SOME ASPECTS OF WESTERN HEMLOCK AIR PERMEABILITY

by

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Abstract

This study is intended to explore the variability in longitudinal and radial air permeability of western hemlock and to determine the effect of tracheid length and wood density on measured permeability.

Western hemlock (*Tsuga heterophylla*) is one the most abundant species in British Columbia’s and it is one of the demanding species a in North America and Asian market. An important attribute of hemlock is the ease with which it can be pressure impregnated with wood preservatives. In spite of its reputation for treatability, hemlock still varies quite widely in its receptivity to treatment. Although this variability exists, there is little information known on the relative differences in permeability within hemlock, despite of its importance as a treatable wood.

Ten western hemlock trees were randomly selected and samples were selected from three different tree heights of each tree. The specimens were then conditioned to 12% moisture content to nullify the effect of moisture content on permeability. The air permeability of sapwood and heartwood specimens in longitudinal direction at three different tree heights was measured using a dynamic method. Tracheid lengths were measured with a fiber quality analyzer and density of each specimen was measured by water displacement. The effect of tree height, tracheid length and density on longitudinal permeability was then evaluated.

Data analysis revealed that tree height has no effect on heartwood longitudinal permeability whereas in sapwood the longitudinal permeability at 7m height was found to be significantly higher than that of 1m or 4m. It was also clearly apparent that longitudinal
permeability was not influenced by the tracheid length and wood density. The radial permeability of heartwood and sapwood samples were also measured at three different heights and observed that radial permeability of both the samples at 7m is significantly higher than that of 1m or 4m.
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1 Introduction

The importance of liquid or gas flow through the porous structure of wood is widely recognized in processes such as pulping, preservation and drying since they are all affected to a great extent by the ease with which fluids move through the internal wood voids under a static or dynamic pressure gradient.

Specific permeability is a material property that indicates how freely fluids flow through the interconnected void volume in response to a static pressure gradient (Siau 1995). Due to the substantial variation in wood anatomical characteristics, direct investigation into the mechanism of liquid flow is not an easy task, and previous research has not been very successful. Moreover, it is believed that wood undergoes changes in its structure and geometry during contact with liquids particularly polar solvents such as water (Banks and Levy 1980, Hossfeld 1972, Wardrop and Davies 1961). Thus, the complexities of such investigation are only made more difficult.

The flow of inert gases on the other hand, does not appear to cause changes of this kind, provided the moisture content is kept constant (Smith and Banks 1971). Therefore, the simplest mechanism to investigate wood permeability is through meticulous measurement of gas flow as a function of time, pressure gradient and wood dimensions. It has been established that a high degree of correlation exists between gas and liquid permeability (Choong and Tesoro 1974) and an easy way exists to calculate the one from the other (Siau 1995).

Western hemlock (*Tsuga heterophylla*) is a species that is of great value to the coastal wood processing industry. The B.C Ministry of Finance and Corporate Relations reported
that approximately 95 percent of BC coastal sawmills production of baby-squares (105mm x 105mm) from western hemlock and amabilis fir (*Abies amabilis*) are exported to Japan using the commercial name Pacific Coast Hemlock (PCH). Hemlock is an important coastal species in BC, but for many years its commercial value has been overshadowed by the more valuable Douglas-fir (*Pseudotsuga menziessi*). However, changes in purchasing preferences, have led to hemlock gaining in market value and market share, particularly in Asian export markets (Perez-Garcia and Barr 2005).

An important attribute of hemlock is the ease with which it can be pressure impregnated with wood preservatives. However, in spite of its reputation for treatability, hemlock still varies quite widely in its receptivity to treatment (Cooper 1973, Kumar and Morrell 1989). The reasons for this variability remain unclear, while it has been suggested that treatability is a function of anatomical structure, forest site and elevation (Miller 1961). The indistinguishable color change of heartwood, wet wood, juvenile wood and sinker wood in the heartwood zone and difference in internal anatomy could be possible causes for the variations in permeability and thus, treatability of hemlock. Although this variability exists, there is little information known on the relative differences in permeability within hemlock, despite of its importance as a treatable wood (Erickson and Crawford 1959, Erickson 1960).

In conifers the bordered pits are the principal pathways through which fluids move from one longitudinal tracheid to the next and therefore pore radii (lumen, pit, margo) and tracheid length have a significant influence on this movement (Nicholas and Siau 1973). While a large number of studies have shown good correlation between permeability and pore radii, lack of significant scientific investigation on the relationship between density, tracheid length and permeability at different tree heights is quite conspicuous.
2 Objective

The objective of this study was to investigate the variability in longitudinal and radial air permeability at various cross-sectional locations and tree heights of western hemlock, and to quantify the effect of tracheid length and wood density on this measured permeability.

3 Literature Review

3.1 Tree Structure

Before a detailed discussion on the liquid or gas flow through wood it is important to firstly provide a description of the general structure and anatomy of a tree and its wood, respectively. A tree consists of three parts namely, the roots, the truck and the crown.

Figure 1 has been removed due to copyright restrictions. The information removed is the basic structure of a tree. (from http://www.infovisual.info/01/002_en.html).

Figure 1: The basic structure of a tree (from http://www.infovisual.info/01/002_en.html)

The main function of the roots is to help in the tree anchoring and to absorb minerals and water from the soil. The trunk is the portion of the tree above the ground from which the wood material that is used to produce lumber and other wood products is mainly obtained. It
provides mechanical support to the crown and conducts tree-sap from roots to the crown. The top most portion of a tree with branches and leaves is called the crown. The leaves contain chlorophyll that uses carbon dioxide and sunlight from the atmosphere along with water and minerals from the roots to produce the organic nutrients the tree uses to make wood. The basic structure of a tree is illustrated in Figure 1.

3.2 Trunk Structure

A cross section of a tree trunk shows some well defined features as shown in Figure 2. The bark is divided into an outer corky dead part called periderm and an inner thin living part which carries food from the leaves to growing parts of the tree. The wood, in most species is clearly differentiated into sapwood, heartwood and pith.

Figure 2 has been removed due to copyright restrictions. The information removed is a cross-sectional view of a tree and wood. (from http://www.msm.cam.ac.uk/doitpoms/tlplib/wood/structure_wood_pt2.php?printable=1)

Figure 2: A cross-sectional view of a tree and wood.
http://www.msm.cam.ac.uk/doitpoms/tlplib/wood/structure_wood_pt2.php?printable=1

Sapwood which is the living tissue helps in food storage and also conducts sap from the roots to the leaves. Heartwood on the other hand represents a gradual change from sapwood
that differs in chemical composition, density and some physical properties. It contains extractives, which are responsible for the natural durability of the xylem zone and for its usual darker colour. Heartwood was also observed to vary between and within tree species and its attributes have been correlated to growth rates, stand and individual tree biometric features and site conditions (Bamber and Fukazawa 1985, Taylor et al. 2002). Considering its permeance to fluids, heartwood is by far less permeable than sapwood (Siau 1995).

The wood rays - horizontally oriented tissue along the radial plane of the tree - vary in size from one cell wide and a few cells high to more than 15 cells wide and many millimeters high. The rays connect various layers from pith to bark for storage and food transfer.

The cambium layer, which is inside the inner bark, forms xylem and phloem cells that can be seen only with a microscope. Most growth in bark and wood thickness is caused by cell division in the cambium where new growth is purely the addition and enlargement of new cells, not the further development of old ones. The new wood cells, called xylem, are formed on the inner side of the cambium and new bark cells on the outside. Thus, new wood is laid down to the outside of old wood and the diameter of the woody trunk increases. Wood cells formed early in the growth season in temperate regions are known as earlywood or springwood. In conifers, earlywood production coincides with the trees period of height growth (Stamm 1964).

Figure 3 has been removed due to copyright restrictions. The information removed is Microscopic view of earlywood and latewood in Loblolly pine.(From http://www.engr.wisc.edu/centers/wsmtl/WSMTL-WEB-pg02L-NEWS-Pfeil.htm)
When the apical meristem terminates its activity (in late spring), height growth stops and the hormone productions (Auxins) which are responsible for growth decreases. As the hormone level in the cambium falls, the tree begins to produce thick walled cells called latewood or summer wood. The microscopic view of earlywood and latewood is depicted in Figure 3.

3.3 Wood Types

There are different types of wood according to its origin, anatomy and location of wood in a tree.

3.3.1 Sapwood and Heartwood

As mentioned above, one distinction that can be made between wood type is that of, sapwood and heartwood (Figure 2). Sapwood is located between the cambium and heartwood of the trees and contains both living and dead cells. The main function of sapwood is to handle the transport of water or sap from the roots to the leaves. The sapwood may vary in thickness and number of growth rings according to the species and tree location. The thickness commonly ranges from 40mm to 60mm in softwoods of temperate zones, whereas, in certain species, the sapwood contains few growth rings and usually does not exceed 10mm in width. As a rule, the more vigorously growing trees have wider sapwood (Plomion et al. 2001).

Heartwood consists of inactive cells that do not contribute in either water conduction or energy storage, but provide support for the tree. The transition from sapwood to heartwood is accompanied by an increase in extractive content that usually darkens the heartwood and
gives their characteristic color to each species. Heartwood extractives are found to affect the wood by (a) reducing permeability, (b) increasing stability in changing moisture conditions, and (c) increasing weight. However, when sapwood changes to heartwood, no cells are added or taken away, nor do any cells change shape. The basic strength of the wood is essentially not affected by the transition from sapwood to heartwood cells (Panshin and de Zeeuw 1980).

3.3.2 Juvenile and Mature wood

The wood in the stem of a tree can be divided into mature and juvenile based on the location of the vascular cambium at the time of the xylem formation, structure and properties. In a cross section of a tree stem, wood initially formed will be found at the core which is the centre most part of the stem. It is called the core wood or juvenile wood. Juvenile wood is formed within close proximity to the tree’s living crown and often is also called as crown-formed wood. Yang and Benson (1986) defined juvenile wood as the secondary xylem at the centre of a tree that formed throughout the life of the tree where its width is species specific and decreases upward to the tree crown. They also found that the anatomical, chemical and physical features of the juvenile wood increase or decrease gradually from the pith toward the mature wood. But in general juvenile wood is defined as the zone of wood extending outward from the pith where wood characteristics undergo rapid and progressive changes in successively older growth rings. Juvenile wood has also been referred to as crown-formed wood because it is produced either within the living crown or in proximity to physiological processes emanating from the living crown. As juvenile wood is produced in the central core of wood so it is also called as core wood (Philip et al. 2001).
Although there are a variety of methods that have been developed to differentiate the boundary between juvenile and mature wood, none of them demarcate an exact line between the two (Yang et al. 1986, Bendtsen and Senft 1986, Zobel et al. 1959). All these demarcation methods rely on the change in properties, when progressing from the juvenile wood zone to the mature zone. The most accurate method to distinguish the differentiation point between juvenile and mature wood is through examining the density, microfibril angle and cell length measurement (Evans et al. 2000, Yang and Benson 1997).

Figure 4 has been removed due to copyright restrictions. The information removed is the representation of juvenile wood and mature wood in Scots pine. Microscopic view of earlywood and latewood in Loblolly pine. (From http://www.forestresearch.gov.uk/pdf/CEMARE_Oct06_Dunisch_Koch_Richter_Puls_and_Evans_2.pdf/$FILE/CEMARE_Oct06_Dunisch_Koch_Richter_Puls_and_Evans_2.pdf)


The specific characteristics of juvenile wood cannot be described due to considerable species variation and location effects. However, there are some general properties that differentiate juvenile wood from mature wood. Yang et al. (1986), Kretschmann et al. (1993) and later Zobel and Sprague (1998) studied juvenile wood properties and compared them with those of mature wood. They reported that juvenile wood has thinner cell walls, larger cell lumens and is relatively less density than the mature wood. The microfibril angle (MFA) and longitudinal shrinkage was observed to be higher in the former. They also reported lower
cellulose content and higher percentage of lignin in juvenile wood when compared with mature wood. The position and properties of juvenile wood and mature wood are shown in Figure 5.

Figure 5 has been removed due to copyright restrictions. The information removed contains The general location of the juvenile wood and effect of juvenile wood on physical and mechanical properties: (a) juvenile core located in interior of tree bole; (b) properties that increase from juvenile to mature wood; and (c) properties that decrease from juvenile to mature wood (from Kretschmann et al. 1993)

3.3.3 Compression and Tension wood

A tree will produce an erect or vertical stem when it grows under normal conditions, resulting in normal wood production. When trees are forced out of this pattern, which makes the tree to bend or lean due to wind and gravitational forces, abnormal woody tissue formation results in certain parts of the tree that is called reaction wood. In conifers, it forms on the lower side of a leaning stem or branch and is therefore termed as compression wood. In hardwoods, reaction tissue occurs on the upper side of a leaning or bent tree and it is called tension wood. The occurrence of reaction wood in hardwood and softwood trees is shown in Figure 6.
Compression wood differs both physically and chemically from normal wood. In the latter, coniferous tracheids generally appear as square, rectangular or polygonal cells in cross-section, but in the former the latewood tracheids are circular in shape and because of this round structure intercellular spaces are seen in compression wood.

On a macroscopic level, compression wood is often recognised by its characteristic dark colour (Timell 1986), and this colour and the hardness of compression wood are the reasons this tissue has a variety of names, e.g. red wood, glossy wood and hard streak. Compression wood appears dark because it absorbs more light, due to the higher lignin content, and scatters less light, due to thicker tracheid walls. The cell wall is comprised of three structural substances: cellulose, hemicelluloses and lignin (Koch et al. 1990). In normal wood, the cell wall of a mature tracheid consists of an outer primary wall and a secondary wall comprised of three layers S1, S2 and S3. In the primary wall the cellulose microfibrils are randomly distributed, but in the secondary wall varying alignments are found in both the S1 and the S3-layer. In the thickest layer of the secondary wall, the S2-layer, the microfibrils are aligned approximately 30° along the longitudinal axis of the tracheid in later growth.

Microscopic comparison of cell-wall structure between normal and compression wood revealed the lack of S3 layer and extra lignin thickenings in S1 and S2 layers (Wardrop and
In compression wood the microfibrils in the S2 layer are arranged in a flatter helix than that of normal wood which in turn results in higher longitudinal shrinkage in compression wood.

The alignment of the microfibrils in relation to the longitudinal axis of the tracheid is often referred to as the microfibril angle (MFA). In juvenile wood and especially in compression wood the MFA is quite large and to an extent, it is the MFA that governs the longitudinal shrinkage in wood. Koch et al. (1990) reported angles of more than 45° in severe compression wood cases. The mechanical properties also vary more in compression wood than in normal wood. Namely, the modulus of elasticity (MOE) and modulus of rupture (MOR) are commonly found to be significantly lower in the compression wood.

Figure 7 has been removed due to copyright restrictions. The information removed contains the cellular composition of wood (from http://cache.eb.com/eb/image?id=65081&rendTypeId=4)

**Figure 7: Cellular composition of wood (from http://cache.eb.com/eb/image?id=65081&rendTypeId=4)**

### 3.4 Hardwoods and Softwoods

The term hardwood or softwood is used to refer to the taxonomical division that separates a species and have little to do with the actual hardness or softness of the wood. Hardwoods or otherwise “angiosperms” have broad leaves and are deciduous. Softwoods on
the other hand are evergreens and have needles or scale-like foliages. Softwoods are also called gymnosperms and they use cones for their pollination or reproduction. Softwoods differ from hardwoods not only in their physiological characteristics, but also in their anatomical or cellular structure. The cellular composition both in softwood and hardwood is represented in Figure 7.

3.5 Anatomy of Softwoods

Figure 8 has been removed due to copyright restrictions. The information removed contains the gross anatomical structure of softwood (from Howard and Manwiller 1969)

Wood from softwoods is made up mainly of hollow longitudinally disposed narrow cells called longitudinal tracheids. These are tapered and closed at both ends with an average diameter of 10 to 40µm and are 2 to 4mm in length. The primary wall of a tracheid is formed by differentiation of living cells in the cambium layer of the tree. The primary walls of adjacent cells become fused together and form the middle lamella. The two most important chemical constituents in the cell walls of wood cells are cellulose and lignin. The middle lamella is said to contain a much larger concentration of lignin than the secondary and tertiary wall (Philip et al. 2001)

All tracheids in softwood are not the same. In the season when growth is most rapid, the tracheids formed are relatively large, thin walled and loosely aggregated when compared
with those formed in the later season of the year when growth is slower. These differing tracheids serve to mark out the annual rings of the tree. The thin celled part of the annual ring is known as earlywood (springwood) and the thicker celled part with denser structure and darker appearance is called latewood (summerwood). A typical softwood 3-dimensional structure is shown in Figure 8.

The fluid-conducting tissue consists of longitudinal and ray tracheids. Ray tracheids help in radial transport of water to the pith. The parenchyma cells (longitudinal, ray parenchyma) function as storage tissue for reserved food material in a living tree. In a typical softwood structure about 93% of its volumetric composition is made up of longitudinal tracheids where as longitudinal resin canals and wood rays represent only 1 and 6%, respectively (Panshin and de Zeeuw 1980).

In the original cells of the cambial layer, communication between adjacent cells is provided by bundles of fibrils known as plasmodesma. These fibrils disappear when the tracheid is formed. However, during the thickening of the cell walls, the areas through which fibril bundles passes will get perforated. These thin areas with perforations are called pits.

A pit in one cell is normally positioned opposite to a pit in an adjacent cell, forming a pit pair. Pit pairs are the most important wood anatomical factors that influence the flow of fluids through softwood because they are the principle avenues through which fluids pass from one cell to the other (Panshin and de Zeeuw 1980).

Three types of pit pairs are common in softwoods as illustrated in Figure 9. The simple pit pair (a) occurs between two parenchyma cells such as ray and longitudinal parenchyma. A bordered pit (b) is located between two prosenchyma cells such as ray tracheids or
longitudinal tracheids and a half bordered pit pair (c) is seen between a parenchyma and a
prosenchyma cell (tracheid) with the bordered portion facing the prosenchyma cell (Siau
1995).

Figure 9 has been removed due to copyright restrictions. The information removed contains the three basic
types of pit pairs (from Siau 1995)

Figure 9: Three basic types of pit pairs (a) simple pit pair; (b) bordered pit pair; (c) half
bordered pit pair; C, chamber; M, middle lamella-primary wall; S, secondary wall; T,
torus (from Siau 1995)

A greater number of pits are usually found on the tapering side where a tracheid
overlaps with the adjacent tracheid. In softwoods, pits are largely restricted to the radial walls
of the tracheids (Figure 11). They are arranged in such a way that channels for longitudinal
conduction of sap is provided through a series of lumens which form a more or less
continuous pipe.

Figure 10 has been removed due to copyright restrictions. The information removed contains the The fibrillar
structure of the margo in an non-aspirated bordered pit in a sapwood tracheid of eastern hemlock (Tsuga
Canadensis (L.) Carr.), dried by solvent exchange from acetone to prevent aspiration (from Comstock and Côté
1968)

Figure 10: The fibrillar structure of the margo in an non-aspirated bordered pit in a
sapwood tracheid of eastern hemlock (Tsuga Canadensis (L.) Carr.), dried by solvent
exchange from acetone to prevent aspiration (from Comstock and Côté 1968)

In softwoods, the pits are mainly of the bordered pair type where a membrane is
separating the two lumens. This membrane has a thickened central portion called the torus
and also numerous perforations in the marginal portion surrounding the torus. The diameter of the torus, when present, is one-third to one-half the overall diameter of the chamber. The membrane surrounding the torus is called the margo and it consists of strands of cellulose microfibrils radiating from the torus to the periphery of the pit chamber. The openings between the microfibrils permit the passage of fluids and small particles through the pit membrane (Panshin and de Zeeuw 1980). The fibrillar structure of the margo in a bordered pit is illustrated in Figure 10.

### 3.6 Softwood Tracheid Structure

The anatomical structure of softwoods is simpler when compared to the cellular structure of hardwoods. As mentioned earlier, longitudinal tracheids comprise 93% of the total wood volume in softwoods with a small percentage of parenchyma cells also found in rays and resin canal epithelia. Longitudinal tracheids are long and imperforate cells, whereas in cross section, they are polygonal in shape, more or less square in earlywood and flattened radially in the latewood. Round shaped tracheids are also seen in the transverse section of the compression wood. As stated earlier, the walls of these cells can be thick or thin walled, depending on location of the cell in the growth increment. Latewood tracheids have thicker cell walls when compared to earlywood ones. A schematic diagram of an earlywood and latewood tracheid is depicted in Figure 11 where it can be observed that the majority of the pits are on the radial surface of the tracheids and the pits are concentrated on the tapered ends that are in contact with the adjacent cells. This is the reason why most of the fluid flow between tracheids is in the tangential direction (Siau 1995).
Other than longitudinal tracheids, in some conifers, ray tracheids are also found that are usually located at the upper or lower margins of the wood rays. These prosenchymatous cells have bordered pits which are smaller than those of the longitudinal tracheids. Because of the bordered pits the ray tracheids can be easily distinguished from the parenchyma cells that have only simple pits.

Figure 11 has been removed due to copyright restrictions. The information removed contains Radial surfaces of earlywood and latewood tracheids: (a) inter-tracheid bordered pits (b) bordered pits to ray tracheids(c) pinoid pits to ray parenchyma  (from Siau 1995)

**Figure 11: Radial surfaces of earlywood and latewood tracheids: (a) inter-tracheid bordered pits (b) bordered pits to ray tracheids(c) pinoid pits to ray parenchyma**  
(from Siau 1995)

Numerous studies have been conducted on softwoods and hardwoods in order to identify the variation in cell length both horizontally and vertically (Honjo *et al.* 2005, Monteoliva *et al.* 2005, Koubaa *et al.* 1998, Yanchuk and Micko 1990, Bhat *et al.* 1989, Taylor and Moore 1981, Parameswaran and Liese 1974). Due to the manner in which cambial cells divide and the new wood cells elongate, tracheids vary widely in length. As a general rule, tracheid length increases rapidly from rings nearest to the pith outward. Within a growth ring it has been found that summerwood tracheids are longer than springwood tracheids. In radiata pine, tracheid length has been found to increase abruptly at the springwood-summerwood transition, attain a maximum in the mid- to late-summerwood zone, and then decrease sharply at season’s end (Nicholls *et al.* 1973). In addition to variation with age and position within stems of individual trees, tracheid length has also been found to vary among trees according to stand density, site, geographic location (Zobel *et al.* 1960).
3.7 Western Hemlock Structure

The wood of western hemlock is moderately light in weight and in colour. The growth rings are distinct, delineated by a band of darker latewood. The earlywood zone usually occupies at least two-thirds of the annual ring and is lighter and less dense than the latewood. The rays are fine and not distinct on the transverse surface with the naked eye. The tracheids are up to 50µm (average 30-40µm) in diameter and average 4.2mm (1.8 to 6.0mm) in length. The volume occupied by the tracheids is more than 90%. The rays are uniseriate or very rarely biseriate. Ray tracheids are present and usually restricted to one row on the margins of the ray. Volume occupied by the rays is only 10% of total (Alden 1997).

Like other species, hemlock also contains juvenile wood in the heartwood zone. It is also characterized by localized regions of high-moisture-content wood, often referred to as wet pockets, or wetwood. Wetwood develops in living trees as a result of bacterial infections. It can also be caused due to injury and normal age growth formation (Ward and Pong 1980). It also causes boards to have higher initial moisture content, slower drying, and be more susceptible to drying defects (Ward 1986).

3.8 Fluid Flow in Wood

Generally speaking, permeability is the property of a porous material that indicates how freely fluids flow through its interconnected void volume in response to a pressure gradient. A solid must be porous to be permeable, but all porous bodies are not permeable. Permeability can only exist if the void spaces are interconnected by openings. As wood has all these characteristics, it is considered to be porous and permeable (most of the times).
The theory of flow through homogeneous porous media is based on the classical experiment originally performed on a sand bed by Darcy in 1856 (Siau 1995). Darcy’s law relates the volumetric flow rate, \( Q \), of a fluid flowing linearly through a porous medium directly to the energy loss, inversely to the length of the medium \( L \), and proportionally to a factor called the permeability coefficient.

\[
Q = \frac{K_1 A (P_2 - P_1)}{L} = \frac{K_1 A \Delta P}{L}
\]  
(1)

Later, Darcy found out that the rate of fluid flow varies inversely as the fluid viscosity and he modified and generalized the equation

\[
Q = \frac{K_1 A (P_2 - P_1)}{\eta} = \frac{K_1 A \Delta P}{\eta L}
\]  
(2)

or

\[
K_1 = \frac{Q/A}{\Delta P/L} = \frac{QL\eta}{A\Delta P}
\]  
(3)

where \( K_1 \) is the specific permeability of wood for the liquid, \((\text{m}^3/\text{m})\); \( \eta \) is the viscosity of the fluid, \((\text{Pa.S})\); \( Q \) is the volumetric flow rate,\((\text{m}^3/\text{s})\); \( L \) is the length of the specimen in the flow direction, \( (\text{m}) \); \( A \) is the cross-sectional area of the specimen perpendicular to flow direction, \( (\text{m}^2) \); \( P_2 \) is the upstream pressure, \((\text{Pa})\); \( P_I \) is the downstream pressure, \((\text{Pa})\); and \( \Delta P \) is the pressure differential, \((\text{Pa})\).

For a compressible fluid such as a gas, the volumetric flow rate \( Q \) varies with pressure change. It is assumed that

\[
PQ = \bar{P} \bar{Q} \text{ constant}
\]  
(4)
where $\bar{P}$ is the arithmetic average of $P_1$ and $P_2$, and $\bar{Q}$ is the volumetric flow rate. Darcy’s law for gases can be then be then re-written as replacing $Q$ in Eq. (2),

$$Q = \frac{K_g A \Delta P}{\eta L} \frac{\bar{P}}{\bar{P}}$$

(5)

or

$$K_g = \frac{Q \eta L}{A \Delta P} \frac{\bar{P}}{\bar{P}}$$

(6)

where $K_g$ is the specific permeability for a gas; $P$ is the pressure at which the flow rate $Q$ is measured, and all the other factors have the same units as in Eqs. (2) and (4).

Darcy’s law is found to be valid for a wide variety of porous materials and fluids over a wide range of conditions. However, Scheidegger (1974), in dealing with Darcy’s law, notes several conditions where serious deviations have been observed; and reports several conditions which must prevail for the equation to be valid.

1. The porous medium must be homogeneous.

2. The flow of velocity as defined by the Reynolds number must not exceed a certain value.

3. The pore diameter must be significantly greater than the mean free path of gas in the case of gaseous flow.

4. Deviation may be found with ionic liquids.

The flow through a porous medium like wood can also be described by Poiseuille’s equation. However, in this case wood is considered as number of tubes (tracheids) in parallel, each tube is blocked at regular intervals by an obstruction (the tracheids end) penetrated by another tube (the bordered pit pore) whose radius is considerably smaller than that of the
tracheid. In this approach, each tube is assumed to obey Poiseuille’s equation for the flow of liquid in long cylindrical tubes and it can be expressed as

\[ Q = \frac{N \pi r^4 \Delta P}{8 \eta L} \quad (7) \]

or in the case of gases, as

\[ Q = \frac{N \pi r^4 \Delta P}{8 \eta L} \frac{P}{P} \quad (8) \]

where \( N \) is the number of uniform straight circular capillaries in parallel; \( r \) is the radius of uniform straight circular capillary, (m). It is evident from the combination of Darcy’s equation with Poiseuille’s equation, that the specific permeability is only a function of the number and radii of the pores. In other words, the specific permeability is not affected by the measuring fluid (Siau 1995).

It is generally assumed that the steady state of fluid flow through tracheid lumens and vessels is essentially viscous, and therefore Darcy’s and Poiseuille’s law are believed to be obeyed. However, as mentioned above, this is a not strictly true when fluids flow through small structures like pit opening in softwoods. Although the high flow velocities necessary for turbulence are not very probable in wood, nonlinear laminar flow may occur at relatively low velocities where a fluid moves from a large to small capillary such as, from tracheid lumen to a pit opening (Kuroda and Siau 1988). Therefore, Darcy’s law may possibly be true in a certain velocity domain. Some deviations are also found to occur at very low flow rates due to slip flow, and at high flow rates due to nonlinear laminar flow.
3.9 Factors Affecting Fluid Flow in Wood.

There are different factors which affect the permeability of wood in a tree.

3.9.1 Anatomical Effects on Permeability

The rate of flow (or fluid conductivity) of a porous medium has a direct relationship with the microscopic structure of that medium. The arrangement, shape and size of structure elements give wood the quality of an anisotropic porous medium. The large porous volume in softwood is made up primarily of tracheids together with smaller amounts of ray cells and resin ducts (Stamm 1963). The fluid flow through the capillaries of wood may be considered similar to flow through a combination of perfect glass capillaries in a series and parallel combination (Comstock 1967).

Several investigations have been conducted in the past in order to elucidate the path of flow of liquids in wood. Bailey and Preston (1970) studied the flow of liquid in Douglas-fir using silver nitrate. No significant flow between the longitudinal tracheids and ray parenchyma was observed whereas, silver deposits on both sides of the pit chamber indicates the significant flow between the two longitudinal tracheids. Behr et al. (1969) found that the bordered pit pairs and longitudinal and ray tracheids were filled with the preservatives when the earlywood and latewood were treated with creosote and pentachlorophenol. This was clear evidence of the flow of liquids through the simple and half bordered pits.

Banks (1970) studied the radial and tangential permeability of Scots pine and found that the radial permeability was higher than that of the tangential permeability. The higher permeability for the radial direction was attributed to the presence of wood rays. In the treatment of long thin poles or timbers, the effect of longitudinal penetration is negligible.
because majority of the pits are on the radial surfaces of the cells. Therefore, the most important radial flow path into the sapwood of long specimens is through the rays to the longitudinal tracheids. Nicholas and Siau (1973) studied the flow of polar and non-polar liquids in wood. It was found that the flow rates of the non-polar liquids were much higher than of the polar liquids, when viscosity was equal. The lower rate flow by polar liquids is due to the frictional drag caused by hydrogen bonding of polar liquids to cell wall constituents during flow through small capillaries.

### 3.9.2 Specimen Length Effect on Permeability

The effect of specimen length on wood permeability has been investigated by many researchers. In most cases, wood permeability was found to increase when specimen length decreases. Sebastian et al. (1965) reported an increase in the longitudinal superficial oxygen permeability as the length was decreased from 20 to 3.2mm. Later, Bramhall (1971) carried out longitudinal superficial air permeability measurements in Douglas-fir specimens for lengths between 35mm and 5mm. He reported an increase in air permeability with a decrease in length that was more pronounced at lower permeability profiles.

Siau (1972) also carried out similar experiment using Douglas-fir and loblolly pine. The dimensions of the specimens were 20mm by 20mm in cross-section with three different lengths as 300mm, 100mm and 50mm, respectively for sapwood and heartwood of Pacific coast Douglas-fir, loblolly pine and sapwood of intermountain Douglas-fir. Whereas, for inter mountain Douglas-fir heartwood the specimen lengths were 100, 50, 20mm. It was observed that the effect of specimen length was almost negligible at permeabilities exceeding 0.2µm³/µm.
Perng (1980) measured the superficial air permeability of several softwoods and hardwoods, using specimen lengths varying from 4 to 154mm. He reported a species dependent critical value which is 50mm for softwoods and diffuse-porous hardwoods and 100mm for the ring porous hardwoods such as white ash (*Fraxinus americana*). It was found that when the specimen was longer than the critical length, the permeabilities values were nearly identical for the various lengths of the tested species. On further investigation, two conflicting effects of length on permeability within the critical length range were observed. When the specific permeability was above $2 \mu m^3/\mu m$, it decreased abruptly with decreasing specimen length. Perng (1980) explained this increase in permeability with an increase in length as the result of turbulence or nonlinear laminar flow.

Although the above results suggest a significant effect of specimen length on permeability, other studies show no effect. Kumar (1981) observed no significant change in specific permeability values when the specimen lengths were decreased from 50 to 25mm. Later, Fogg and Choong (1989) measured the longitudinal permeability of American sycamore (*Platanus occidentalis*), American elm (*Ulmus americana*), hickory (*Carya spp.*), and mesquite (*Prosopis juliflora*) and observed that the permeability remained constant as specimen length decreased from 91 to 51mm.

In summary, in most cases permeability is reported to be inversely proportional to its specimen length, but some researchers also report that there is no significant effect of specimen length on permeability. It was also identified that the effect of specimen length on permeability was related to its permeability magnitude.
3.9.3 Moisture Content Effect on Permeability

A number of experiments have been conducted in the past, to reveal the effect of moisture content on permeability. Choong and Tesoro (1974) used 22 hardwood species and reported that the gas permeability values between 0 and 20% moisture content remain constant for a given species, regardless of the thickness of the specimen and the flow direction. They also found that the permeability value for 0% and 20% moisture content was 2 to 1$\mu m^3/\mu m$ for impermeable specimens and 1.35 to 1$\mu m^3/\mu m$ for permeable specimens, respectively.

Siau (1984) carried out a study on softwoods above the fiber saturation point and observed an increase in permeability with decreasing moisture content. He speculated that this increase was due to the shrinkage of the fibrous strands in the pits and corresponding increase in the size of opening in the pits.

The effect of moisture content below fiber saturated point in softwoods and hardwoods was also investigated by Comstock (1968) who reported that the permeability of softwoods generally increases about two- to three-fold as moisture content decreases from 24% to 6%. He explained the trend by the shrinkage of the microfibrillar strands in the margo of the pit membrane.

3.9.4 Drying Effect on Permeability

The drying of wood is an important industrial process that can affect wood permeability. During drying and due to the high capillary forces the pit membrane tends to move into the aspirated position where the torus undergoes hydrogen bonding to the surface of the pit aperture. This phenomenon is called pit aspiration and a typical aspirated pit is
shown in Figure 12. This phenomenon closes off the flow through the pits thus resulting in reduced permeability coefficient (Usta and Hale 2006).

Figure 12 has been removed due to copyright restrictions. The information removed contains the aspirated pit in Radiata pine (from Kollman and Côté 1968)

**Figure 12: Aspirated pit in Radiata pine (from Kollman and Côté 1968)**

Philips (1933) demonstrated by microscopic observation that pit aspiration increases rapidly as the moisture content approaches the fiber saturation point with no significant further aspiration below that. The fraction of aspirated pits in dried earlywood was much higher than that in latewood. The thicker membrane and smaller diameters in latewood were possibly the reason for this phenomenon. Later, Comstock (1968) studied the effect of drying temperature on the pit aspiration of wood. He discovered a direct correlation between the drying temperature and the magnitude of pit aspiration.

Liese and Bauch (1967) studied the effect of drying on the aspiration of pits in Norway spruce (*Picea abies*), Scots pine, silver fir (*Abies alba*) and white cedar (*Thuja occidentalis*). As cedar has no torus in its pits, the permeability was not affected by drying. The earlywood pits of the other species were all aspirated when dried with water, but were not when dried with alcohol or acetone. Comstock and Côté (1968) dried specimens of red pine (*Pinus resinosa*) and Douglas-fir at temperatures from -18°C to 140°C, slowly over P₂O₅ in a desiccator and with rapid drying in an oven. The permeability of the dried material was found to decrease with both an increase in drying temperature and rate.
Thomas and Kringstad (1971) investigated several factors influencing pit aspiration in never dried earlywood of loblolly pine (*Pinus taeda*) sapwood. They observed that hydroxyl groups have a greater influence on pit aspiration and that chemical blocking of hydroxyl groups by esterification and etherification prevented complete aspiration of pits after drying with water, while all pits were aspirated when there was no chemical treatment. It was also discovered that the pits could be de-aspirated by water soaking to break the hydrogen bonds between the torus and border, followed by solvent exchange and drying from pentane.

Bolton and Petty (1978) proposed a model for determination of the force required to deflect the pit membrane in Scots pine. They calculated a pressure of $5.4 \times 10^5$ Pa in the pits of first formed earlywood and $690 \times 10^5$ Pa in the centre of the latewood.

### 3.9.5 Species Effect on Permeability

A wide range in the permeability values has been shown for different wood species by several researchers. Smith and Lee (1958) measured over 100 species and found that permeability ranges with a ratio of $5 \times 10^6:1$ in hardwoods and $5 \times 10^5:1$ in softwoods. Within the 100 species, red oak had the highest value because of the large earlywood vessels. American basswood and the maples had the highest values in diffuse porous hardwood category. Among the softwoods, pines were showing higher values that cedars or spruces.

In softwoods, a direct relationship exists between longitudinal and tangential permeabilities because the same pit openings are traversed in both cases. Due to the smaller number traversed in series and the larger number in parallel in longitudinal flow, the ratio of longitudinal to transverse permeabilities can vary from 10,000 to 40,000, depending on the degree of overlap of the tapered ends of the tracheids (Comstock 1970).
The radial permeability has also more practical applications because poles must be penetrated radially. A greater range of 15:1 to 50,000:1 in longitudinal to radial permeabilities was explained by large differences in the permeability of ray tissue, impermeable rays would give rise to a high permeability ratio because most of the intertracheid pits are on the radial surfaces of the cells. The higher ratios in hardwoods than softwoods can also be explained by the generally poor penetrability of ray tissue in the former (Siau 1995).

3.10 Wood Density

Density is defined as the dry weight per unit volume of wood (Haygreen and Bowyer 1996) and is regarded as the single most important physical property of wood. Density has an effect on the strength, stiffness and general quality of the most of the products produced from wood (Jozsa et al. 1989). Moreover, many of the mechanical properties of wood are highly correlated with relative density (Zobel and van Buijtenen 1989, Haygreen and Bowyer 1996).

Density varies widely both within and between the trees. This variation is due to the difference in the cellular structure and the presence of extraneous constituents. Physiological, mechanical and also hereditary characters affect the cellular structure which affects the wood density (Cown et al. 1991, Zobel and Jett 1995). Environmental conditions also impact the density in a tree (Clarke et al. 2004). The density variation from different perspective in Western hemlock is shown in Figure 13.

Figure 13 has been removed due to copyright restrictions. The information removed contains the density variation in western hemlock wood from different perspectives (from Jozsa et al. 1998)
Studies on the density variation of the cross section of the stem revealed that the density of a wood is significantly affected by the width of the annual rings or percentage of summerwood (Jozsa 1998, Fabris 2000). Most workers have reported that wood density is highest in the first five rings from the pith in several species (Wellwood and Smith 1962, Jozsa 1998, Fabris 2000), usually within the first or second ring if the individual rings were assessed separately. However, Megraw (1985) found no significant differences in wood density of the outer 25 rings of increment cores extracted from fast grown trees and also from slow grown ones.

Within individual trees, density varies from earlywood to latewood within rings, from pith to bark at a given height in the stem, and from stump to tip (Jozsa et al. 1989, Kennedy 1995, Gartner et al. 2002). It was reported that the density increases outward from the centre of the stem, reaches a maximum up to an age and then decreases (Jozsa and Kellogg 1986, Gartner et al. 2002).

The density of wood is influenced by many anatomical features and the presence of some chemical constituents (Harris 1981). Compression wood for example is 20 to 40% denser than that of the normal wood. It was also observed that tropical woods are denser than the temperate ones. The darker heartwood was observed to be denser than the light coloured heartwood. This variation is due to the difference in extractives in wood. Barton 1968 found that the phenolic component of inner heartwood of western hemlock was higher when
compared to the outer sapwood which in turn showed an increase in density for heartwood specimens.
4 Materials and Methods

4.1 Raw Material and Specimen Preparation

Ten green Western hemlock (*Tsuga heterophylla*) trees, grown in Harris Creek, B.C., were randomly selected. The average age of the trees were 85 years old with average height of 27.4m. From each tree a 50mm thick disk was cut at three different heights, namely, 1, 4 and 7 meters. The north face of the trunk was identified along its length with a stripe of paint and the disks were marked and divided into 4 quadrants: North-East, South-East, North-West and South-West (Figure 14).

![Figure 14: Disk markings at each tree height investigated](image)

The size of each permeability specimen was 20x20mm\(^2\) in cross-section and 35mm in length and the cutting was done with a band saw. The specimens having end cracks are removed and all other specimens in the North-South direction were used to measure the longitudinal permeability and density variation across the tree cross-section. The first and
fifth specimen from each end of the North-South and East-West directions, were used to study the effect of tree height, tracheid length and density on permeability. Two cubical specimens of 20x20x20mm³, one from the sapwood and the other from the heartwood zone, were cut from each of the four quadrants of each disk to measure the radial permeability. The cutting pattern and specimen sizes are illustrated in Figure 15.

![Diagram showing the cutting pattern and dimensions of the permeability specimens](image)

**Figure 15: The cutting pattern and dimensions of the permeability specimens**

In order to eliminate the influence of moisture content on permeability readings, the green specimens were dried in a conditioning chamber to 10% moisture content. A moderate drying at constant temperature and relative humidity (T = 60°C and H = 67%) was implemented in order to avoid internal checking and minimize possible pit aspiration (Figure
After reaching the target moisture content, the specimens were taken out from the conditioning chamber and their end surfaces were shaved with a sharp razor blade to remove loose fibers and create fresh ends before each experimental run. The side surfaces of the specimens were coated with epoxy resin to prevent transverse air flow during experimentation.

Figure 16: The permeability specimens in the conditioning chamber

4.2 Superficial Permeability Measurements

All specific permeability measurements were carried out by using the Falling Water Displacement Method (FWDM) explained in detail in Siau (1995) and shown in Figures 17 and 18. The apparatus for this method consists of a large aluminum water tank and a cylindrical glass column which is mounted on a wooden platform above the water tank. The glass column is connected to a vacuum pump and to the specimen holder by means of
interchangeable rubber tubes. The specimen holder of the apparatus consists of a large vacuum rubber tube, a glass adapter and a clamp which tightly fix the specimen into the specimen holder which is a high vacuum hose; which connects the specimen with the glass column and the vacuum pump by means of a three way valve (Figure 18).

Figure 17 has been removed due to copyright restrictions. The information removed contains the schematic diagram of the falling-water permeability apparatus with corresponding model parameters (from Siau 1995)

**Figure 17: The schematic diagram of the falling-water permeability apparatus with corresponding model parameters (from Siau 1995)**

For measuring the superficial permeability of the specimens, the aluminium tank was filled with water in such a way that the lower end of the glass column was fully immersed with water. The specimen was clamped into the specimen holder which connects the glass column by means of a three way valve. A known length, $\Delta z$, which is a change in height of water during a time (s), was marked on the glass column and a partial vacuum was applied to the downstream end of the specimen which results in rise of water in the glass column from the tank.
When the vacuum is turned off, air flows through the specimen and into the glass column, which results in the drop of water in the glass column. The time required for the level of water to drop by $\Delta z$ was recorded and used to measure the permeability by using the equation

$$k = \frac{V_d \cdot C \cdot L \cdot (P_{am} - 0.074 \bar{z})}{t \cdot A \cdot (0.074 \bar{z}) \cdot (P_{am} - 0.037 \bar{z})} \times \frac{0.760m Hg}{1.013x10^5 Pa}$$

where $V_d = \pi r^2 \Delta z$ and it is the volume of gas displaced by water in glass column, (m$^3$); $\Delta z$ is the distance between two marked points, (m); $L$ is the length of the specimen, (m); $\bar{z}$ is the average height of water over surface of the reservoir during period of measurement, (m); $t$ is time, (s); $A$ is the area of cross-section of the specimen, (m$^2$) and $C$ is the correction factor where,
\[ C = 1 + \frac{V_c(0.074 \Delta z)}{V_d(P_{atm} - 0.074 \overline{z})} \]  

(10)

The specific permeability of the specimens was calculated by the product of superficial permeability and viscosity of air \((1.81 \times 10^{-5})\).

\[ K_g = k \mu \]  

(11)

Where \(K_g\) is specific air permeability and \(\mu\) is viscosity of air \((\text{Pa s})\).

The data analysis was conducted using a factorial experimental design with height, type of specimen, and direction as dependant factors. Tables 1 and 2 illustrate the experimental design, the data analysis scheme and the number of specimens used in this study.

**Table 1: The experimental design of the permeability study**

<table>
<thead>
<tr>
<th>Source</th>
<th>Types</th>
<th>Degrees of Freedom</th>
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<tbody>
<tr>
<td>Heights(L)</td>
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<td></td>
<td>• 4m</td>
<td></td>
</tr>
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<td>• 7m</td>
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<td></td>
<td>• Heartwood</td>
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<td>• South</td>
<td></td>
</tr>
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<td></td>
<td>• East</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• West</td>
<td></td>
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<tr>
<td>All the interactions</td>
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</table>
Table 2: The total number of specimens used in the permeability experiments

<table>
<thead>
<tr>
<th>Number of specimens</th>
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<tr>
<td>Longitudinal direction</td>
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<tr>
<td>Radial direction</td>
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<td>Total number of specimens</td>
</tr>
</tbody>
</table>

4.3 Fiber Length Measurements

The length of the wood tracheids was measured using an OpTest Laboratory’s Fiber Quality Analyzer (FQA) that utilizes circular polarized light to project images of the tracheids and thus automatically measures the trachied length (Figure 19). For these measurements, a small sample taken from each of the 240 specimens (1st and 5th specimen from each end of N- S and E -W directions of each disc), was cut out using a chisel and then soaked in 50% Franklin solution (glacial acetic acid equivalent to 6% hydrogen peroxide) and digested at 70°C for approximately 24 hours. Before measuring the tracheid length, a tracheid suspension solution was prepared after washing, disintegrating and diluting the digested wood pulp with water. In FQA, as the tracheid suspension joins the water sheaths and passes through the optics box, the digital camera takes pictures of the tracheid projections and calculates the weighted average of tracheid length for each specimen.
As in the permeability, the data analysis for tracheid length was carried out using a factorial experiment with height, type of specimen, and direction as factors. The correlation analysis was also conducted to observe if any relationship exist between the permeability and tracheid length. Table 3 illustrates the design of the data analysis and number of specimens used for tracheid length experiment.

**Table 3: The experimental design of the tracheid length measurements**

<table>
<thead>
<tr>
<th>Source</th>
<th>Types</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
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<tr>
<td></td>
<td>• 4m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 7m</td>
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<td>Wood types(S)</td>
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<td>1</td>
</tr>
<tr>
<td></td>
<td>• Heartwood</td>
<td></td>
</tr>
<tr>
<td>Direction(D)</td>
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<td>3</td>
</tr>
<tr>
<td></td>
<td>• South</td>
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<tr>
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<tr>
<td></td>
<td>• West</td>
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<tr>
<td>All the interactions</td>
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<tr>
<td>Number of specimen used</td>
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</table>
4.4 Density Measurements

The density of the North-South direction of each disc was used for analysis in this research. For measuring density, an electronic balance measured the mass of wood sample and the water displacement method was used to measure the volume of the specimens (Figure 20). For water displacement method a container capable of holding the sample is filled with water and placed on a digital balance. The container is filled with water in such a way there is enough room for the sample. The balance is then re-zeroed and the sample is then carefully sunk in the water, without contact on the sides or bottom of the container. The specimen is then forced underwater with a thin needle. The measured weight of displaced water is measured which will be equal to the sample’s volume and density is calculated by using this volume.

**Figure 20:** A schematic diagram which illustrates the water displacement method for measuring the volume and thus the density of a specimen
5  Result and Discussion

5.1  Longitudinal Permeability

The variation in inherent properties of wood such as xylem anatomy can result in variation of permeability both within and between trees (Gartner 1995, Panshin and de Zeeuw 1980). The results from this study confirm these findings. The distributions of longitudinal specific permeability of heartwood and sapwood specimens at three different tree heights are shown in Figures 21 and 22, respectively. It can be observed that the overall longitudinal specific permeability values ranged from 0.02 to 2.34\(\mu m^3/\mu m\) that is in agreement with those previously reported (Koumoutsakos and Avramidis 2002, Siau 1995). The variation in pit and tracheid dimensions, pit aspiration, degree of encrustation of pit membranes and difference in proportion of earlywood and latewood are factors that can be assumed responsible for this wide variability range (Erickson 1970, Petty and Puritch 1970, Olsson et al. 2001).

5.1.1  Longitudinal Permeability in Sapwood and Heartwood

Among the heartwood samples studied, 80% of the specimens showed a permeability range of 0.01 – 0.1\(\mu m^3/\mu m\) with 0.38 and 0.0158\(\mu m^3/\mu m\) as maximum and minimum range respectively (Figure 21). In sapwood samples, the maximum and minimum range was 2.34 and 0.12\(\mu m^3/\mu m\) in which 90% of the specimens were in the range of 0.5 – 2.0\(\mu m^3/\mu m\) (Figure 22). Thus the sapwood of hemlock is 5 to 200 times more permeable than heartwood in the longitudinal direction. As mentioned above the variation in pit and tracheid dimensions and pit aspiration could be the reason for this wide difference.
Figure 21: Distribution of longitudinal specific permeability of heartwood at different tree heights

Figure 22: Distribution of specific longitudinal permeability of sapwood at different tree heights
The average longitudinal specific permeability of sapwood and heartwood specimens from all trees was also statistically analyzed and plotted in Figure 23. From Table 4, it is apparent that average specific permeability of sapwood (1.184 with SD=0.49) is significantly higher than the average specific permeability of heartwood (0.070 with SD=0.06) at 95% confidence level.

![Average Specific Permeability of Sapwood and Heartwood](image)

**Figure 23: Average specific permeability of sapwood and heartwood samples from all trees with error bar representing 95% confidence level**

The lower permeability of heartwood in hemlock might be due to the high degree of aspiration in the bordered pits and also the incrustation of the bordered pit membranes (Koumoutsakos and Avramidis, 2004). Another reason might be extractive deposition, which is not uniform and is generally confined to the heartwood so that their presence might have contributed to the variation of heartwood and sapwood permeability in hemlock as previously reported (Gray and Rickey 1982). In addition, maximum effective pit pore radii vary greatly
between heartwood and sapwood, which in turn could result in the variation of permeability (Bailey and Preston, 1970).

Table 4: ANOVA for longitudinal permeability of sapwood and heartwood specimens

<table>
<thead>
<tr>
<th>Source</th>
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<th>Type III SS</th>
<th>Mean Square</th>
<th>F Value</th>
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<tr>
<td>Total</td>
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<td>103.51</td>
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<td></td>
</tr>
</tbody>
</table>

S=Section (Sapwood and Heartwood) D=Direction (North, South, East and West) H=Height (1m, 4m and 7m)

This difference has also been reported with many other softwood species (Bao et al. 1999, Rice and D’Onofrio 1996, Bailey and Preston 1970, Vete 1963, Krahmer and Cote 1963). Bao et al. (1999) measured the longitudinal permeability of heartwood and sapwood samples in 40 Chinese species. They reported that the sapwood permeability of both softwoods and hardwoods was generally much higher than that of heartwood with 3 to 144 in softwood and 1 to 1302 times higher in hardwood, respectively. In white pine (Pinus strobus), Rice and D’Onofrio (1996) observed that the average sapwood permeability (4.03 x 10⁻⁷µm³/µm) was almost seven times greater than the average heartwood permeability (5.99x10⁻⁸µm³/µm). Bailey and Preston (1970) showed that on average, the flow of water through the sapwood of Douglas fir is 1000 - 8000 times higher than that of heartwood, whereas that through the sapwood of eastern larch is 124,000 times as great as that through
the heartwood. Parsapajouh et al. (2005) measured longitudinal permeability of heartwood and sapwood samples in hornbeam wood (*Carpinus betulus*) and found that the amount of heartwood permeability was approximately 55% less than that of sapwood.

### 5.1.2 Longitudinal Permeability Along The Height of The Tree

The average specific permeability of heartwood and sapwood specimens measured at 3 different heights is shown in Figure 24. At all three heights, the sapwood specimens exhibited significantly higher specific permeability than the heartwood ones. However, when average specific permeability of heartwood and sapwood specimens was compared separately for each tree height, the average permeability of heartwood samples showed no significant difference among them. In contrast, in sapwood specimens, the specimens at 7m tree height showed higher average specific permeability than the specimens at 1m and 4m.

![Figure 24: Comparison of longitudinal permeability between heartwood and sapwood at three tree heights with error bar representing 95% confidence level](image-url)
Average specific permeability value of sapwood at 7 meters high was found to be 1.421 $\mu m^3/\mu m$ (SD=0.51), whereas values at 1m and 4m height these values were 1.112 $\mu m^3/\mu m$ (SD=0.48) and 1.018 $\mu m^3/\mu m$ (SD=0.38), respectively. Statistical analysis showed that there is a significant difference between the average permeability of sapwood specimens at 7m height with that of the specimens at 1m or 4 m. Tables 5 and 6 lists the ANOVA and Least Square Means (LSM) data for longitudinal specific permeability of sapwood and heartwood samples at three different tree heights. The comparisons of LSM values are listed in the Table 7 and any t-value below 0.0033 (calculated by confidence level by number of pairs which is .05/15) will indicate a significant variation between the compared values.

Table 5: ANOVA for longitudinal permeability of sapwood and heartwood sections at different tree heights

<table>
<thead>
<tr>
<th>Source</th>
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<th>F Value</th>
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<td>74.45</td>
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<td>0.09</td>
<td>0.82</td>
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<td>8.14</td>
<td>0.0004</td>
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<tr>
<td>D*S</td>
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<td>0.11</td>
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<td>H<em>D</em>S</td>
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<td>0.44</td>
<td>0.07</td>
<td>0.67</td>
<td>0.6779</td>
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<tr>
<td>Model</td>
<td>23</td>
<td>79.73</td>
<td>3.46</td>
<td>31.48</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>216</td>
<td>23.78</td>
<td>0.11</td>
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<tr>
<td>Total</td>
<td>239</td>
<td>103.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Least Square Means of sapwood and heartwood at 3 different heights

| H | S | Y LSMEAN | Error  | Pr > |t| | Number |
|---|---|----------|--------|------|---|--------|
| 1 | 1 | 1.112    | 0.05246947 | <.0001 | 1 |
| 1 | 2 | 0.067    | 0.05246947 | 0.1984 | 2 |
| 2 | 1 | 1.018    | 0.05246947 | <.0001 | 3 |
| 2 | 2 | 0.072    | 0.05246947 | 0.1677 | 4 |
| 3 | 1 | 1.421    | 0.05246947 | <.0001 | 5 |
| 3 | 2 | 0.070    | 0.05246947 | 0.1824 | 6 |
Table 7: Least Squares Means for effect of height and section

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<td>&lt;.0001</td>
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</tr>
</tbody>
</table>

1=Sapwood at 1m; 2=Heartwood at 1m; 3=Sapwood at 4m; 4=Heartwood at 4m; 5=Sapwood at 7m; 6=Heartwood at 7m

Due to the limitation of number of tree heights selected, the present result cannot be stated as increasing specific permeability with increasing tree heights as observed by Comstock (1965) in eastern hemlock. Variation in permeability with tree height has been investigated with mixed result in the past. Isaacs et al. (1971) found that there is an increasing trend of permeability with tree height in cotton wood, while Chen and Tang (1991) observed no significant effect of tree height on permeability. Therefore, further investigation on sapwood permeability with different tree heights will only confirm this trend.

The increase in permeability at 7m height in sapwood can be explained by two distinct processes such as ‘cambial maturation’ and ‘sapwood aging’. In wood, new xylem cells are produced by the divisions of cambial initials which are the meristematic cells found between the xylem and phloem. Cambial maturation is affected by height within the tree and can be described as a developmental process that results in a change in the dimensions of cambial
initials over time. This in turn affects the dimensions of xylem cells (Oleson 1978, Panshin and de Zeeuw 1980, Fabris 2000). As permeability is dependant on the dimension of the tracheid cells any change in the xylem cells will also affect the permeability of the wood. Previous studies have examined the effect of lumen diameter and tracheid length on permeability. Taras (1965) reported that lumen diameter and tracheid length have a positive effect on permeability in slash pine. Bethel (1941) found that the tracheid length increased from base of the tree upward to a maximum and then decreased towards the top and Manwiller (1966) noticed a positive correlation between tracheid length and lumen width in spruce pine (*Pinus glabra*). These findings together imply that permeability may increase with increasing tree height. The ‘sapwood aging’, which includes changes in relative water content due to accumulation of emboli (Chalk and Bigg 1956, Sellin 1991, Sperry *et al.*1991, Shupe *et al.* 1995), aspiration and incrustation of bordered pit membranes (Krahmer and Côté 1963, Panshin and de Zeeuw 1980), and loss of integrity or flexibility of pit membranes (Sperry *et al.* 1991) can also accounted for the increase in permeability with height.

5.1.3 **Longitudinal Permeability Across a Tree Cross-section**

In this study the permeability profile across a tree cross-section in the North-South direction at all three heights were investigated. The main observation was that there was a marked difference in permeability while moving from outer bark towards the pith. The sample representation of a longitudinal permeability profile across a single tree cross-section at three different heights is shown in Figures 25, 26 and 27.

The plots indicate that permeability tended to decrease with distance from the outer bark. This may be due to the transformation of wood from sapwood to heartwood where in heartwood specimens has aspirated bordered pits and margo incrustation, despite the absence
of a visible sapwood/heartwood interface in this species (Koumoutsakos and Avramidis 2004). However, it is a possible that the decreasing trend in permeability near the pith may also be due to the presence of juvenile wood that has shorter tracheids that in turn can reduce permeability (Passialis and Kiriazakos 2004)

Figure 25: Variation of specific permeability across a tree cross-section at 1m height
Figure 26: Variation of specific permeability across a tree cross-section at 4m height

Figure 27: Variation of specific permeability across a tree cross-section at 7m height
Tracheid dimensions could also explain the permeability changes in the horizontal direction. Generally, earlywood tracheids have larger lumen size relative to latewood tracheids which in turn can increase the permeability of earlywood tracheids (Petty 1970). It was found that lumen width and tracheid length in earlywood increased with increasing distance from the pith (Taras 1965, Jackson 1959). Park et al. (1999) also reported that earlywood has a large lumen diameter than in latewood Douglas-fir. Manwiller (1966) also found a positive correlation exists between tracheid length and lumen width in spruce pine (Pinus glabra) which was shown to display an increases in permeability with increasing distance from the pith. There are also some contradictory reports indicating that latewood is more permeable than earlywood. Milota et al. (1995) reported that the air permeability was lower for the air-dried earlywood samples than that for the latewood samples.

5.2 Radial Permeability

Radial permeability deserves priority attention in the industrial context especially in drying, preservative or chemical treatments where utility poles are penetrated radially. In conifers, horizontally aligned ray tracheids constitute the principle pathway for radial flow. Usually radial permeability is far lower than that in the longitudinal direction because of the comparatively higher refractory nature of the ray cells.

The radial specific permeability values obtained in the present study ranged from 0.001 to 0.32µm³/µm which reflects a 7:1 to 2340:1 times lower permeability than that of longitudinal permeability. The values reported with other species range from 15:1 to 50,000:1. This high difference is due to impermeable rays and the fact that most of the inter-tracheid pits are on the radial surfaces on the pits (Siau 1995). The result of this study also
reflects the refractory nature of hemlock. Therefore, any treatment that could “open up” the ray structure might likely enhance the radial permeability.

![Graph showing specific permeability comparison between sapwood and heartwood](image)

**Figure 28: Average longitudinal and radial permeability of heartwood and sapwood samples with error bars representing 95% confidence level**

It is also interesting to note that like longitudinal permeability, radial permeability of sapwood is many times higher than that of heartwood (Figure 28). Radial permeability in most of the sapwood specimens at 1m and 4m height ranged from 0.04 to 0.16µm³/µm (Figure 29). However, at 7m height, most of the specimens showed permeability of 0.12 to 0.24µm³/µm, but a few exhibited radial permeability values even up to 0.28 to 0.32µm³/µm. This suggests a distinct difference in the radial permeability of sapwood as tree height increases beyond 4 meters from ground level. The increase in permeability at 7m height has also been observed with the sapwood longitudinal permeability values (Figure 24).
Figure 29: Distribution of radial specific permeability of sapwood samples at different tree heights

Figure 30: Distribution of radial specific permeability of heartwood samples at different tree heights
In heartwood, at all tree heights investigated, 80% of the samples fall in the range of 0.006-0.016µm³/µm as shown in Figure 30. However, the maximum permeability range for 1m height was 0.01 - 0.015µm³/µm, the same value stands for the minimum permeability range at 7m. In other words heartwood also shows an incremental distribution pattern for permeability with respect to height.

![Graph comparing average radial permeability of sapwood and heartwood samples](image)

**Figure 31:** Comparison of average radial permeability of sapwood and heartwood samples at three different tree heights with error bar representing 95% confidence level

The average radial permeability of sapwood and heartwood samples was also compared separately with different tree heights and is presented in Figure 31. It is observed that the specimens at 7m tree height showed a higher average permeability value than the specimens at 4m and 1m. The statistical analysis confirmed that there was a significant difference variation between the values at 7m with that of 4m and 1m of sapwood samples (Table 8 and 9). However, lack of significant variation was evident between the permeability values of 1m
and 4m when they were compared separately (Table 9). The reason for this increase in permeability at 7m height might be due to a phenomenon called “cambial maturation” that was explained earlier.

Table 8: ANOVA of sapwood samples at three different tree heights

<table>
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<th>ANOVA</th>
<th>Source</th>
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<th>MS</th>
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<th>P-value</th>
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Table 9: ANOVA of sapwood samples at 1m and 4m tree heights

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For heartwood samples, unlike heartwood longitudinal permeability samples, the absolute values of the radial permeability seem to numerically increase with the tree height. However, statistical analysis shows that there is only significant difference between specimens at 7m and with that of 1m or 4m. Like sapwood samples, radial permeability of specimens at 1m and 4m also showed no significant difference between them (Table 10 and 11).
Table 10: ANOVA of heartwood samples at three different tree heights

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Table 11: ANOVA of heartwood samples at 1m and 4m tree heights

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5.3 Tracheid Length

Western hemlock, like all other softwood species, consists primarily of long tubular fibres with sealed ends that are “cemented” together along their length in a parallel fashion with a continuous lignin-hemicellulose sheath. The voids of softwoods are thus almost entirely intra tracheid lumen voids, which act as the principal pathway for the movement of fluids in wood (Usta and Hale 2006). It is therefore interesting to explore the distribution and pattern of tracheid length in western hemlock and any possible correlation to permeability. The distribution of tracheid length values among all heartwood and sapwood samples at all tree heights are plotted in Figures 32 and 33. In sapwood, 75% of the tracheids fall within the range of 3 – 3.5mm whereas in heartwood, 60% of the values were in the range of 2 – 2.5 mm. The overall range of tracheid length for all wood samples was 1.30 – 3.66mm.
Figure 32: Frequency distribution of tracheid length of sapwood at different tree heights

Figure 33: Frequency distribution of tracheid length of heartwood at different tree heights
Many researchers have reported this wide variation in tracheid length in several other softwood species (Debell et al. 1998, Honjo et al. 2006) and speculated possible reasons for this. One main reason is the lack of an unbiased method for the selection/isolation of tracheids (Han et al. 1999). As earlywood tracheids have thinner cell walls, it is always possible that it will break during the measurement and broken tracheids are measured, thereby providing biased results. In addition, it has been shown that latewood tracheids are longer than earlywood tracheids, which automatically give rise to differences in the tracheid lengths even within the same growth ring (Honjo et al. 2006).

5.3.1 The Effect of Tree Height on Tracheid Length

At all selected heights investigated, it was clear that the average tracheid length of sapwood is significantly longer compared to that of heartwood. From the Figures 32, 33 and 34 it is evident that the tracheid length of all sapwood samples studied ranged from 2.033 to 3.664mm with average value of 3.098mm while for heartwood the average tracheid length was found to be 2.104mm with values ranged from 1.303 to 2.886mm. The statistical analysis showed that there is a significant difference between the sapwood and heartwood specimens at 95% confidence level (Table 12).

This variation can be attributed to the increase in length of the cambial initials with age combined with an enhanced intrusive growth (Honjo et al. 2006). Numerous published reports have shown the same trend with many other conifers including radiata pine, loblolly pine and Douglas-fir (Zobel et al. 1960, Boyce and Kaeiser 1961, Dadswell et al. 1961, Koch 1972, Piedra and Zobel 1986, Goyal et al. 1999). Basically, all these studies confirm Sanio’s laws on increasing tracheid length with increase in distance from the pith.
Table 12: ANOVA for average tracheid length of sapwood and heartwood sections

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Type III SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2</td>
<td>0.05</td>
<td>0.03</td>
<td>0.40</td>
<td>0.6722</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>0.09</td>
<td>0.03</td>
<td>0.42</td>
<td>0.7377</td>
</tr>
<tr>
<td>S</td>
<td>1</td>
<td>59.29</td>
<td>59.29</td>
<td>864.67</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>H*D</td>
<td>6</td>
<td>0.49</td>
<td>0.08</td>
<td>1.19</td>
<td>0.3143</td>
</tr>
<tr>
<td>H*S</td>
<td>2</td>
<td>0.11</td>
<td>0.05</td>
<td>0.78</td>
<td>0.4596</td>
</tr>
<tr>
<td>D*S</td>
<td>3</td>
<td>0.05</td>
<td>0.016</td>
<td>0.24</td>
<td>0.8681</td>
</tr>
<tr>
<td>H<em>D</em>S</td>
<td>6</td>
<td>0.48</td>
<td>0.08</td>
<td>1.18</td>
<td>0.3188</td>
</tr>
<tr>
<td>Model</td>
<td>23</td>
<td>60.55</td>
<td>2.63</td>
<td>38.40</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>216</td>
<td>14.81</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>239</td>
<td>75.37</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 34: Average tracheid length of sapwood and heartwood samples from all trees with 95% confidence level.

The tracheid length of sapwood and heartwood samples exhibited no particular trend with tree height when they were compared separately. It is evident from Figure 35 that the
average tracheid length of sapwood samples at 1m height was found to be 3.07mm (SD=0.22) where as for 4m and 7m it was 3.09mm (SD=0.28) and 3.14mm (SD=0.23), respectively. Although the absolute values of the tracheid lengths are slightly different and they seem to numerically increase with the tree height, statistical analysis shows that there is no significant difference amongst (Table 13). In heartwoods, the average tracheid length at 1m height was found to be 2.09mm with standard deviation of 0.29 where as at 4m and 7m meter the average remains as 2.14mm (SD=0.26) and 2.09 (SD=0.27), respectively, showing no definite trend.

Table 13: ANOVA for average tracheid length of sapwood and heartwood sections at three different heights

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Type III SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.03</td>
<td>0.40</td>
<td>0.6722</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>0.09</td>
<td>0.03</td>
<td>0.42</td>
<td>0.7377</td>
</tr>
<tr>
<td>S</td>
<td>1</td>
<td>59.29</td>
<td>59.29</td>
<td>864.67</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>H*D</td>
<td>6</td>
<td>0.49</td>
<td>0.08</td>
<td>1.19</td>
<td>0.3143</td>
</tr>
<tr>
<td>H*S</td>
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<td>0.11</td>
<td>0.05</td>
<td>0.78</td>
<td>0.4596</td>
</tr>
<tr>
<td>D*S</td>
<td>3</td>
<td>0.05</td>
<td>0.016</td>
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</tr>
<tr>
<td>H<em>D</em>S</td>
<td>6</td>
<td>0.48</td>
<td>0.08</td>
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<td>0.3188</td>
</tr>
<tr>
<td>Model</td>
<td>23</td>
<td>60.55</td>
<td>2.63</td>
<td>38.40</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>216</td>
<td>14.81</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>239</td>
<td>75.37</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The variation of tracheid length with respect to the height of the tree has been subjected to many contradictory findings. Taylor (1982) showed that the tracheids of white spruce were longest near the bottom of the tree and tracheid length decrease steadily with increase in height. On the other hand, Koubaa et al. (1998) has shown that tracheid length of different poplar clones increases with increase in both tree height and annual growth rings. Tracheid length of Taiwan red cypress (Taxodium distichium) shows an increasing trend in the first
few meters height from the base of the tree and then decreases when it reaches the top of the tree (Wang and Hong 1988).

Contrary to all these findings, in this study, it was observed that there was no significant variation in tracheid length at the selected tree heights studied. However, the present study has a limitation as it is subjected to a small number of tree heights. Therefore, a more elaborate study on the effect of a large range of tree heights of western hemlock on tracheid length can only corroborate this preliminary observation.

![Figure 35: Comparison of tracheid length between heartwood and sapwood at different tree heights with error bars representing 95% confidence level](image)

**5.3.2 The Effect of Tracheid Length on Longitudinal Permeability**

In the past, there have been no significant research efforts that focused on the relation between tracheid length and permeability. However, given the fact that water movement occurs through the void lumens in the tracheids and then through the pits, it would be
interesting to explore whether the differences in the tracheid length and consequent differences in the lumen area has any effect on the rate of water movement which is directly proportional to air permeability. Theoretically, tracheid length should have an influence in the permeability of the wood samples because the longer the tracheid, the fewer end-wall crossings per unit length, and so the greater the permeability (Sperry and Hacke 2004). In the present study, there were no definite correlation observed between tracheid length and permeability of both heartwood and sapwood.

![Graph showing the relationship between tracheid length and longitudinal specific permeability](image)

**Figure 36: Longitudinal specific permeability of heartwood as a function of tracheid length**

The relationship between tracheid length and permeability are shown in Figures 36 and 37. It is clear that no apparent correlation between the tracheid length and longitudinal
permeability both in sapwood and heartwood and apparently it can be concluded that tracheid length has no significant effect on the longitudinal permeability of hemlock.

![Figure 37: Longitudinal specific permeability of sapwood as a function of tracheid length](image)

5.4 Density

Wood density is complex; it is influenced by cell wall thickness, the proportion of different kinds of cells and percentage of lignin, cellulose and extractives. In this study the density of hemlock specimens at three different heights were measured and shown to range from 341-854kg/m$^3$ with average density of 469kg/m$^3$ and standard deviation of 68.6. The average density of samples at 1m, 4m and 7m were found to be 494, 459 and 446kg/m$^3$, respectively and are plotted in the Figure 38.
Although the absolute values of density seem to numerically decrease with the tree height, statistical analysis showed that there is only significant difference between the average density at 1m with that of 4m or 7m (Table 14 and 15). Table 15 clearly shows that the density between 4m and 7m heights have no significant difference.

Table 14: ANOVA for average density of specimens at three different heights

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>Df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>84947.77</td>
<td>2</td>
<td>42473.88</td>
<td>11.842</td>
<td>1.38E-05</td>
<td>3.041286</td>
</tr>
<tr>
<td>Within Groups</td>
<td>713744.9</td>
<td>199</td>
<td>3586.658</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The tree height effect on density has been many contradictory findings in the past. The decreasing trend with tree height was reported by Donaldson et al. (1995). They carried out
an experiment with radiata pine and observed that density decreases with increasing tree height. However, constant or even increase in density with increases in tree height was also reported in some species like Douglas-fir (Ward 1975). Therefore, the effect of height on the density of tree height has further research possibilities including additional tree heights and also considering the silvicultural effects.

Table 15: ANOVA for average density of specimen at 4m and 7m height

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>Df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>5619.624</td>
<td>1</td>
<td>5619.624</td>
<td>1.618</td>
<td>0.205606</td>
<td>3.91455</td>
</tr>
<tr>
<td>Within Groups</td>
<td>447936.1</td>
<td>129</td>
<td>3472.373</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Within individual trees, density varies from pith to bark at a given height in the tree (Jozsa and Kellogg 1986). In this study it was observed that the density is relatively high near the pith, then decreases in the juvenile wood and then again increases when reaching the sapwood. Density variation across the cross section of a single tree is depicted in the Figure 39. The broad range of density values is mainly due to the percentage of earlywood and latewood differences and also differences in the densities of earlywood and latewood in which latewood cells are having thicker cell walls and less pore size. This trend has also been reported by other researchers in the past (Megraw 1986, Jozsa et al. 1989, Kennedy 1995, Gartner et al. 2002).
5.4.1 Density Effect on Longitudinal Permeability

As wood density is highly determined by the type of cells and extractive deposition in tracheids, it is likely that density can have a direct impact on permeability. However, research has shown that the density has no affect on the permeability (Bao 1984, Koga and Zhang 2004). Bao (1984) showed that wood density did not directly affect the permeability within the same species. In this study, no significant correlation could be observed between these two properties (Figure 40).
Figure 40: Longitudinal permeability of western hemlock wood as a function of density
6 Conclusion

Understanding the mechanism of fluid flow and the controlling factors affecting it, is vital to ensure effective industrial utilization of commercially important softwood species such as western hemlock. The present investigation has therefore aimed to determine the internal variations in longitudinal and radial permeability in western hemlock and investigate the effect of tree height, tracheid length and density on these variations.

Experiments on longitudinal and radial permeability revealed the following finding:

- Longitudinal permeability is in the range of 0.01-2.34$\mu$m$^3/\mu$m whereas for radial permeability it is of the range 0.001-0.32$\mu$m$^3/\mu$m, i.e., the former is 7 to 2340 times higher than the latter.

- The longitudinal permeability of sapwood was found to be 5 to 200 times higher than that of heartwood. Hence, the sapwood of western hemlock can be recommended for applications that demand of higher permeability.

- The longitudinal and radial permeability of sapwood at 7m height from the ground was found to be significantly higher than that of 1m or 4m height.

- The longitudinal permeability of heartwood showed no significant difference in permeability with respect to height. However, in radial permeability of heartwood samples at 7m height was observed to be significantly higher than that of specimens at 1m or 4m. Statistical analysis between 1m and 4m revealed a non significant difference.
Tracheid length of all wood specimens measured, varied from 1.3 to 3.7mm in which most of the sapwood specimens were in the range of 3-3.5 and 2-2.5mm for heartwood specimens.

Tracheid length does not change significantly with respect to height and there was no statistical correlation observed between tracheid length and longitudinal specific permeability.

Density of western hemlock was found to be in the range of 314 to 858kg/m³. It is relatively higher near the pith decreases and then levelled off in the sapwood.

Though variation in density is likely to change permeability, in the present study there was no statistically significant difference observed between density and longitudinal specific permeability.
7 Recommendations for Future Research

Fluid exchange between the tracheids and rays is mainly through the bordered or no bordered pit pairs. Because the average diameter of the pit pores are much smaller than that of the tracheid lumens, the permeability of wood is largely dependent on the size and condition of pit structure. Therefore, parameters such as effective pore size and number of pit opening per unit area should be measured to know more about the western hemlock permeability. The diameter of the tracheid lumen can also be considered for further research.

In addition, the major reasons behind the low permeability in hemlock heartwood need more elaborate research. The reason behind low permeability is due to the pit aspiration and extractive deposition. Thus the degree of pit aspiration and amount of wood extractives in wood should be taken into consideration while doing the further research. Theoretically, the permeability can be enhanced by pre exchange of organic solvents with free water. Therefore research can also be focused upon finding the suitable organic solvent and further process optimization with respect to western hemlock.

Lastly this research also needs to be extended in order to find out the variability of both permeability and tracheid length in western hemlock with more number of tree heights, different age class and also with different site location. The effects of seasonal variation and silvicultural effect on permeability of western hemlock should also be further studied.
8 References


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Helmuth, R., Barton, A. E. (1964) Kiln drying of heavy segregation redwood lumber. Report on meeting proceedings of Research Council California Redwood, Association, Forest Products Laboratory, University of California, USA


