qualitative measurements of liquid penetration into wood chips to be carried out on a continuous basis in a wide range of process conditions.

The advantages of efficient presteaming of wood chips prior to impregnation are well known in the pulping industry. However, industrial applications of this technique need to be improved, especially in batch cooking systems. To achieve the ultimate target of effective heating and fast gas removal from the chips, special attention has to be paid to optimisation of steaming parameters such as retention time and the pressure-temperature relationship. Against this background, developing a model of chip presteaming is particularly important. The design of industrial equipment used for chip presteaming will also play an important role. In addition, more effort has to be directed to the research concerning other “penetration aid” techniques, including the use of surface-active additives, bio-treatment of the wood chips, and some new approaches aiming at altering the structure of wood chips.

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Figures

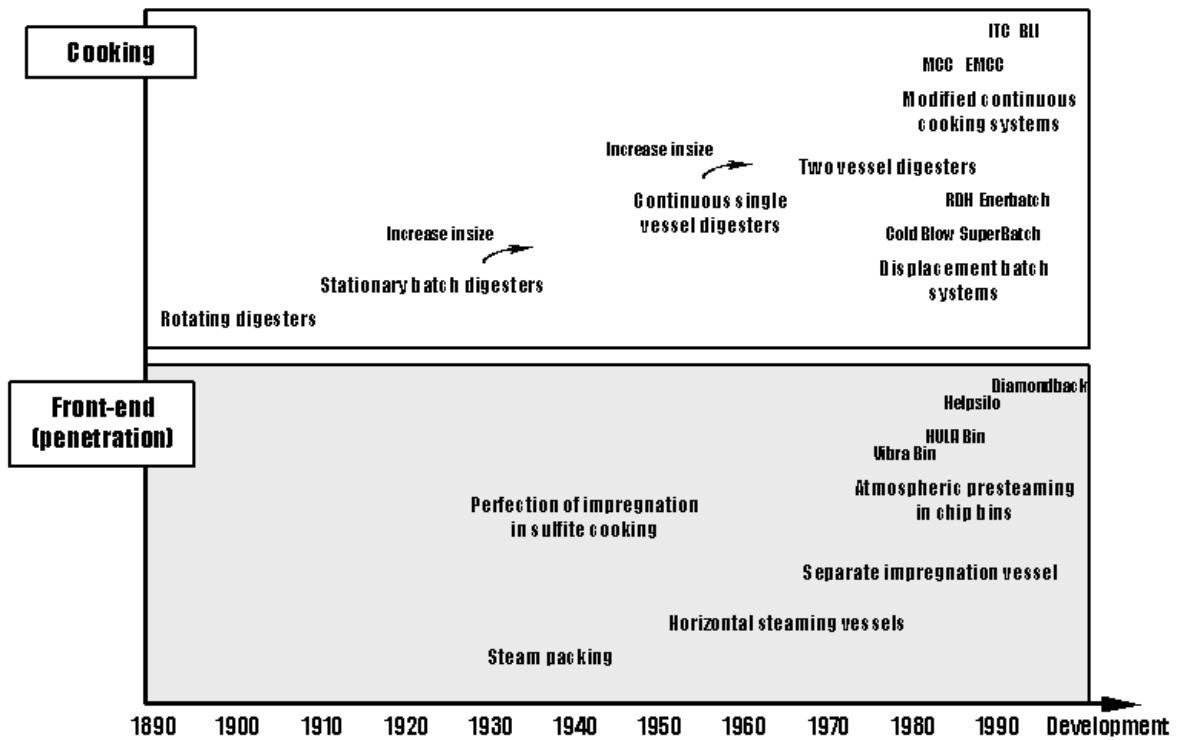


Fig. 1. Retrospective view on the development of pulping systems.

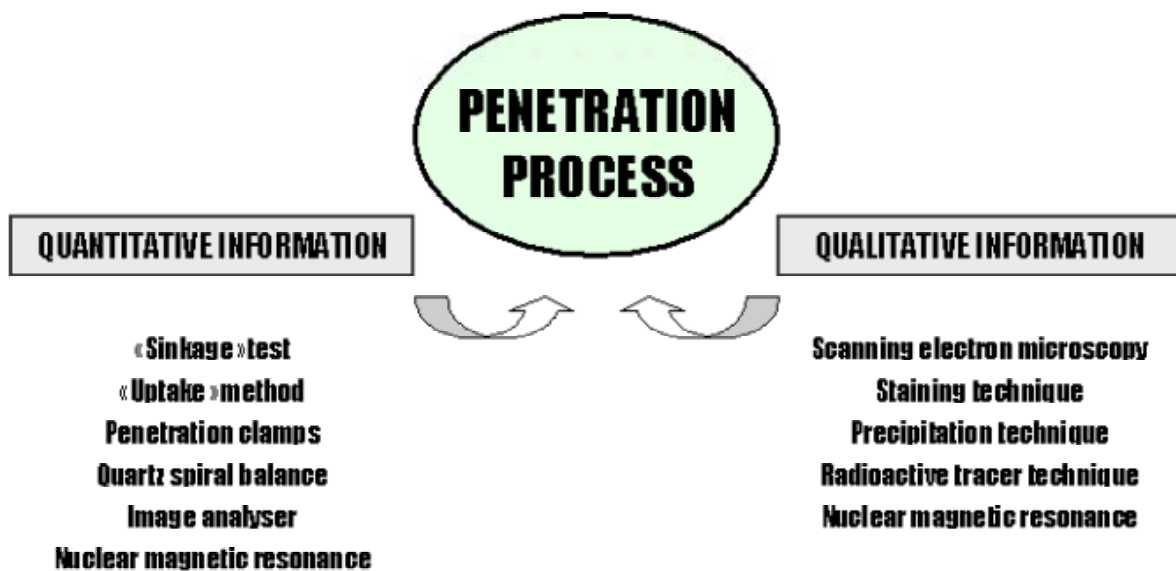


Fig. 2. Methods used for studying liquid penetration.

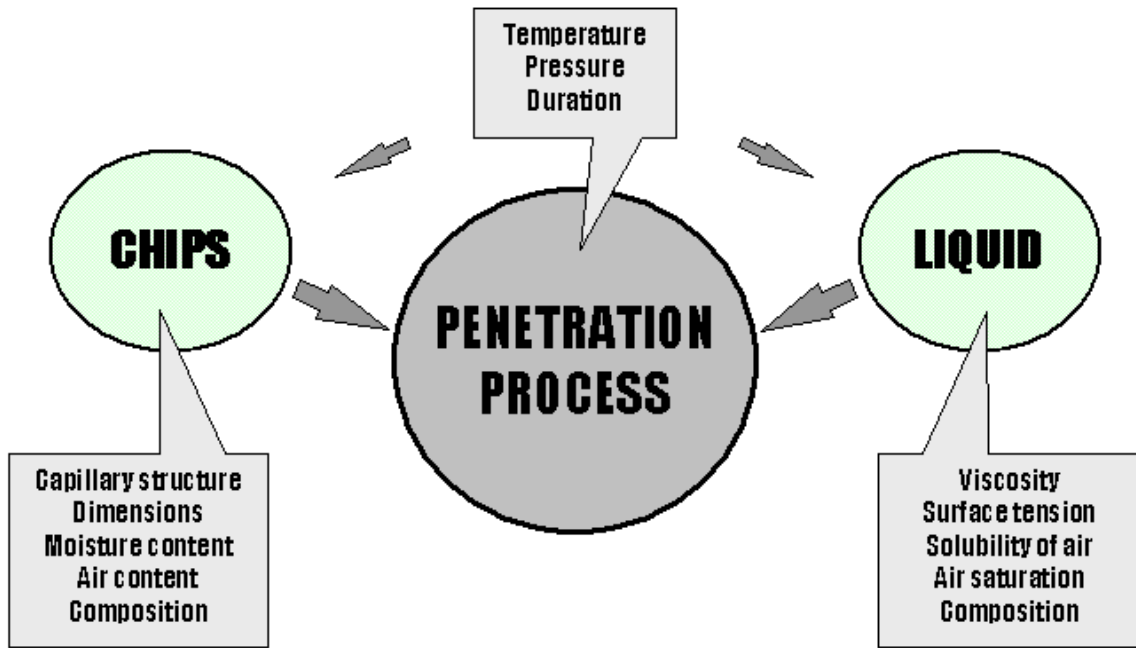


Fig. 3. Factors affecting penetration process.

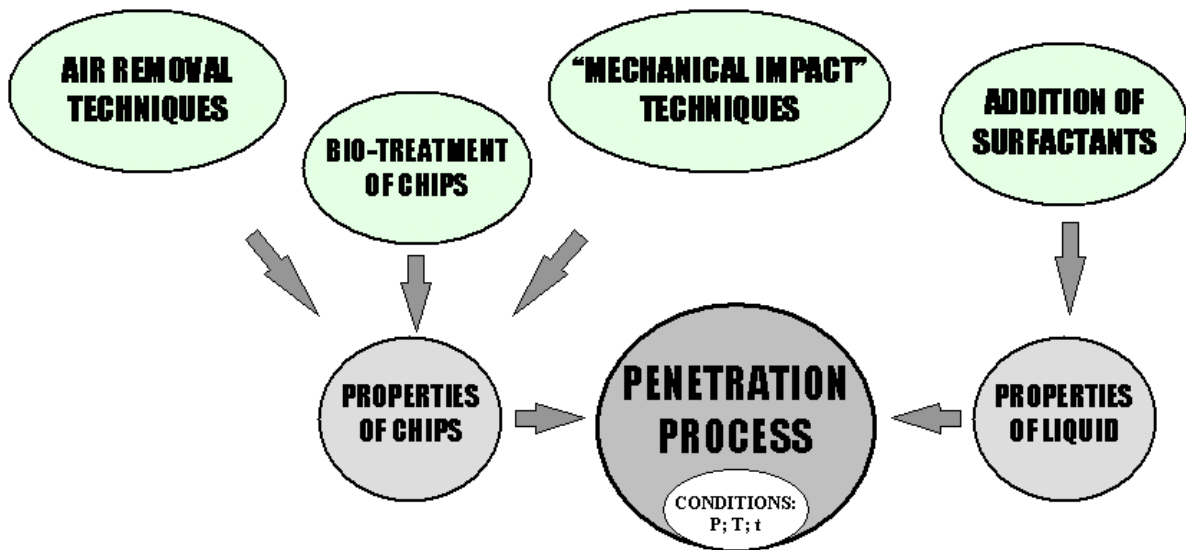


Fig. 4. "Penetration aid" techniques.