NON-DARCIAN AIR FLOW IN WOOD

by

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Abstract

The purpose of this thesis research was to better understand the nature of gas flow in wood, and especially the phenomenon of non-Darcian air flow. Specifically, the objectives were to evaluate the non-Darcian air flow due to (1) specimen length; (2) nonlinear flow; and, (3) slip flow in wood, through a systematic investigation of the air flow phenomena in two softwoods and two hardwoods. Throughout the thesis, over the experimental range, the hypothesis that Darcy's law is not of universal application to gas flow in wood was shown to be true.

Firstly, non-Darcian behaviour due to specimen length seemed common in the studied species. In the experimental range of specimen lengths, there was an existence of a certain length above which the permeability values were nearly identical for the various lengths of the tested species. These specimen lengths were found to be 140, 100, 60 and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. When the specimen length was below a critical value for the different species described above, permeability increased drastically with decreasing specimen length. The higher the air permeability of a species, the greater was the critical specimen length. When the specimen length is above a critical value for the different species described above, the pressure drop caused by end effects due to the shape and condition of the specimen entrance is negligible.

Secondly, except for red oak heartwood, there was no evidence of non-Darcian flow due to nonlinear flow in the studied species throughout the entire measured range of flow rates. For red oak heartwood, when the lower flow rates are used (Q≤19.57 cm³/s), the test results for the detection of nonlinear air flow were exactly the same as the specimen groups of red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood. That is, both permeability
measurement and pressure-flow rate-relationship methods for the detection of nonlinear flow, indicated the existence of linear flow components only within the specimen. However, when the flow rates used were above 19.57 cm$^3$/s, the test results showed that, the superficial specific permeability at the mean pressure of 0.5x10$^5$ Pa decreased with the increase of the flow rates, and the expression equation of pressure drop and flow rate at a given mean pressure of 0.5x10$^5$ Pa involved both a linear and quadratic dependence of the pressure drop on the flow rate, thus demonstrating the presence of the nonlinear flow components in the specimen. The calculated value of Reynolds' number in the range of 0.263 to 1.05 further suggested that, the nonlinear flow found in the red oak heartwood at higher flow rates in this study was probably nonlinear laminar flow due to the kinetic-energy losses occurred in the curved openings.

Finally, the test results indicated that the non-Darcian air flow due to slip flow existed in all the studied specimen groups. The true permeability of red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood was 20.91, 7.05, 0.51 and 0.068 μm$^3$/μm, respectively. The average ratios of the superficial specific permeability at 0.5x10$^5$ Pa mean pressure to the true permeability were found to be: red oak heartwood: 1.047; red alder heartwood: 1.204; ponderosa pine sapwood: 1.292; and, Douglas-fir sapwood: 1.53. The slip flow constant b was highest (0.265x10$^5$Pa) for Douglas-fir sapwood, higher (0.146x10$^5$Pa) for ponderosa pine sapwood, lower (0.102x10$^5$Pa) for red alder heartwood, and lowest (0.023x10$^5$Pa) for red oak heartwood. The radius (r) and the number (n) of average effective openings were found to be: red oak heartwood: 17.432 μm and 0.066x10$^6$ per cm$^2$; red alder heartwood: 3.955 μm and 7.5x10$^6$ per cm$^2$; ponderosa pine sapwood: 2.972 μm and 3.3x10$^6$ per cm$^2$; and, Douglas-fir sapwood: 1.552 μm and 3.6x10$^6$ per cm$^2$. 
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1.0 Introduction

On the whole, the movement of fluids through wood can be subdivided into two categories: flow and diffusion (Stamm 1967a, b, Siau 1995). Since the flow of fluids and diffusion through wood follow different laws they are always divided into two different topics. This research is concerned only with fluid flow.

Fluid flow through wood is encountered in a broad range of wood industrial processes which include such diverse fields as preservative and fire-retardant pressure treatments, fumigation, wood impregnation with monomers, impregnation of wood chips with pulping chemicals, and the drying of timber, veneers and chips.

A porous medium is a solid with voids in it of equal or variable diameter and shape. Wood can be considered as a consolidated and ordered medium (Greenkorn 1983), but in reality it has a much more complicated structure. There is a great pore size and shape variation within the body of wood.

In softwoods, the flow of fluids primarily takes place through the tracheid lumens which are mainly interconnected by bordered pit pairs. The pit openings are very small in diameter compared to the lumens, and are therefore assumed to provide almost all resistance to flow. The structure of hardwoods is more complex, and thus fluid flow occurs through channels of greater variety compared with softwoods. Fluid flow through hardwoods is mainly through the vessel elements which are interconnected by perforation plates. For the sake of simplicity, the description of the flow phenomena in wood is usually based upon the uniform-parallel-circular-capillary model (Siau 1995) in spite of its structure being extremely complex and nonhomogeneous.
Fluid flow through wood mainly results from a mechanical pressure gradient, but it may also be caused by other driving forces, such as thermal or electrical gradients (Resch and Ecklund 1968). This research project is only concerned with steady-state, one directional, mechanical single-phase flow with air as the flowing medium.

Darcy's law states that the volumetric flow rate of a fluid flowing through a porous medium is related linearly to the energy loss, inversely to the length of the medium, and proportionally to a constant conductivity.

Most of the early work in the area of fluid flow phenomena through wood was concerned with the flow of liquids, and the linear Darcy's law was used to describe the flow process. Interest then turned to the flow of gases through wood, and again, the linear Darcy's law was used to describe the flow characteristics, with compressibility and slip flow taken into account.

Although the gas flow through wood has extensively been studied by various investigators, some mechanisms have still been a matter of conjecture, especially in the area of non-Darcian fluid flow. Therefore, it seems that the need for more systematic and comprehensive research on fluid flow in wood is necessary.

This study is concerned with the general case of air flow through wood, with emphasis on the non-Darcian flow regime. Its purpose is to better understand the mechanisms of gas flow in wood, and especially the phenomenon of the non-Darcian gas flow. Increased knowledge in the theory and principles of the fluid flow in wood, would undoubtedly lead to more efficient lumber drying methods, and wood impregnation with preservatives, fire retardants and other chemical modifiers. Specifically, the objectives were to carry out a systematic investigation of the air flow phenomena in two softwoods and two hardwoods through rigorous experimentation and analysis.
of permeability coefficients, flow rates and pressures from the following three areas: (1) examination of non-Darcian flow due to specimen length and evaluation of critical specimen length; (2) examination of non-Darcian flow due to nonlinear air flow in wood; (3) detection of non-Darcian flow due to slip flow, and evaluation of the true gas permeability, the superficial specific permeability, slip flow constant, and the number and sizes of effective capillaries in wood based on the derivation of a viscous-slip flow model.
2.0 Literature Review

2.1 Wood structures related to fluid flow

Wood can be considered as a consolidated and ordered medium (Greenkorn 1983). It is highly porous, but not a very permeable material. Dry wood in the normal specific gravity range of 0.3 to 0.6 has fractional void volumes ranging from 0.795 to 0.59 (Stamm 1963). This large void volume is made up primarily of fibre and vessel capillaries together with smaller amounts of ray cell and resin duct capillaries. Communication between these microscopically visible capillaries occurs through small, normally submicroscopic pit and perforation plate openings. These capillaries constitute the various paths for fluid flow into, through, or out of wood, in both parallel and series arrangement. The fluid flow through the true capillaries of wood may be considered analogous to flow through a combination of perfect glass capillaries in a series and parallel combination. According to Poiseulle's equation, flow is chiefly controlled by the smallest path in series combination and the largest path in parallel combination. Therefore, the flow of fluids through wood is undoubtedly related to the anatomical structure of wood.

Wood has an extremely complex and nonhomogeneous structure. This is reflected by the wide ranges in its physical properties such as permeability. Before continuing the discussion of fluid flow in wood it is necessary to understand the main structural features governing the movement of fluids in and through wood.

2.1.1 Structure of softwoods

Softwoods evolved on earth before hardwoods, and they have a greater uniformity
compared with the more specialized and complex anatomy of the latter. A typical softwood structure is revealed in Figure 1 representing the wood of loblolly pine (*Pinus taeda* L.).

The fluid-conducting tissue, or prosenchyma, consists of the longitudinal and ray tracheids. The parenchyma which functions in the living tree as storage tissue for reserve food material and radial transport includes the longitudinal parenchyma, the epithelial cells surrounding resin canals, and the ray parenchyma. Longitudinal and horizontal resin canals are present in genus *Pinus, Picea, Larix*, and *Pseudotsuga*. A typical volumetric composition of softwood structure, represented by white pine (*Pinus strobus* L.) (Panshin and de Zeeuw 1980), is

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<tr>
<td>Longitudinal tracheids</td>
<td>93%</td>
</tr>
<tr>
<td>Longitudinal resin canals</td>
<td>1%</td>
</tr>
<tr>
<td>Wood rays</td>
<td>6%</td>
</tr>
</tbody>
</table>

Since the rays and resin canals form a small fraction of the volume, their contributions to the overall flow is of secondary importance. If these flow paths are neglected, a very simple flow model for softwoods results, in which fluids flow from tracheid to tracheid through the bordered pit.

Voids in the secondary walls of cells are called pits. A pit in one cell normally occurs opposite a pit in an adjacent cell, forming a pit pair. Pit pairs are the most important structural factors to the flow phenomena through softwood because they are the principal avenues through which fluids pass from cell to cell. Three types of pit pairs are common in softwoods, illustrated in Figure 2. The simple pit pair (a), which occurs between two parenchyma cells such as ray and longitudinal parenchyma. A half-bordered pit pair (c) is located between a parenchyma and a prosenchyma cell (tracheid) with the bordered portion facing the prosenchyma cell. A bordered pit
Figure 1  Gross structure of a typical southern pine softwood.

Transverse surface. 1, latewood of one growth ring; 2-2a, earlywood; 3-3a, latewood of growth ring formed subsequent to 1; 4-4a, row of longitudinal tracheids initiated by earlier anticlinal division of cambial initials at 4; 5, longitudinal resin canal; 6-6a, row of sectioned ray tracheids; A, B, C, D, bordered pits; E, epithelial cell; F, longitudinal parenchyma.

Radial surface. 7-7a, sectioned uniseriate ray; 8-8a, sectioned fusiform ray; G, dentate ray tracheid; H, ray parenchyma; I, transverse resin canal; J, ray epithelial cells; K, ray tracheid.

Tangential surface. 9-9a, longitudinal parenchyma strand; 10, fusiform ray; 11, 13, 14, 15, uniseriate heterogeneous rays; 12, homogeneous ray composed of ray tracheid; E, epithelial cells; G, ray tracheid; H, ray parenchyma; I, transverse resin canal; J, ray epithelium; L, opening connecting longitudinal transverse resin canals; M, longitudinal tracheid in latewood; N, longitudinal tracheid in earlywood. [from Howard and Manwiller (1969), and Haygreen and Bowyer (1996)].
Figure 2  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)].
pair (b) is situated between two prosenchyma cells such as ray tracheids or longitudinal tracheids. Therefore, communication between parenchyma cells occurs through a simple pit pair, between a parenchyma cell and a tracheid through a half-bordered pit pair, and between tracheids through a bordered pit pair.

Of the three types of pit pairs, the bordered pit pair has the most significant influence on flow properties, because nearly all of the softwood tissue consists of prosenchyma cells. As illustrated in Figure 2(b), the typical bordered pit pair is characterized by the separation of the cell wall from either side of the middle lamella to form a dome. The overall diameter of the pit chambers of softwoods bordered pits has an approximate range of 6 to 30µm, earlywood pits being larger than latewood pits. The diameter of the torus, when present, is one-third to one-half the overall diameter of the chamber, and that of the aperture is about one-half the diameter of the torus. The torus is the thickened centre portion of the pit membrane, consisting of primary wall material, and it is typical of species of softwoods. Usually there are no apparent openings in the torus, thus it is generally considered impermeable to fluids. 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 as illustrated in Figure 3. The openings between the microfibrils permit the passage of fluids and small particles through the pit membrane.

2.1.2 Structure of hardwoods

Hardwoods are much more complex in structure than softwoods because more cell types enter their composition. The structure of a typical hardwood is illustrated in Figure 4 with identification of the principal cell and tissue types including vessels, fibres, and rays in earlywood
Figure 3  The fibrillar structure of the margo in an unaspirated 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) and Siau (1971)].
Gross structure of a typical diffuse-porous hardwood.

Transverse surface. 1-1a, latewood; 1a-1b, earlywood of succeeding growth ring; c, earlywood fibre; d, latewood fibre; e, longitudinal parenchyma; f, vessel-to-vessel pitting; g, vessel-to-ray parenchyma pitting; h, vessel-to-fibre pitting; 2a-2b, 2c-2d, 2e-2f, rays.

Radial surface. c, earlywood fibre; d, latewood fibre; e, longitudinal parenchyma; g, vessel-to-ray parenchyma pitting; h, vessel-to-fibre pitting; l, perforation plate between vessel elements; j, ray composed of procumbent ray parenchyma.

Tangential surface. c, fibres; l, perforation plate between vessel elements; k, rays in end view; m, fibre-to-fibre pitting (bordered). [from Haygreen and Bowyer (1996)].
and latewood. Hardwoods are usually classified into diffuse-porous, semi-diffuse-porous, and ring-porous types based on the variation in size or shape of pores (vessels as seen in the transverse section) throughout the growth rings. The prosenchyma or conductive tissue of hardwoods includes vessels and the fibres. The fibres are usually sparsely pitted and thick walled and include both fibre tracheids with bordered pits and libriform fibres with simple pits. Panshin and de Zeeuw (1980) listed a typical volumetric composition of diffuse-porous hardwood structure, represented by sweetgum wood (*Liqiudambar styraciflua* L.) as:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessels</td>
<td>55%</td>
</tr>
<tr>
<td>Fibre tracheids</td>
<td>26%</td>
</tr>
<tr>
<td>Longitudinal parenchyma</td>
<td>1%</td>
</tr>
<tr>
<td>Wood rays</td>
<td>18%</td>
</tr>
</tbody>
</table>

Hardwoods are characterized by the presence of vessels, composite tube-like structures of indeterminate length. The component cells of a vessel are called vessel elements. The communication between vessel elements is ensured by the openings called perforation plates. There are two main types of perforation plates in hardwoods. One is the simple perforation plate which has a single opening almost as large as the vessel lumen. The other is the scalariform perforation plate which has several openings separated by thin bars. The flow resistance of either plate is low since the openings are relatively large and the plates are thin. There is also communication between vessels through intervessel pit pairs.

The inclusions that are most frequent in vessel elements are tyloses and various amorphous exudations that are gummy, resinous, or chalky in nature. The existence of these substances in vessel elements greatly increases the resistance to flow since they occlude partially
or completely the flow path through vessels.

2.2 The flow path of longitudinal flow in wood

It is well known that a solid must be porous to be permeable, but it does not necessarily follow that all porous bodies are permeable. Permeability can only exist if the void spaces are interconnected by openings.

In softwoods, as described in Section 2.1.1, longitudinal tracheids make up the bulk of the structure of softwood. They may account for 90-93 percent of the volume, and their average diameter and length may be taken as 35μm and 3,500μm, with a length-to-diameter ratio of approximately 100 (Siau 1995). Therefore, the longitudinal fluid flow through a softwood is essentially through the tracheids. In the meantime, these tracheids are in series with bordered pit pairs. The pit openings are very small in diameter compared with the tracheid lumens, and thus, they are assumed to provide all the resistance to the flow. Therefore, it is the number and condition of the pits that determines the permeability of softwood. In other words, a softwood is permeable because the tracheid lumens are connected by pit pairs with openings in their membranes. One of the classic flow model for softwood presented by Comstock (1970) is illustrated in Figure 5. He assumed that all of the pits are on the radial surfaces of the tapered ends of the tracheids.

In hardwoods, as described in Section 2.1.2, the perforation plates, tyloses, other deposits, fibres and parenchyma cells are the primary controlling factor of longitudinal flow. However, it is generally believed that fluid passes primarily through the interconnected vessel elements. The fibres and parenchyma cells in the longitudinal direction may have much smaller openings in the
Figure 5  Softwood flow model according to Comstock (1970). Tangential section showing pits on the radial surfaces of the tapered ends of the tracheids. [from Siau (1984)].
path of flow, and therefore they may contribute less to the overall flow. Tyloses or other deposits in the vessels decrease significantly the permeability of hardwoods. A generalized flow model for hardwoods suggested by Siau (1995) is depicted in Figure 6. It is obvious from Figure 6 that the vessels are the most open flow path in hardwoods except when they are occluded by tyloses or other deposits. Fluids then flow from vessels to vertical parenchyma, fibres, and rays.

2.3 Fluid flow theoretical considerations

The various kinds of flow which may occur in a porous medium are: (a) viscous or linear laminar; (b) turbulent; (c) molecular slip flow; and (d) nonlinear laminar.

2.3.1 Viscous or linear laminar flow

When viscous forces are overcome, the flow results in an even streamlined flow called viscous or linear laminar flow. In the laminar type, the elements of fluid follow each other in streamlines. The streamlines are steady (and stable) with a strong tendency towards symmetry before and after the particle. The theory of linear laminar flow through homogeneous porous media is based on a classical experiment originally performed on a sand bed by Darcy in 1856. 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, and proportionally to a factor called the permeability coefficient, \( K \). For an incompressible fluid such as a liquid, Darcy's law may be written as,

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

(1)
Figure 6 Generalized flow model for hardwoods. The relative magnitude of the flows are indicated by the size of the arrows. [from Siau (1995)].
where $K_i$ is the specific permeability of wood for the liquid, $m^3/m$; $\mu$ is the viscosity of the fluid, Pa·s; $Q$ is the volumetric flow rate, $m^3/s$; $L$ is the length of the specimen in the flow direction, m; $A$ is the cross-sectional area of the specimen perpendicular to flow direction, $m^2$; $P_2$ is the upstream pressure, Pa; $P_1$ is the downstream pressure, Pa; and $\Delta P$ is the pressure differential, Pa.

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

$$PQ = \bar{P}Q = \text{constant}$$

where $\bar{P}$ is the arithmetic average of $P_1$ and $P_2$, and $\bar{Q}$ is the volumetric flow rate at $\bar{P}$. Darcy's law for gases can then be obtained with $\bar{Q}$ ($= PQ/\bar{P}$) replacing $Q$ in Eq.(1),

$$Q = \frac{K_sA\Delta P}{\mu L} (\frac{P}{\bar{P}})$$

or

$$K_s = \frac{Q\mu L}{A\Delta P} (\frac{P}{\bar{P}})$$

where $K_s$ is the specific permeability for gas in the absence of slip flow or true gas permeability; $P$ is the pressure at which the flow rate $Q$ is measured, and all the other factors have the same units as in Eqs.(1) and (2).

According to Eq.(4), the gas flow rate is directly proportional to the pressure drop ($\Delta P$) at
a constant mean pressure, provided that the porous structure of the medium remains constant in the direction of flow, that is, the permeability is independent of the length of the specimen in the flow direction.

Furthermore, viscous flow in a porous medium can be also exactly described by Poiseuille's equation. If it is assumed that the porous medium is comprised of a bundle of straight, parallel capillaries, and every capillary follows the well-known Poiseuille's law, the viscous flow of a liquid through a porous medium can then be expressed as,

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

(6)

or in the case of gases, as,

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

(7)

where \( N \) is the number of uniform straight circular capillaries in parallel; and \( r \) is the radius of uniform straight circular capillary, m.

Comparing Eqs.(1) and (6), or Eqs.(4) and (7), it is evident that the specific permeability is only a function of the number and radii of the pores when the Poiseuille's equation is combined with Darcy's equation,

$$K = K_1 = K_g = \frac{N\pi r^4}{8A} = \frac{n \pi r^4}{8}$$

(8)

where \( n \) is the number of capillaries per unit cross-sectional area, \( m^{-2} \). In other words, if a fluid
flow through a porous medium exactly obeys Darcy's law, the specific permeability is not affected by the measuring fluid.

Poiseuille's equation can be deduced exactly from the best known equation of Navier and Stokes (Scheidegger 1974), and Darcy's equation is also the empirical equivalent of the Navier-Stokes equation (Greenkorn 1983). However, both of them were derived under the assumption that the flow is steady and the inertial term, which is also called the nonlinear term by Wiegel (1980) in the Navier-Stokes equation, is zero.

2.3.2 Turbulent flow

Theory and experiment show that for very high flow rates or velocities of a fluid parallel to a wall, the flow pattern becomes transient. At that time the laminar flow breaks down, streamlines become unstable, the flow becomes chaotic, and substantial motion normal to the wall is produced. For any one system, there seems to be a "transition point" below which laminar flow is stable. Above the "transition point" the laminar flow is more likely to become unsteady and to form eddies upon the slightest disturbance. This kind of flow containing eddies is often termed turbulent flow. The transition point for which laminar flow exists in a long smooth pipe or capillary tube is usually defined by Reynolds' number,

$$Re = \frac{2\rho Q}{\pi \mu} = \frac{2\rho v}{\mu}$$

(9)

where $\rho$ is the density of the fluid, kg/m$^3$; and $v$ is the average flow velocity (m/s) in the straight capillary tube.

When the Reynolds' number exceeds approximately 2,300 in a long, straight capillary, it
has been found that laminar flow begins to break down and eddies or disturbances arise in the fluid. It may therefore be stated that the critical Reynolds' number \( (R_c) \) below which flow is completely viscous in a long, straight capillary, is equal to 2,300.

When turbulence occurs, the laws of Poiseuille and Darcy are no longer valid—where the necessary resistance (or pressure drop) is approximately proportional to the square of the flow rate. Therefore, the energy requirement to transfer a given quantity of fluid is greatly increased as a result of the turbulence introduced into the porous medium. In practice the fully developed turbulence begins at \( R_c \) of about 4,000. In the range of \( 4,000 \leq R_c \leq 10^5 \), the volumetric flow velocity of a liquid in a smooth pipe or cylindrical capillary tube may be calculated using the following empirical Blasius equation (Denn 1980),

\[
Q = \frac{14.79 r^{19/7}}{\mu^{1/7} \rho^{3/7}} \left( \frac{\Delta P}{L} \right)^{4/7} .
\] (10)

When Eq.(10) is applied to gases, the expansion of the gas must be taken into account. In this case, the relationship for the turbulent flow of gases may be written as (Siau 1995),

\[
Q = \frac{14.79 r^{19/7}}{\mu^{1/7} \rho^{3/7}} \left( \frac{\Delta \bar{P}}{PL} \right)^{4/7} .
\] (11)

It is expected that such true turbulence is unlikely in any of the capillaries in most wood species because the critical Reynolds' number for transition from laminar to turbulent flow is much higher than that which can be achieved in most woods. However, it must be kept in mind that the critical Reynolds' number mentioned above is only for a long, straight tube. If the channels for fluid flow are of some curvature, such as pits or curved tracheids, it must be expected that there is
no such thing as a definite "critical" Reynolds' number for wood at which turbulent flow would set. That is because the critical Reynolds' number at which fluid flow in a tube becomes turbulent is changed greatly by a slight curvature of the tube (Scheidegger 1974).

2.3.3 Slip flow or Knudsen diffusion

Deviations from Darcy's law or its equivalent Poiseuille's law, have not only been observed at high flow rates, but also at very low ones caused by molecular effects. Such deviations are particularly manifested in the flow of gases. When the capillary dimensions are smaller or in the same order of the mean free path, slip flow occurs. In this case, molecule-molecule collisions are gradually negligible and molecule-wall collisions occur. If the mean free path is much greater than the capillary radius, viscosity plays no part in flow since molecules collide only with capillary walls, and not with one another. Such free molecular flow is really a process of diffusion, which was called Knudsen flow by Carman (1956). Slip flow (or molecular flow) is, therefore, a function of the mean free path of the gas and the radius of the capillary.

According to the kinetic theory of gases, the mean free path of gas molecules may be calculated from the following equation (Siau 1995),

\[
\lambda = \frac{2\mu}{P} \sqrt{\frac{RT}{M_w}}
\]  

(12)

where \( \lambda \) is the mean free path, \( \mu \); \( R \) is the universal gas constant (\( = 8.314 \text{ J/mol.K} \)); \( T \) is the temperature in Kelvin; \( M_w \) is the molecular weight, and equal to 0.029 Kg/mol for air (\( \sqrt{\frac{RT}{M_w}} = 290 \text{ m/s for air at } 20^\circ\text{C and } 1.01x10^5 \text{ Pa ambient pressure} \)).
The mean free path of air molecules at 20°C and 1.01x10^5 Pa ambient pressure, is 0.1μm, and the average pore radius for the pit opening could vary between 0.01 and 4μm (Siau 1995). As a result, slip flow is expected to be significant in wood, especially in softwoods. However, slip flow is not an important factor with liquids because of the relatively short mean free path of liquid molecules. The slip flow for circular capillaries can be described by Knudsen's equation as follows:

\[ Q = \frac{4}{3} \sqrt{\frac{2\pi RT}{M_w}} \frac{Nr^3\Delta P}{PL} \]  

(13)

As a result of slip flow, the quantity of gas flowing through wood is larger than that expected from the viscous flow equations of Poiseuille or Darcy. This is attributed to "slippage" at the capillary walls because the velocity of the fluid at the walls of the channel is not zero as it is assumed in the case of Darcy's law. Therefore, the calculated superficial permeability of wood is higher when measured with a gas than with a liquid. If the fluid's mean molecular free path is very large compared with the capillary radius, only Knudsen's equation can describe the flow correctly. However, it is quite common that both viscous and slip flow may exist during the flow of a gas through wood. It is therefore a conjecture that, for such intermediate cases, the two equations have to be combined. This has been proposed by Adzumi (1937) who combined the viscous and slip components of gas flow into one equation for determination of the total flow,

\[ Q = \frac{N\pi r^4 \Delta P D}{8\mu L P} + \phi \frac{4}{3} \sqrt{\frac{2\pi RT}{M_w}} \frac{Nr^3\Delta P}{PL} \]  

(14)

where \( \phi \) is the Adzumi constant, and equal to 0.9 for single gases. Equation (14) may be
reorganized as,

\[
\frac{Q \rho L \mu}{A \Delta P \bar{P}} = \frac{n \pi r^4}{8 A} + \frac{3N}{A} \sqrt{\frac{RT}{M_w}} \frac{r^3 \mu}{\bar{P}}
\]

\[
= \frac{n \pi r^4}{8} + \frac{3n(8\pi r^4)}{8\pi \bar{P}} \sqrt{\frac{RT}{M_w}}
\]

\[
= \frac{n \pi r^4}{8} \left(1 + \frac{7.6\mu}{Pr} \sqrt{\frac{RT}{M_w}}\right)
\]

(15)

The left hand side of the above equation represents the specific permeability (cf. Eq.(5)). This specific permeability is, however, superficial or apparent specific permeability (\(K_{gs}\)) containing both viscous and slip flow components. Substituting Eqs.(8) and (12) into Eq.(15), then

\[
K_{gs} = K_g \left(1 + \frac{3.8\lambda}{r} \right) = K_g s
\]

(16)

where \(s\) is the slip-flow factor (\(= 1 + \frac{7.6\mu}{Pr} \sqrt{\frac{RT}{M_w}}\)), substituting

\[
b = \frac{3.8\lambda \bar{P}}{r} = \frac{7.6\mu}{r} \sqrt{\frac{RT}{M_w}}
\]

(17)

into Eq.(16), then

\[
K_{gs} = K_g \left(1 + \frac{b}{Pr} \right)
\]

(18)

where \(K_{gs}\) is the superficial specific permeability, that includes both the viscous and the slip flow contribution, and its value generally exceeds liquid permeability; \(K_g\) is the specific permeability or true gas permeability (i.e., when there is no slip flow), which should equal the permeability of
liquid because it is only a function of the wood structure; and $b$ is the slip flow constant, Pa, which depends on the mean free path of the gas and the radius of the capillary.

Eq.(18) is usually called the Klinkenberg's equation (Klinkenberg 1941). It is clear that the superficial specific permeability is a function of the reciprocal mean pressure. The intercept is $K_g$ and the slope is $K_gb$. This way, $r$ may be calculated from the slope and intercept of Klinkenberg's equation as

$$r = \frac{7.6\mu}{RT} \left( \frac{\text{intercept}}{\text{slope}} \right) \tag{19}$$

If air at 20°C is used as the flowing medium and the pressure is expressed in Pascal, Eq.(19) just simplifies to:

$$r = 0.04 \left( \frac{\text{intercept}}{\text{slope}} \right) \tag{20}$$

where the 0.04 has the unit of Pa.m.

Experiments have shown that the relationship between the longitudinal superficial specific permeability and reciprocal mean pressure for wood specimens are frequently curvilinear (Petty 1970; Siau et al. 1981; Bao et al. 1986) rather than a linear relationship as predicted by the Klinkenberg's equation (Eq.(18)). Petty (1970) explained this on a basis of high and low conductances existed in series, which may correspond to tracheids and pit openings in softwoods or to vessels and perforation plates or intervessel pits in hardwoods. The two conductances are each assumed to obey the Klinkenberg’s equation independently, that is, each linear components will have a slope and intercept. Therefore, a curvilinear relationship between permeability and
reciprocal mean pressure can be written as,

\[ K_{gs} = \frac{(E + \frac{e}{P})(F + \frac{f}{P})}{(e + f)/P + E + F} \]  

(21)

where \( E + \frac{e}{P} \), \( F + \frac{f}{P} \) are the linear functions of conductive versus \( 1/P \) in accordance with Klinkenberg's equation for two conductances in series, \( E \) and \( F \) are the intercepts, and \( e \) and \( f \) are the slopes. Since this phenomenon was first reported by Petty (1970), the above equation is usually referred to as the Petty's model. By the application of a nonlinear curve fitting technique to the Petty's model, the respective slopes and intercepts can then be used to calculate the average radii of the tracheid and pit openings, or of the vessels and perforation plates or intervessel pits on the basis of Eq.(20).

It is evident from Eq. (14) that Adzumi's equation for gas flow in which both viscous and slip flow components are included, predicts a linear relationship between \( Q \) and \( AP \) at a given constant mean pressure. Meanwhile, it is clear from Eqs.(18) and (21) that the superficial specific permeability is only a function of the reciprocal mean pressure, and is independent of the flow rate or pressure drop.

2.3.4 Nonlinear laminar flow

As noted before, both the Poiseuille's equation and Darcy's law, which are used to describe the steady-state viscous flow of fluids through porous media, were derived under the assumption that the inertial term of the Navier-Stokes equation can be neglected. However, this is only true for straight capillaries. In curved capillaries or in very short capillaries which is usually the case in
porous media such as wood, and where kinetic-energy effects and end-effects are appreciable, the inertial term become gradually important. The net result of introducing the inertial term is to produce a relationship between the pressure drop and the flow rate that is no longer linear. The oldest argument attributes this departure from Darcy's law to the onset of turbulence within the pores of the medium (Scheidegger 1974). This explanation appears unsatisfactory, however, since the value of the Reynolds' number above which Darcy's law is no longer valid for various porous media has been found to range between 0.1 and 75 (Scheidegger 1974), which is much lower than that at which the incidence of turbulence will occur.

Various physical interpretations for the deviation from Darcy's law due to nonlinear flow have been proposed in the literature. Happel and Brenner (1973) maintained that it was a serious misinterpretation of the phenomenon to attribute the breakdown of Darcy's law to turbulence. They further pointed out that the failure of Darcy's law resulted when the distortion that occurred in the streamlines owing to changes in the direction of motion was great enough so that inertial forces became significant compared with viscous forces.

As the inertial forces increase relative to the viscous ones, the streamlines become more distorted and the pressure drop increases more rapidly than linearly with the velocity. However, the streamlines still remain stable, that is, they do not fluctuate. Some steady secondary flow may also appear at the higher velocities of this regime. In order to differentiate this nonlinear flow from the turbulent one at much higher Reynolds' number, this kind of flow regime in porous media due to the kinetic-energy and end-effects is called nonlinear laminar flow or steady inertial flow (Hannoura and Baredds 1981). Laminar flow, therefore, is not necessarily characterized by a proportionality between the pressure drop and flow rate.
Mickelson (1964) presented an equation for liquid flow in which the total pressure driving a liquid through a capillary tube can be separated into three components: the pressure drop caused by friction, $\Delta P_f$, as expressed by Eq.(6); the pressure drop caused by kinetic-energy losses due to sudden contractions and enlargements of the cross-sectional area of the fluid filaments, $\Delta P_k$; and the pressure drop caused by end effects due to both the shape and condition of the entrance, $\Delta P_e$.

The total pressure drop and its component can be written as,

$$\Delta P = \Delta P_f + \Delta P_k + \Delta P_e$$

$$= \frac{8\mu LQ}{\pi r^4} + \frac{m_k \rho Q^2}{\pi^2 r^4} + \frac{m_e \rho Q^2}{\pi^2 r^4}$$

$$= \frac{8\mu LQ}{\pi r^4} + \frac{m \rho Q^2}{\pi^2 r^4}$$ (22)

where $m_k$, $m_e$ are coefficients for kinetic-energy and end-effect, respectively; and $m$ is the coefficient for kinetic-energy and end-effect losses. An average value of 1.19 was found for $m$ from a large number of experiments.

It is interesting to note in Eq.(22) that the pressure drop caused by kinetic-energy losses and end-effects is proportional to the square of the flow rate. This way, it is difficult to distinguish the nonlinear laminar flow due to kinetic-energy effect and end-effect from turbulent flow by measuring the relationship between these two quantities. This is because, in both cases, the pressure drop is approximately proportional to the square of the flow rate.

Eq.(22) may be rearranged in a more useful form by substituting Eq.(9) for one of the powers of $Q$ in the nonlinear term,
If this equation is applied to short capillaries, the Couette correction should be applied (Petty 1974). This is done by the substitution of a longer corrected length, \( L' \), for \( L \). Then,

\[
\Delta P = \frac{8\mu LQ}{\pi r^4} [1 + 0.074R_e \left( \frac{r}{L} \right)]
\]  

(23)

where \( L' \) accounts for the Couette correction (\( = L + 1.2r \)).

Eq.(24) may be modified for gas flow by the addition of a correction for slip flow and gas expansion:

\[
\Delta P = \frac{8\mu L'/Q}{\pi r^4 sP} [1 + 0.074R_e \left( \frac{r}{L'} \right)]
\]  

(25)

where \( s \) is the slip-flow factor, and its equivalent form of \( 1 + 7.6 \frac{\mu}{Pr} \sqrt{\frac{RT}{M_w}} \), expressed in Eq.(15).

When Eq.(25) is solved for gas permeability, \( K_{gs} \), it assumes the form:

\[
K_{gs} = \frac{QLP\mu}{\Delta P\Delta P} = \frac{\pi r^4 sL}{8L'/A[1 + 0.074R_e \left( \frac{r}{L'} \right)]}
\]  

(26)

Eq.(25) indicates that the nonlinear laminar component of flow, which is principally due to kinetic-energy and end-effects losses, seems to be a function of Reynolds' number and the length-to-radius ratio of the capillary, and independent of the radius alone. It is apparent from this
equation that there is an effective critical Reynolds' number \( R_{e''} \) for the onset of nonlinear laminar flow which has a value approximately equal to the \( L'/r \) ratio of the capillary. More exactly, according to Siau and Petty (1979), the critical Reynolds' number \( R_{e''} \) for a short capillary may be expressed as,

\[
R_{e''} \approx 0.8 L'/r
\]  

(27)

where \( R_{e''} \) is the critical Reynolds' number below which flow is viscous and linear in a short capillary. Since most wood capillaries have \( L'/r \) ratios much less than \( R_e' \) of about 2,300, it is expected that nonlinear laminar flow occurs at a much lower Reynolds' number than turbulent flow does.

Eqs.(25) and (26) predict an increase in \( \Delta P \) and a corresponding decrease in \( K_{gs} \) owing to kinetic-energy and end-effect losses. They also predict that, when \( R_e \) becomes equal to \( R_{e''} \), \( \Delta P \) will increase by approximately 6% and \( K_{gs} \) will decrease by approximately the same amount.

It is also clear from Eq.(22) that, the higher the flow rate, the higher the possibility of nonlinear laminar flow in the short capillaries such as the pit openings in softwoods and the perforation plates in hardwoods, to occur.

2.4 Studies on non-Darcian flow of gases

Past research work on fluid flow in wood has revealed that the permeability of softwoods depends on the interconnection of tracheid lumens by pit membranes, and of hardwoods on the interconnection of vessel elements by perforation plates or intertissue pitting (Kuroda and Siau 1988, Bao and Lu 1992). It is generally assumed that the steady state of fluid flow through
tracheid lumens and vessels is essentially viscous, and therefore Darcy's or Poiseuille's law is believed to be obeyed. However, this is not strictly true when fluids flow through small structures like pit openings in softwoods and perforation plates or intertissue pitting in hardwoods. Although the high flow velocities necessary for turbulence are improbable in wood, nonlinear laminar flow may occur at relatively low velocities where a fluid moves from a large to a small capillary such as, from a tracheid lumen to a pit opening in softwoods, or from a vessel element to a perforation plate or intertissue pitting in hardwoods (Kuroda and Siau 1988, Siau 1995). Therefore, Darcy's law may possibly be valid in a certain velocity domain.

For gases, Darcy's law represents a linear relationship between the flow rate and the pressure drop at a constant mean pressure in accordance with Eq.(4). Strictly speaking, the straight line representing the relationship between the specific flow rate and the mean pressure as expressed by Darcy's law for gases, should pass through the origin of the coordinates. Any deviation from this type of relationship represents a "non-Darcian flow". Therefore it is expected that Darcy's law will have limitations when applied to gas flow in wood. Such deviations may occur at very low flow rates due to slip flow, and high flow rates due to nonlinear laminar flow. Non-Darcian flow due to slip flow implies a straight line between the specific flow rate and the mean pressure in accordance with Adzumi's equation with a slope and an intercept other than zero. Non-Darcian flow due to nonlinear flow implies a nonlinear relationship between flow rate and pressure drop at a constant mean pressure.

Although it is generally accepted that one exception to Darcy's law is molecular slip flow when a gas is used as the flowing fluid, disagreement exists as to if another exception due to nonlinear flow exists, and whether this nonlinear flow is either nonlinear laminar or turbulent flow.
Moreover, the validity of Darcy's law applied to wood with regard to specimen length has been questioned by many researchers. For these reasons, examination of non-Darcian behaviour of gas flow in wood needs to be studied more thoroughly. The purpose of this section was to briefly present what has already been done on these three main possible deviations from classical Darcy's behaviour.

2.4.1 Non-Darcian behaviour due to specimen length

The deviation from Darcy's law due to specimen length increases greatly the difficulty not only in extrapolating the results of flow studies using small specimens to expected results with large pieces of wood, but also in interpreting the fluid flow mechanisms in wood. That is because, all past models used for the description of flow through wood were based upon the assumption of wood structure uniformity in the flow direction, i.e., permeability being independent of the specimen dimension in the flow direction.

Investigations on the effect of specimen length on wood permeability have been carried out by many researchers. In general, wood permeability was found to increase when specimen’s length decreases. Sebastian et al. (1965) reported an increase in the longitudinal superficial oxygen permeability of white spruce (*Picea glauca* (Moench) Voss) sapwood and heartwood as the length was decreased from 20 to 3.2 mm. Bramhall (1971) carried out longitudinal superficial air permeability measurements on interior and coastal type Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) sapwood and heartwood specimens with original lengths of 35 mm and at successively shorter lengths in decrements of 5 mm. He also reported an increase of the air permeability with a decrease in length; this trend being more pronounced at lower permeabilities.
A model in which there is an exponential decrease of the effective conducting area with the depth of penetration due to the random blockage by aspirated pits was also derived to describe this behaviour.

Siau (1972) conducted a study on the influence of specimen length on superficial air permeability of Douglas-fir and loblolly pine. The cross-sectional dimensions were approximately 20 by 20 mm, and the lengths were 300, 100 and 50 mm for loblolly pine, sapwood and heartwood of Pacific coast Douglas-fir, and sapwood of intermountain Douglas-fir; and 100, 50, 20 mm for intermountain Douglas-fir heartwood. The results revealed that the decrease in permeability with length of intermountain Douglas-fir was drastic while that of loblolly pine and Pacific coast Douglas-fir was almost negligible.

Perng (1980b) measured the superficial air permeability of several softwoods and hardwoods, using specimen lengths from 4 to 154 mm. He reported a species dependent critical length. When the specimen was longer than the critical length, which was about 50 mm for softwoods and diffuse porous hardwoods, and 100 mm for ring porous white ash (Fraxinus americana L.), the permeability values were nearly identical for the various lengths of the tested species. He further observed two conflicting effects of length on permeability within the critical length range. When the superficial specific permeability was less than 2 μm³/μm (=2 darcy), the permeabilities of both softwoods and hardwoods increased drastically with decreasing specimen length in agreement with the results of previously reported studies. However, when the superficial specific permeability was above 2 μm³/μm and specimen lengths were within the critical range, the permeability decreased abruptly with decreasing specimen length. He explained this increase of permeability with an increase in length as the result of turbulence or nonlinear laminar flow.
Kumar (1981) found no significant change in woods with superficial specific permeability values between 0.01 and 22.5 μm³/μm when the specimen lengths were decreased from 50 to 25 mm. Fogg and Choong (1989) measured the longitudinal superficial nitrogen permeability of American sycamore (*Platanus occidentalis* L.), American elm (*Ulmus americana* L.), hickory (*Carya* spp.), and mesquite (*Prosopis juliflora* (Schwarts) De cand.). Specimens of 51 mm in length, were subsequently shortened to 44, 38, 32, 25, 19, 13, and 4 mm after each permeability determination at a mean pressure of 1.2x10⁵ Pa. Their results showed that, with the exception of American elm sapwood, measured permeability remained constant as specimen length decreased from 51 to 19 mm. Thereafter, a further reduction in specimen length drastically increased permeability.

In summary, the deviation from Darcy’s law due to specimen length has been reported by many authors. Although in many cases the permeability was found to be inversely proportional to specimen length, the opposite effect was also reported. Moreover, it was reported that the effect of specimen’s length on its permeability, was related to its permeability magnitude.

The present work was undertaken to gain a better level of understanding of non-Darcian behaviour in wood. In order to focus on the study of non-Darcian air flow phenomena in wood, the basic assumption that the structural variation in the flow direction within the tested wood specimens is negligible had to be made. Consequently, the application of Darcy’s law to the tested wood specimens in regards to the specimen’s length, should be tested at first. If the permeability is found to vary with specimen length, then, it is important to try to find out the appropriate specimen length above which the permeability values remain constant for the various lengths of the tested species, for the subsequent tests of Darcy’s law due to other factors such as slip and
nonlinear flow.

2.4.2 Non-Darcian flow due to slip flow

Darcy's law is usually found to be valid for very low permeability ranges. However, this may be only true for liquid flow. Since the molecular mean free path of gases is longer than that of liquids and usually in the order of the radius of the capillaries in wood, the assumption of zero velocity at a capillary surface (i.e., boundary condition), as predicted by Darcy's or Poiseuille's laws, is not always valid for the flow of gases. In this case, because there is some motion of individual gas molecules along the surface, the quantity of gas flowing through a capillary is larger than that predicted from Poiseuille's formula. The error due to this kind of slip flow is negligible in a large capillary or at high flow rates (i.e., high mean pressure). On the other hand, the error becomes significant when the radius of capillary is in the order of the mean free path of the gas molecules or at extremely small flow rate (i.e., very low mean pressure). Comstock (1967) presented a region of slip flow for practical purposes, which indicates that slip flow occurs in the region for $x$ between 0.014 and 1, where

$$x = \frac{\lambda}{2r} \sqrt{\frac{8}{\pi}}$$

(28)

For values of $x > 1$ flow is essentially molecular, and for values of $x < 0.014$ flow is essentially viscous.

The mean free path of air molecules at atmospheric pressure is about 0.1μm, and the corresponding region of pore radii for slip flow according to Eq.(28) is between 0.16 and 11.4μm.
Therefore, the flow of air through wood is generally in the slip flow region, and because of this, almost all studies on gas flow in wood were based on the viscous-slip flow model. Under such circumstances, a straight line between the specific flow rate and the mean pressure exists in accordance with Adzumi's equation. This correlation line does not pass through the origin; instead, it has both a slope and an intercept other than zero.

As mentioned above, viscous-slip flow in wood can be expressed correctly by Adzumi's (Eq.(14)) or Klinkenberg's equation (Eq.(18)). In fact, this set of equations are identical except for the interchange of the slope and intercept terms. It is apparent from these two equations that the introduction of slip flow into the laminar flow equation makes possible the calculation of both the number of pores and their average effective radius. However, flow data in wood can not be used directly in Poiseuille's equation (Eq.(7)) to determine the radii of the pores, since the number of pores and their radii cannot be separated mathematically.

The use of viscous and slip flow measurements with a gas in order to characterize the structure of wood has been discussed in a number of papers, but the results vary greatly. Comstock (1967) used Klinkenberg's equation for calculating the pit-opening radii of eastern hemlock. Sebastian et al. (1965) used an approximation of Adzumi's equation for calculating the pore radii of white spruce sapwood and heartwood. Calculated values for sapwood were approximately 2, and for heartwood 4 times the observed radii measured by electron microscopy. These differences were attributed to the assumption of circular capillaries used in deriving the flow equation.

Perng (1981a, b) used the Adzumi's equation to calculate the effective pit openings in spruce wood, including white spruce, red spruce (*Picea rubens* Sarg.) and black spruce (*Picea*
mariana (Mill.) B.S.P.), and the effective openings in hardwoods such as yellow birch (Betula alleghaniensis Britton), white ash, sugar maple (Acer saccharum Marsh.), beech (Fagus grandifolia Ehrh.) and red oak (Quercus rubra L.). Concurrently, he compared the slip flow percentage of hardwoods to the average value of this percentage for spruce wood, and found a smaller contribution of slip flow to the total flow-rates in hardwoods.

Bao et al. (1986), showed linear plots of permeability versus reciprocal mean pressure for Chinese spruce (Picea jezoensis var. komarovii (V. Vassile) Cheng et L. K. Fu) (Figure 7a) and pine (Pinus koraensis Sieb. et Zucc), and also calculated the effective pit opening of the same species by using the Klinkenberg's equation. Later, Bao and Lu (1993) compared the magnitude of slip flow components within these two species. They reported that the slip flow component of spruce was higher than that of pine. For example, the ratio of superficial specific permeability at a mean pressure of 5x10^4 Pa to true gas permeability, and the slip flow constant (b), were 1.69 and 3.56x10^4 Pa for the former, and 1.36 and 1.97x10^4 Pa for the latter species. All the above investigations resulted in linear plots in accordance with either Adzumi's or Klinkenberg's equations. This linearity indicates that there was only one conductance for flow in wood such as, pit openings for softwoods and vessels for hardwoods.

Petty and Preston (1969), and Petty (1970) reported a curvilinear relationship between permeability and the reciprocal mean pressure rather than a linear relationship as predicted by the Adzumi's or Klinkenberg's equations. This phenomenon was attributed by Petty (1970) to the effect of two conductances in series, namely high and low, which may correspond to tracheids and pit openings in softwoods, or to vessels and perforation plates or intervessel pits in hardwoods. If the two conductances are assumed to obey the Klinkenberg's equation independently, then the
Figure 7  Superficial specific permeability versus reciprocal mean pressure for specimen of (a) Chinese spruce and (b) birch wood. [from Bao et al. (1986)].

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Petty's model as expressed in Eq.(21) can be derived.

Petty (1978), measured the axial permeability of birch (Betula pubescens) and found a curvilinear relationship between permeability and the reciprocal mean pressure. The length of the specimens ranged between 15 and 30mm, less than the length of vessels. Analysis of the two conductances yielded a value of 29.5μm for $r_1$, which was assumed to represent the vessel radius, and a small value 1.46μm for $r_2$ as a short capillary or 2.54μm as a long capillary, which was interpreted as the opening between the scalariform perforation plates. In a latter study, Petty (1981) made similar measurements with sycamore (Acer pseudoplatanus) wood, but with a specimen length exceeding that of the vessels (200mm). In this case, for air-dried wood the calculated large radius $r_1$ (vessel radius) was 23.3μm, and small radius $r_2$ was 0.16μm as a long capillary and 0.073μm as a short capillary, which was assumed to be the pores of intervessel pits.

Siau et al. (1981) carried out the viscous and slip flow measurement on several types of membranes, and one softwood and two hardwoods species. They reported that the membranes exhibited a linear permeability versus the reciprocal mean pressure relationship, thus indicating the absence of high and low conductances in series. However, the wood specimens exhibited curvilinear plots of permeability versus the reciprocal mean pressure, thus indicating high and low conductances. The calculated large radii were 32.9, 64.7, 20.2μm, and the small radii were 0.17, 0.34, 0.30μm for basswood (Tilia americana L.), sugar maple and sugar pine (Pinus lambertiana Dougl.), respectively. They interpreted the large radii as the vessels in the hardwoods and the tracheid lumen in the softwood, and the small radii as pit openings between the tracheids for sugar pine and the intervessel pits in the two hardwoods.

As mentioned before, Bao et al. (1986) found a linear plot of permeability versus the
reciprocal mean pressure for spruce and pine, but the plot of permeability versus the reciprocal mean pressure for Chinese birch (*Betula platyphilla*) was curvilinear (Figure 7b). Furthermore, they interpreted the presence of high and low conductances in series in birch, as the result of the vessels and the openings in the scalariform perforation plates between them.

### 2.4.3 Non-Darcian flow due to nonlinear flow

As described previously, the deviations from Darcy's law at low flow rates, indicate that the flow rates exceed those predicted by Poiseuille's law by a factor proportional to the third power of the capillary radius. However, a deviation in the opposite direction can be observed for high flow rates. In other words, the deviations from Darcy's law at high flow rates show that increases in flow rates with increased pressure drop, will be below those predicted. Therefore, the evident characteristic of deviation from Darcy's law owing to high flow rates, is the fact that the correlation between pressure drop and flow rate is no longer linear, obeying instead a quadratic relationship (cf. Eq.(22)).

Based on the assumption of an analogy between the flow in tubes and the flow in a porous medium, many scientists have been looking for a phenomenon in porous media similar to the onset of turbulence in tubes that takes place at a definite Reynolds' number. Thus, it was expected that above a certain Reynolds' number, which would be universal for all porous media, deviations from Darcy's law owing to high flow rate would occur. Experimental attempts for the determination of this "critical" Reynolds' number have been reviewed by Scheidegger (1974). Several investigators have reported such values ranging from 0.1 to 75. These results indicate that the critical Reynolds' number above which "turbulence" is believed to occur is much lower for porous media than for
long, straight tubes (where it is around 2,300). The only conclusion that can be drawn is that the alleged "turbulence" is not turbulence at all, but an expression of nonlinear laminar flow, and that the breakdown of Darcy's law at high flow rates is thus primarily due to the emergence of inertial effects in laminar flow (Scheidegger 1974). Furthermore, from these results it must be concluded that there is no such thing as a "universal" Reynolds' number in porous media at which non-linearity would set in, since the critical Reynolds' number for the emergence of inertial effects (cf. Eq.(27)) is very much affected by the curvature of the capillaries.

Like other porous media, true turbulence at very high flow rates is unlikely in the lumens of tracheids and vessels in wood. However, it is possible for nonlinear laminar flow to occur in the constricted flow passages of small, short capillaries such as pit openings due to kinetic energy losses, where local flow rates are much higher than those in the lumens. Siau and Petty (1979), suggested that nonlinear laminar flow may occur in wood at Reynolds' numbers in the region of 0.1 to 10 according to the results obtained for air flow through short, straight circular capillaries.

In comparison with the intensive studies of the viscous and slip flow, the nonlinear laminar flow of fluids through wood may be just in the beginning. Sucoff et al. (1965) found that by increasing the pressure differential for water flowing in the axial direction through northern white cedar (Thuja occidentalis L.) sapwood, the increases in flow rates were substantially below those predicted by Darcy's law, following instead the equation:

\[ Q = a + b(\Delta P) - c(\Delta P)^2 \]  

They reported that air blockage and pit closure were not the causes of deviation, and attributed to turbulence and nonlinear laminar flow.
It is evident from Klinkenberg's equation (Eq.(18)) or its modified version based on Petty's model for conductances in series (Eq.(21)), that the superficial specific permeability is only a linear or curvilinear function of the reciprocal mean pressure, and does not depend on other factors such as pressure drop and flow rate. The reason for this is, the flow rate is linearly proportional to the applied pressure drop according to the Adzumi's equation (Eq.(14)). However, Klinkenberg's or Adzumi's equations only apply when the flow is viscous-slip. If there is turbulent or nonlinear laminar flow, the superficial specific permeability will drastically decrease with the increase of flow rate or pressure drop at a constant mean pressure because a less than proportional increase in flow rate with pressure drop occurs in this kind of flow. Therefore, nonlinear fluid flow due to kinetic energy losses or to turbulence can be detected experimentally, if the superficial specific permeability is independent of flow rate or pressure drop at a constant mean pressure.

Wiley and Choong (1975) found that the plots of $K_{np}$ versus $1/\bar{P}$ in several hardwoods and softwoods were generally lower and with somewhat steeper slopes at $1.36 \times 10^4 \text{Pa} (=102 \text{ mm-Hg})$ compared to $6.665 \times 10^3 \text{Pa} (=50 \text{ mm-Hg})$ pressure drop, and the effect of pressure drop became more pronounced in the higher permeability range. At the same time, they also found that the effect of pressure drop was negligible for woods with nitrogen permeability coefficients less than $0.2 \mu\text{m}^3/\mu\text{m} (=0.2 \text{ darcy}).$ Later, Choong et al. (1988) confirmed their initial findings by permeability measurements on seven hardwood species. They reported that the graphs of nitrogen permeability as a function of the reciprocal mean pressure indicated the reduction of the former with the pressure drop. Furthermore, in order to show the dependency of nitrogen permeability on pressure drop, they generated the plots of permeability versus pressure drop at constant mean
pressure $P = 1.05 \times 10^5 \text{Pa}$ and $2.0 \times 10^5 \text{Pa}$. These indicated that the curves remained horizontal up to some critical value of pressure drop, and then began to drop sharply with an increase in pressure drop. Meanwhile, they also found that at low permeability (below $1 \mu m^3/\mu m$), the curves of permeability versus pressure drop appeared nearly horizontal, thus indicating no apparent effect of pressure drop.

Kuroda and Siau (1988) studied the validity of Klinkenberg's equation. They also reported that the air permeability of loblolly pine, Douglas-fir and white spruce was dependent on flow rate, and the permeability was found to be decreasing with flow rate. They reported this phenomenon as evidence of the onset of either turbulent or nonlinear laminar flow. The critical Reynolds' numbers reported for the decrease in permeability and also for the increase in the applied pressure drop with flow rate were between 0.41 and 1.62. They further attributed the decreased gas permeability to nonlinear laminar flow at the pit openings. However, no evidence was found of nonlinear laminar flow in specimens of high permeability such as paper birch ($Betula papyrifera$ Marsh.) and basswood, which contradict the experimental results reported by Wiley and Choong (1975) and Choong et al. (1988).

When Perng (1980b) studied the effect of specimen's length on the permeability coefficient, he also found that when permeability was above $2 \mu m^3/\mu m$ and samples had lengths within the critical range, both flow rate and permeability values decreased abruptly with decreasing sample length. He attributed this phenomenon to the influence of turbulence or nonlinear laminar flow in terms of the plot of flow rate against pressure drop. This result appeared similar to the results reported by Choong et al. (1988). On the other hand, he observed that when permeability was below $2 \mu m^3/\mu m$ and samples had lengths within the critical range, the flow rate
and permeability changed drastically and showed an inverse relationship with the sample length. He considered that this was due to depressed flow resistance as explained by Bramhall (1971).

Kauman et al. (1994) measured the longitudinal air permeability of Chilean Tepa (Laurelia philippiana (Phil.) Loesser), using specimen length of 20, 40, 60mm, and pressure drops of 0.5x10^5, 1.0x10^5, 1.5x10^5 Pa. They reported a decrease of permeability with the decrease of specimen length in agreement with Perng (1980b). Kauman et al. (1994) attributed this non-Darcian behaviour to an entrance effect which decreased the permeability for shorter specimens. They also observed an increase of permeability with the increase of pressure drop used and attributed this non-Darcian behaviour to a pressure effect which increased the permeability. Kauman et al. (1994) explained that the entrance effect was probably due to an additional resistance at or near the entry face of the specimen, and the pressure effect was probably due to the opening or dilation of certain flow channels above a threshold pressure.

On the basis of these experiments, deviations from Darcy's law at high flow rates due to the onset of either turbulent or nonlinear laminar flow may be related to the species of wood, i.e., the magnitude of wood permeability. However, experiments from these investigators yielded even the opposite results. Therefore, nonlinear laminar flow in wood should be researched more for its better understanding.

2.5 Rational

From the theoretical considerations presented above, the following summary of research goals can be made.

1. Since one of the assumptions for Darcy’s law is that the permeability is
independent of the specimen length in the flow direction, the influence of specimen length on permeability must be investigated first in order to focus on non-Darcian flow due to nonlinear and slip flows. If there is a critical length above which the structural variation in the flow direction within the tested samples is negligible, this critical length should be used in the subsequent tests on non-Darcian flow due to nonlinear or slip flow. Also, since the various wood species exhibit a wide range of permeabilities, it is impossible to have the same critical length for different species.

2. Regardless of slip flow, both Darcy's law (Eq.(4)) or Poiseuille's law (Eq.(7)) and Adzumi's equation (Eq.(14)) show a linear relationship between pressure drop and flow rate at a constant mean pressure, while turbulent flow (Eq.(11)) and nonlinear laminar flow (Eq.(25)), show that the pressure drop is approximately proportional to the square of the flow rates at the constant mean pressure, the evidence of non-Darcian flow due to nonlinear flow should be examined first. Basically, there are two methods of detection for nonlinear flow in wood based on the theoretical considerations described in Section 2.3. The first is the permeability measurement method, that is, the plots of superficial specific permeability versus reciprocal mean pressure based on the Klinkenberg's equation or Petty's model. According to the Klinkenberg's equation (Eq.(18)) and Petty's model (Eq.(21)), the relationship between superficial specific permeability and reciprocal mean pressure is independent of the flow rates or pressure drop. If there is nonlinear flow within the specimen, the superficial specific permeability at a given constant mean pressure will decrease with the increased flow rates or pressure drops. The second method is based on the flow rate-pressure-relationship, i.e., the plots of flow rate versus the total pressure drop at a constant mean pressure. According to Adzumi's equation for gas flow (Eq.(14)), the straight line representing the linear relationship between the pressure drop and flow rate at a
constant mean pressure, should pass through the origin of the coordinates. If the pressure drop exhibits a curvilinear relationship with flow rate at a given constant mean pressure, then the presence of nonlinear laminar or turbulent flow in the specimen is proven. Furthermore, the separation of the nonlinear laminar from turbulent flow can be carried out based on the Reynolds’ number, if the nonlinear flow component is detected within the tested specimens. In addition, it should be noted that, the higher the flow rate, the higher the possibility of nonlinear flow to occur. Therefore, an effort must be made to attain high flow rates as possible within each tested species in order to evaluate the possibility of nonlinear flow existence in wood.

3. If the specimens tested show no evidence of nonlinear flow throughout the entire range of measured flow rates, the non-Darcian flow due to slip flow should be evaluated. Similarly to what was described above, both the permeability measurement and flow rate-pressure-relationship method can be employed as the detection of non-Darcian air flow due to slip flow. If there is only Darcian air flow in wood, the former method based on Klinkenberg’s equation should show no relationship between superficial specific permeability and the reciprocal mean pressure. Therefore, the slope of straight line representing the relationship between the superficial specific permeability and the reciprocal mean pressure as expressed by Klinkenberg’s equation, should be zero. The latter is based on flow rate-pressure-relationship and must show that, the straight line, representing the relationship between the specific flow rate (QLP/ΔP) and the mean pressure (P̅) as expressed by Adzumi’s equation (Eq.(14)), should pass through the origin of the coordinates. However, slip flow is usually expected to be significant in wood when gases are used as the flowing fluid, since the mean free paths of the gases are in the same order of the average pore radius in wood. Therefore, further evaluation based on the viscous-slip flow
model must be investigated in detail. In fact, the existence of slip flow results in one of the main advantages of permeability research in that it may be used to estimate the anatomical structure of wood quantitatively by the determination of the sizes and the number of pit openings, tracheids, and vessels. Using Eqs. (8), (18), (20), and (21) which are based on the viscous-slip flow model, the superficial specific permeability, true gas permeability, slip flow constant, and the number and sizes of effective openings in wood can be then obtained for each of the tested specimens. If the tested specimens exhibit nonlinear flow phenomena, the experimental data which are obtained under a linear flow regime (i.e., at lower flow rates), can still be used to test and calculate slip flow components in wood. The methods are exactly the same as described above for the specimens without nonlinear flow over the entire range of flow rates.
3.0 Materials and Methods

3.1 Materials

In order to observe the non-Darcian behaviour in specimens representing a wide permeability range two softwoods species and two hardwoods species were collected from a variety of sources. The two softwoods chosen for this study were interior Douglas-fir and ponderosa pine (*Pinus ponderosa* Laws.) from the Okanagan valley, British Columbia, and the two hardwoods were red oak from Chalk River, Ontario and red alder (*Alnus rubra* Bong.) from Maple Ridge, British Columbia. One tree from each species was cut for this study.

On delivery to the laboratory, the sapwood and heartwood zones of fresh logs were marked. Since ponderosa pine does not have a visible sapwood-heartwood boundary, benzidine reagent was used to test heartwood-sapwood differentiation (Barton 1973). The reagent formed a scarlet dye with heartwood, however, the reaction was much less intense with sapwood, producing only small red flecks.

Since only narrow sapwood portion was available in the two studied hardwoods and usually sapwood permeability is much higher than heartwood permeability, specimens cut from the heartwood zone of hardwoods and sapwood zone of softwoods were chosen for this research. For the two hardwoods and Douglas-fir, approximately 20 specimens, each about 35 by 35 by 400 mm long were cut from the outer heartwood or outer sapwood of each log. From the ponderosa pine, approximately 20 specimens, about 60 by 60 mm in cross section and 400 mm in length were cut from the outer sapwood of the log because of its thick sapwood.

To prevent any drying defects such as internal checking, and severe pit aspiration, a very
moderate drying schedule was used (T=25~40°C, H=90~70%, totally 4 months period) for the specimens in a conditioning chamber. After their moisture content reached about 10%, the specimens were turned into cylindrical shape in a lathe. The diameters of the cylindrical specimens were approximately 25mm for Douglas-fir sapwood and the two hardwoods, and 50mm for the ponderosa pine sapwood. All the cylindrical specimens (length in the fibre direction) were slowly dried in an oven at 60°C for one week from about 10% equilibrium moisture content to approximately 0%. The specimens were then stored in a plexiglass box with a drierite container (desiccant) until use in the experiments.

Each initial specimen used in the permeability measurements at various lengths, was first obtained by means of a cross-cutting circular saw at a slow feeding speed. Then both end-surfaces were carefully shaved with a sharp razor blade to free them from loose fibres and create fresh ends before each experimental run. The side surfaces of the specimens were coated with epoxy resin to prevent transverse flow.

Throughout the thesis, the abbreviations used for the specimen groups are denoted as follows: ROH for red oak heartwood, RAH for red alder heartwood, DFS for Douglas-fir sapwood, and PPS for ponderosa pine sapwood.

### 3.2 Description of equipment

All experimental measurements were carried out by using the steady-state flow measurement apparatus. The schematic diagram of the permeability apparatus set-up is shown in Figure 8. The air is drawn through a flowmeter (BF or RF and MF), the specimen (S), and needle valves (N), all in series, by a vacuum pump. The pressure differential (ΔP) across the specimen is
Figure 8  Schematic design of the permeability measuring apparatus.
BF: buret flowmeter; RF: rotameter flowmeter; MF: electronic mass flowmeter;
F: filter; D: drierite; P1: closed mercury manometer; P2: open mercury manometer;
MM: differential mercury manometer; S: specimen; N: needle valves;
SC: stopcock; R: vacuum reservoir.
measured by a mercury manometer (MM). The closed manometer on the vacuum side ($P_1$) is also used to simplify the measurements by not only providing the barometric pressure ($P_{atm}$) before flow measurements, but also by eliminating the need to use the barometric pressure for the determination of the mean pressure ($\bar{P}$) within each specimen. In this case, $\bar{P}$ can be easily calculated by the sum of direct readings from the closed manometer and the half value of the pressure differential, i.e., $\Delta P_1 + \Delta P/2$. An open mercury manometer on the high pressure side ($P_2$) is included to be used only for the examination of air leaks between the stainless steel cylinder and rubber tubing. That is, the pressure on the air side, $P_2$, which can be obtained from the reading ($\Delta P_2$) of the open mercury manometer ($P_2 = P_{atm} - \Delta P_2$), should be equal to the sum of the direct reading from the closed manometer on the vacuum side and the pressure differential ($\Delta P_1 + \Delta P$). The pressure differential or mean pressure is controlled by the valve on the vacuum side. Each constant flow rate is controlled by the electronic mass flowmeter (MF). However, the reading of flow rate was taken from the rotameter flowmeter (RF), which was calibrated by a buret flowmeter (BF) both connected in series. At a given constant flow rate, its reading by buret flowmeter is calculated based on the time that a bubble formed from a soap solution goes through a certain amount of volume in the buret which has a calibrated volume scale.

The sample holder shown in Figure 9, is comprised of two stainless steel cylinders (50 mm in length and 25 or 50 mm outside diameter), a high vacuum thick-walled rubber tubing of approximately 25 or 50 mm inside diameter, and a set of hose clamps. The specimen is inserted into the centre of the tubing. With the exception of the 20 mm long specimens, three clamps were used in order to prevent air leaks between the tubing wall and the specimen. One was in the middle of the specimen, and another one at its two ends, respectively. The rubber tubing
Figure 9  Schematic design of the specimen holder.
containing the specimen was then connected with the two stainless steel cylinders. Since vacuum was used in this study, the rubber tubing was actually pushed against both the steel cylinders and the specimen by the ambient air thus securing the seal. At the same time, two hose clamps were also used in both ends of the rubber tubing in order to prevent air leaks between the stainless steel cylinder and the rubber tubing. Trial measurements were made on impermeable specimens, which were made by coating their high pressure end surfaces (i.e., air side) with epoxy resin, to assure that the experimental assembly excluded measurable leaks between the tubing wall and the specimen.

The permeability of each specimen with various lengths was measured at about nine different mean pressures within the tested specimen under one constant flow rate. After each change of the mean pressure, enough time was allowed for pressure stabilization before a further reading was taken. For example, approximately 10 minutes was needed for the specimens of two hardwoods, 15 minutes for the specimens of ponderosa pine sapwood, and 30 minutes for the specimens of Douglas-fir sapwood. All these measurements were taken at successively larger mean pressures, with one of them taken exactly at a mean pressure of 0.5 x 10^5 Pa (=0.5 atmosphere) by carefully adjusting the valve at the vacuum side in order to make a direct comparison of the permeability values at different specimen lengths or flow rates.

Based on the apparatus described above, the superficial specific permeability was calculated by the following equation (cf. Eq.(5)),

\[
K_s = \frac{760 QL P_{atm} \times \mu}{A \Delta P (\Delta P_1 + \Delta P/2) \times 1.013 \times 10^5}
\] (30)
where $\Delta P$ is the pressure differential across the specimen, mm-Hg; $\Delta P_1$ is the closed manometer reading on the vacuum side, mm-Hg; $P_{\text{atm}}$ is the barometric pressure, mm-Hg; $\mu$ is the viscosity of the gas, Pa s ($\mu_{\text{air}}=1.81\times10^{-5}$ Pa s); and all the other factors have the same meaning and units as described in Section 2.3. It should be noted that here, the expression $(\Delta P_1 + \Delta P/2)$ is actually the mean pressure, the 760 has the units of mm-Hg/atm and converts the pressure to atmospheres, and the value of $1.013\times10^5$ has the units of Pa/atm and converts the pressure to Pascal.

3.3 Experimental procedure

3.3.1 Effect of length

In order to focus on the study of various kinds of gas flow in wood, the basic assumption that the structural variation in the flow direction within the tested wood samples is negligible has to be made. Therefore, the procedure used to obtain the experimental data began by investigating the effect of specimen length on the air permeability of studied wood species. If there is a specimen length effect, then the next step was to try and find out the critical length above which the permeability values was nearly identical for the various lengths of the tested species. This critical length was obtained by the measurement of air flows through various specimen's lengths under a constant flow rate. The permeability value calculated by Eq.(30) at a given constant mean pressure should have the same value when the specimen's length is greater than the critical one.

In this study, five single specimens randomly selected from each of the four specimen groups, were used for the test of specimen length effect. Since these four specimen groups belong to different permeability classes, the specimen lengths within each specimen group were selected
incrementally by the various trials. For example, in red oak heartwood, the initial specimen length for permeability measurements was 340 mm, then reduced incrementally to a final 60 mm with a total of 8 different lengths in between. In red alder heartwood, the initial specimen length was 260 mm, then shortened down to 20 mm in a 40 mm progression with a total of 7 different lengths. For ponderosa pine sapwood, the permeability was first determined for a specimen length of 180 mm, the specimen was then continuously shortened by 40 mm long sections to a final length of 20 mm with a total of 5 different lengths. However, Douglas-fir sapwood permeability could only be measured at an initial length of 100 mm, that was subsequently shortened by 20 mm increments after each permeability test until a final length of 20 mm with a total of 5 different lengths in between.

The permeability was first determined for the initial length of every single specimen, and then repeated at each subsequent shorter length under the same flow rate. The permeability of each tested specimen was measured at about nine different mean pressures. These different mean pressures were obtained by the adjustment of the valve on the vacuum side, starting from the full vacuum to higher pressure on vacuum side until it was not possible any more to keep the constant flow rate. Therefore, all these permeability measurements were taken at successively larger mean pressures.

After each change of the mean pressure, enough time was allowed for pressure stabilization before a further reading was taken. In order to make a direct comparison of the permeability values at different specimen lengths under a given mean pressure, one of the nine points was taken exactly at a mean pressure of one-half atmosphere (380 mm-Hg or 0.5x10^5 Pa) by carefully adjusting the valve. If a set of nine data points taken as described above was defined
as one run of permeability measurement here, there were 8, 7, 5, 5 runs within each single specimen for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. Therefore, there was a total of 125 runs of permeability measurements in this stage, that took about 4 months.

3.3.2 Nonlinear flow and slip flow

After the determination of the critical length for each tested species, the evaluation of the non-Darcian flow due to nonlinear flow and slip flow in wood was then followed. As mentioned in Section 2.5, two methods for the detection of non-Darcian flow in wood can be employed. In this study, the permeability measurements method was used as the detection of non-Darcian flow due to nonlinear and slip flow, and the calculation based on the viscous-slip flow model. At the same time, the flow rate-pressure-relationship method was also used as the detection of non-Darcian flow due to nonlinear and slip flow.

According to the Klinkenberg's equation (Eq.(18)) and Petty’s model (Eq.(21)), the relationship between superficial specific permeability and reciprocal mean pressure (1/P) is independent of the flow rates if there is no nonlinear flow component, and this relationship shows an horizontal line if there is only an existence of Darcy’s flow. In the meantime, according to the Adzumi’s equation (Eq.(14)), the straight line representing the linear relationship between the pressure drop and flow rate at a constant mean pressure, should pass through the origin of the coordinates if there is no nonlinear flow component, and the straight line representing the relationship between the specific flow rate (QLP/ΔP) and the mean pressure (P) should pass through the origin of the coordinates if there is only an existence of Darcy’s flow. Therefore, the
plots of permeability versus reciprocal mean pressure, of pressure drop versus flow rate at a constant mean pressure, and of specific flow rate versus the mean pressure for a wide range of flow rates were used to test the validity of Darcian air flow in this study.

To do so, ten specimens from each specimen groups were selected. Each specimen was cut to its corresponding length based on the results of evaluation of critical length for each specimen groups. Five different flow rates were used in each specimen group first. Trail measurements were made to select these different flow rates for each specimen groups over the entire range of flow rates. Under each flow rate chosen, about nine data points were taken exactly the same as described above. The sequence of different flow rates used within each specimen was randomly selected. The superficial specific permeability at the mean pressure of one-half atmosphere was also taken in order to make a direct comparison of the permeability values at different flow rates. This way, there were 5 runs for each specimen, thus resulting to a total of 200 runs of permeability measurements at this stage, that took about 6 months.

If there was no nonlinear flow components in tested specimen, i.e., the relationship between superficial specific permeability and reciprocal mean pressure is independent of the flow rates, or the straight line representing the relationship between pressure drop and flow rate at a constant mean pressure pass through the origin of the coordinates, data points under each flow rate could be added together (about 45 points) and then used to evaluate slip flow within the tested specimen based on Klinkenberg's equation. For the specimen group exhibiting the presence of nonlinear flow, more measurements at lower flow rates were added to obtain more data for the subsequent evaluation of slip flow. If the experimental results indicate that the nonlinear flow phenomena only exist above some range of flow rates, then the experimental data points which
were obtained under a linear flow regime (i.e., at lower flow rates), were added together and used to test and evaluate slip flow components in wood.
4.0 Results and Discussions

4.1 Specimen length effect and pressure drop due to end effects

4.1.1 Specimen length effect and critical length

Since the four specimen groups belong to different permeability classes, preliminary experiments were carried. These indicated that the arrangement of specimen lengths and flow rates for testing must be made according to the species. In red oak, the initial specimen length for permeability measurements was 340 mm and then, successively reduced to 300, 260, 220, 180, 140, 100, and 60 mm. In red alder, the initial specimen length was 260 mm, then shortened down to 20 mm in a 40 mm progression. For ponderosa pine, the permeability was first determined for a specimen length of 180 mm, the specimen was then continuously shortened by 40 mm long sections to a final length of 20 mm. Finally, Douglas-fir specimens with an initial length of 100 mm were used that, were subsequently shortened by 20 mm increments after each permeability test until a final length of 20 mm was achieved.

The superficial specific permeability was calculated at each mean pressure using Eq.(30), and plotted against the reciprocal of mean pressure (1/P) for every single specimen. Figures 10 and 11 show the superficial specific permeability changes of one typical single specimen from each species as a function of the reciprocal mean pressure in accordance with the Klinkenberg's equation. It is clear that the permeability was decreased as the specimen length increased until a

\[1\] This section closely follows a previously published paper (Lu and Avramidis, 1997).
Figure 10  Plot of superficial specific permeability, $K_p$ ($\mu m^3/\mu m$), versus reciprocal mean pressure, $1/P$ ($Pa^{-1}x10^5$) at various specimen lengths, for one single specimen of red oak heartwood (ROH) and red alder heartwood (RAH). +20mm, ×60mm, □100mm, ▼140mm, ●180mm, ■220mm, △260mm, □300mm, ○340mm.
Figure 11  Plot of superficial specific permeability, $K_{gs}$ ($\mu$m$^3$/um), versus reciprocal mean pressure, $1/P$ (Pa$^{-1} \times 10^5$) at various specimen lengths, for one single specimen of ponderosa pine sapwood (PPS) and Douglas-fir (DFS) sapwood. ▼20mm, ×40mm, ■60mm +80mm, ▲100mm ⊙140mm, ●180mm.
certain length, beyond that, the permeability remained almost constant. From Figures 10 and 11, it is also apparent that the length above which permeability became independent of length, was 140, 100, 60 and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively.

Since the mean free path for air molecules is in the same order of capillary dimensions in wood, slip flow is expected to take place during air flow through wood. As a result of slip flow, superficial specific permeability includes both the viscous and slip flow contributions. Since the mean free path is inversely proportional to the mean pressure, superficial specific permeability increased with the reciprocal mean pressure as shown in Figures 10 and 11. It was obvious that, when a gas is the measuring fluid medium, the superficial permeability value that is used for comparison purposes has to be calculated at the same mean pressure. However, with the exception of Fogg and Choong’s work (1989), in which the same mean pressure of $1.2 \times 10^5$ Pa was maintained for all permeability measurements, all other previous works on specimen length effects did not mention the mean pressure at which the superficial permeability value was measured. Therefore, the conclusions drawn from these investigations may have limited applications.

In this study, in order to avoid obtaining the regression equation of superficial specific permeability against the reciprocal mean pressure, one of the nine different mean pressures used was adjusted to exactly $0.5 \times 10^5$ Pa for every run of permeability measurements. The calculated superficial specific permeability value at this mean pressure was then used to test the effect of specimen length. Table 1 summarizes the superficial specific permeability values at the mean pressure of $0.5 \times 10^5$ Pa for the tested species at various specimen lengths. Figures 12 and 13 show
Figure 12  Plot of superficial specific permeability ($K_{sp}$) at mean pressure of $0.5 \times 10^5$ Pa, against specimen lengths for all five single specimens of red oak heartwood (ROH) and red alder heartwood (RAH). □ No.1, △ No.2, ▼ No.3, ○ No.4, ◊ No.5.
Figure 13  Plot of superficial specific permeability ($K_{ps}$) at mean pressure of $0.5 \times 10^5$ Pa, against specimen lengths for all five single specimens of ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS). • No.1, ▲ No.2, ▼ No.3, ● No.4, ◼ No.5.
Table 1: Superficial specific permeability at mean pressure of $0.5 \times 10^5$ Pa for four different species at various specimen lengths. The coefficients of variation as % in parenthesis.

<table>
<thead>
<tr>
<th>Species</th>
<th>$L$ (mm)</th>
<th>$K_{ss}$ ($\mu m^3/\mu m$)</th>
<th>Species</th>
<th>$L$ (mm)</th>
<th>$K_{ss}$ ($\mu m^3/\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red oak heartwood</td>
<td>340</td>
<td>17.997 (25.8)</td>
<td>Red alder heartwood</td>
<td>260</td>
<td>6.496 (28.9)</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>17.731 (24.0)</td>
<td></td>
<td>220</td>
<td>6.454 (27.6)</td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>18.257 (25.5)</td>
<td></td>
<td>180</td>
<td>6.495 (27.5)</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>18.959 (31.0)</td>
<td></td>
<td>140</td>
<td>6.422 (31.5)</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>19.664 (28.7)</td>
<td></td>
<td>100</td>
<td>6.199 (30.6)</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>21.716 (33.8)</td>
<td></td>
<td>60</td>
<td>7.467 (30.7)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>30.537 (33.7)</td>
<td></td>
<td>20</td>
<td>10.50 (19.4)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>42.931 (33.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ponderosa pine sapwood</td>
<td>180</td>
<td>0.559 (49.7)</td>
<td>Douglas-fir sapwood</td>
<td>100</td>
<td>0.060 (33.3)</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>0.587 (46.5)</td>
<td></td>
<td>80</td>
<td>0.058 (35.4)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.620 (44.3)</td>
<td></td>
<td>60</td>
<td>0.061 (42.2)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.669 (43.8)</td>
<td></td>
<td>40</td>
<td>0.065 (36.3)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.889 (41.9)</td>
<td></td>
<td>20</td>
<td>0.161 (56.5)</td>
</tr>
</tbody>
</table>

directly the permeability changes with specimen length for all five single specimens of each species. Each superficial specific permeability shown in Figures 12 and 13 was the value obtained at a mean pressure of $0.5 \times 10^5$ Pa. It is interesting to note that within the four species groups, every single specimen showed the same trend of relationship between permeability and its length.

Since there was a high variability of permeabilities among single specimens (Table 1), it was considered to pair different lengths of specimen within a single specimen. Although the degrees of freedom were reduced by pairing the values, the sensitivity of the test could be considerably improved by removing the variation between single specimens. Therefore, a paired t-
test was used to analyse the differences of the permeability values at the mean pressure of $0.5 \times 10^5$ Pa among various specimen lengths (Tables 2 and 3).

Table 2 shows that beyond a specimen length of 140 mm, there was no significant difference of measured permeabilities between various pairs ($\alpha = 0.05$) for red oak heartwood. However, there was a significant increase of permeability with the decrease of specimen length after the latter was less than 140 mm. For red alder heartwood, there was no significant difference of permeabilities between various pairs for specimen lengths over 100 mm.

Table 3 also shows that there was a significant difference of permeability values only between specimen lengths of 20 mm and 60, 100, 140, 180 mm for ponderosa pine sapwood, and 40, 60, 80, 100 mm for Douglas-fir sapwood. Therefore, it was concluded that within the range of specimen lengths used for the four different species in this study, when they were longer than 140, 100, 60, and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively, their permeability values were nearly constant for the various lengths tested. A further decrease in specimen length resulted in a considerable increase of the measured permeability. The change in permeability was of the order of approximately two times for all studied species.

The effect of specimen length on permeability reported here was in agreement with results reported by Fogg and Choong (1989), and Perng (1980b). Fogg and Choong (1989) found that the longitudinal superficial nitrogen permeability of four hardwoods remained relatively identical above 19 mm, but increased two to four times with decreasing lengths below 19 mm. In Perng’s data, the longitudinal superficial air permeability was constant above 50 mm for red spruce and white spruce, and above 100 mm for white ash. However, when the length was shorter than the
Table 2: Comparison of $K_{sp}$ at mean pressure of $0.5 \times 10^5$ Pa for various specimen lengths of two hardwoods. The probability level of paired t-test in parenthesis.

<table>
<thead>
<tr>
<th>Species</th>
<th>L(mm)</th>
<th>340</th>
<th>300</th>
<th>260</th>
<th>220</th>
<th>180</th>
<th>140</th>
<th>100</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red oak</td>
<td>340</td>
<td>0.266</td>
<td>-0.261</td>
<td>-0.962</td>
<td>-1.668</td>
<td>-3.720</td>
<td>-12.54</td>
<td>-24.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.553)</td>
<td>(0.714)</td>
<td>(0.231)</td>
<td>(0.064)</td>
<td>(0.059)</td>
<td>(0.011)</td>
<td>(0.006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-0.526</td>
<td>-1.228</td>
<td>-1.993</td>
<td>-3.985</td>
<td>-12.81</td>
<td>-25.2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>(0.348)</td>
<td>(0.185)</td>
<td>(0.100)</td>
<td>(0.065)</td>
<td>(0.012)</td>
<td>(0.006)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>(0.355)</td>
<td>(0.270)</td>
<td>(0.117)</td>
<td>(0.017)</td>
<td>(0.006)</td>
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<tr>
<td></td>
<td>220</td>
<td>-0.705</td>
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<td>-11.58</td>
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<td></td>
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<td>(0.386)</td>
<td>(0.075)</td>
<td>(0.01)</td>
<td>(0.004)</td>
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<td></td>
<td>(0.073)</td>
<td>(0.011)</td>
<td>(0.004)</td>
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<tr>
<td></td>
<td>140</td>
<td>-8.82</td>
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<td></td>
<td></td>
<td>(0.007)</td>
<td>(0.003)</td>
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<td></td>
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<table>
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<tr>
<th>Species</th>
<th>L(mm)</th>
<th>260</th>
<th>220</th>
<th>180</th>
<th>140</th>
<th>100</th>
<th>60</th>
<th>20</th>
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<tr>
<td>Red alder</td>
<td>260</td>
<td>0.042</td>
<td>0.0012</td>
<td>0.074</td>
<td>0.297</td>
<td>-0.971</td>
<td>-4.004</td>
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<td></td>
<td></td>
<td>(0.818)</td>
<td>(0.992)</td>
<td>(0.626)</td>
<td>(0.150)</td>
<td>(0.029)</td>
<td>(0.001)</td>
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<tr>
<td></td>
<td>220</td>
<td>-0.041</td>
<td>0.032</td>
<td>0.255</td>
<td>-1.012</td>
<td>-4.046</td>
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<td>(0.874)</td>
<td>(0.901)</td>
<td>(0.185)</td>
<td>(0.048)</td>
<td>(0.001)</td>
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<td>0.296</td>
<td>-0.972</td>
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<td></td>
<td>(0.762)</td>
<td>(0.202)</td>
<td>(0.045)</td>
<td>(0.002)</td>
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<tr>
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<td>140</td>
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<td>(0.458)</td>
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<td>(0.001)</td>
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</tr>
<tr>
<td></td>
<td>100</td>
<td>-1.267</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>(0.031)</td>
<td>(0.001)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>60</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>-3.034</td>
</tr>
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<td></td>
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<td>(0.002)</td>
</tr>
</tbody>
</table>
Table 3: Comparison of $K_{ws}$ at mean pressure of $0.5 \times 10^5$ Pa for various specimen lengths of two softwoods. The probability level of paired t test in parenthesis.

<table>
<thead>
<tr>
<th>Species</th>
<th>L (mm)</th>
<th>180</th>
<th>140</th>
<th>100</th>
<th>60</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa pine</td>
<td>180</td>
<td>-0.028</td>
<td>-0.061</td>
<td>-0.11</td>
<td>-0.33</td>
<td>(0.131)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sapwood</td>
<td>140</td>
<td>-0.033</td>
<td>-0.082</td>
<td>-0.302</td>
<td>(0.149)</td>
<td>(0.185)</td>
</tr>
<tr>
<td></td>
<td>100</td>
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<td></td>
<td>-0.049</td>
<td>-0.27</td>
<td>(0.211)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td>-0.22</td>
<td>(0.021)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir sapwood</td>
<td>100</td>
<td>0.001</td>
<td>-0.001</td>
<td>-0.005</td>
<td>-0.101</td>
<td>(0.628)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.659)</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>-0.003</td>
<td>-0.006</td>
<td>-0.102</td>
<td>(0.449)</td>
<td>(0.056)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
<td>-0.003</td>
<td>-0.099</td>
<td>(0.190)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>-0.096</td>
<td>(0.038)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

critical length of 50 mm or 100 mm, permeability values increased sharply with decreasing specimen length.

An explanation of this increasing permeability phenomenon with decreasing specimen length within a certain range, could be an either partial or total blockage of some of the conductive pathways in both softwoods and hardwoods. In softwoods, the aspirated pits between tracheids could have been attributed to the blockage whereas in hardwoods, the blockage is
usually caused by the existence of tyloses or perforation plates in the vessels.

From the results of this study, it seems that the specimen length above which the
permeability remains constant, is related to the permeability magnitude of the particular studied
species. This could be explained by the model that was proposed by Bramhall (1971). The
hypothesis for this model is that there is an exponential increase in the number of conducting
tracheids with a decrease in length. This can be expressed in terms of a conducting area as:

$$A_c = A e^{-dl}$$  \hspace{1cm} (31)

where $A$ is the area of specimen (cm$^2$); $A_c$ is the effective conducting area (cm$^2$); and $d$ is the
positive constant. Equation (31) can also be rearranged to a more useful form (Bramhall 1970):

$$A_c = A(e^{-d})^L = Aw^L$$  \hspace{1cm} (32)

since $d$ is a positive constant, it follows that $w (= e^{-d})$ must necessarily be a fraction. Bramhall
(1970) defined $w$ as the fraction of all conducting tracheids at a depth of 1 cm. Then, the available
void volume can be expressed as:

$$V = \frac{A\Phi}{\ln w}(w^L - 1)$$  \hspace{1cm} (33)

where $\Phi$ is the porosity or void area of a specimen’s cross section. In theory, it may be assumed
that where the value of $w^L$ is below 0.01, the error may be neglected. For example, if $w = 0.7$, 0.5,
and 0.2, the value of $L$ such that $w^L = 0.01$ is 12.9, 6.64 and 2.86 cm, respectively. Since higher
permeability species have a higher value of $w$, the required specimen length above which the
available void volume or permeability remained nearly constant, should also be greater than that
4.1.2 Evaluation of pressure drop due to end effects

As pointed out in Section 2.3.4, nonlinear laminar flow may be caused by end effects due to both the shape and condition of the specimen end (fluid entrance). In fact, this end effect can be evaluated from the experiments on the specimen length effect. According to Adzumi's equation, at a given mean pressure and a constant flow rate, the relationship between pressure drop and specimen length should pass through the origin of the coordinates. Therefore, the plot of pressure drop versus specimen length at a given mean pressure and a constant flow rate could be employed as the evaluation of pressure drop due to end effects.

As described in Section 3.3.1, during the first experimental step, the flow measurements were carried out on the initial length of every single specimen, and then repeated at each subsequent shorter length under the same flow rate. For each tested specimen one of the nine different mean pressures was taken exactly at a mean pressure of $0.5 \times 10^5$ Pa. Therefore, for each single specimen, the relationship between pressure drop at the mean pressure of $0.5 \times 10^5$ Pa and specimen length at a constant flow rate could be evaluated. Since there was an existence of a critical length for each specimen group, as discussed above, only the experimental points which were obtained above the critical specimen length were used to evaluate the pressure drop due to end effects.

Figures 14 and 15 show the relationship between pressure drop and specimen length at a mean pressure of $0.5 \times 10^5$ Pa and a given flow rate for all five single specimens of each species. The solid lines appearing in Figures 14 to 15 are straight lines through the origin of the
Figure 14  Relation between pressure drop and specimen length at a given mean pressure of $0.5 \times 10^5$ Pa and a constant flow rate for all five single specimens of red oak heartwood (ROH) and red alder heartwood (RAH).
Figure 15  Relation between pressure drop and specimen length at a given mean pressure of $0.5 \times 10^5$ Pa and a constant flow rate for all five single specimens of ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS).
coordinates that have been fitted to the data. These figures show that in all cases there is no evidence of systematic deviations of the data from the respective lines. Furthermore, the correlation coefficient for each regression line is in the range of 0.9959 to 0.9999 for red oak heartwood, 0.9976 to 0.9982 for red alder heartwood, 0.997 to 0.999 for ponderosa pine sapwood, and 0.9962 to 0.9983 for Douglas-fir sapwood. Thus, the linear relationship between pressure drop and specimen length at a constant mean pressure and flow rate in accordance with Eq.(14), is experimentally supported. Based on the results of the relationship between pressure drop and specimen length as described above, it is concluded now that above the critical specimen length for each specimen group the pressure drop exhibits a linear relationship with the specimen length at a constant mean pressure and flow rate, and the intercept of this straight line can be considered as zero. Therefore the pressure drop caused by end effects due to both the shape and condition of the specimen entrance in this study is negligible.

In conclusion, the following remarks may be inferred from the above results of specimen length effects on wood permeability and pressure drop due to end effects:

1. Non-Darcian behaviour due to specimen length appears common in the studied species.
2. In the experimental range of specimen lengths, there is an existence of a certain length above which the permeability values are nearly identical for the various lengths of the tested species. These specimen lengths were found to be 140, 100, 60 and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. This indicates that an approximate uniformity of wood structure can be obtained for these species by the use of the respective specimen lengths mentioned above.
3. When the specimen length is below a critical value for the different species described
above, permeability increases drastically with decreasing specimen length.

4. The higher the air permeability of a species, the greater is the specimen length above which permeability values remain almost constant for various specimen lengths.

5. When the specimen length is above a critical value for the different species described above, the pressure drop caused by end effects due to both the shape and condition of the specimen entrance is negligible.

Since the study on the permeability effects of specimen length is the first step of this research project, the specimen lengths used for the evaluation of slip and nonlinear flows in the subsequent series of tests were 140, 100, 60, and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively.

4.2 Detection of nonlinear flow

After the determination of the critical length for each tested species, the evaluation of the nonlinear flow in wood was carried out. In this study, ten single specimens from each specimen groups were selected. Each single specimen was cut to its corresponding length based on the above results of evaluation of critical length for each specimen groups. For example, ten specimens from the red oak heartwood group were cut to 140 mm in length. The same number of specimens were cut to 100, 60, and 40 mm in length from red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood group, respectively.

Five different flow rates were used in each specimen group first. Trail measurements were made to select these different flow rates for each specimen group over the entire range of flow rates. For red oak heartwood, the five different flow rates selected were 44.52, 36.12, 27.87,
19.57, and 9.85 cm$^3$/s; for red alder heartwood, they were 36.12, 29.33, 22.47, 15.33, and 8.18 cm$^3$/s; and for ponderosa pine sapwood group they were 19.57, 15.73, 11.77, 8.02, and 4 cm$^3$/s. For Douglas-fir sapwood specimens, the maximum flow rates achieved were only 1.75 cm$^3$/s, followed by 1.38, 1.02, 0.67, and 0.33 cm$^3$/s. Under each flow rate used, about nine data points were taken exactly the same way as described above. The sequence of the five different flow rates used within each specimen was randomly selected. It should be noted that the higher volumetric flow rate for ponderosa pine sapwood was related to its larger cross section of the specimen compared to the other three specimen groups.

As described in Section 2.5, there are two methods of detection for nonlinear flow in wood. One is from the air permeability measurements based on Klinkenberg's equation or Petty's model. The other is directly from the relationship between volumetric flow rate (Q) and the total measured pressure drop (ΔP) at a given constant mean pressure. In this study, both methods were employed for the detection of nonlinear flow in wood.

4.2.1 Detection of nonlinear flow according to the permeability measurements

According to the Klinkenberg's equation (Eq.(18)) or Petty's model (Eq.(21)), the relationship between superficial specific permeability and reciprocal mean pressure ($1/\bar{P}$) is independent of the flow rate and pressure drop. Moreover, the permeability coefficient will decrease with the increased flow rate or the increased pressure drop if there is nonlinear flow present in the specimen. In other words, a decrease in the permeability coefficient with increased flow rate or increased pressure drop at a given constant mean pressure may be taken as evidence of the onset of either nonlinear laminar or turbulent flow. Therefore, the plots of permeability
versus reciprocal mean pressure at five different flow rates can be used as the evidence of nonlinear flow in wood first.

Figures 16 and 17 show the relationship between the superficial specific permeability and the reciprocal mean pressure at five different flow rates for one specimen of each specimen groups. It is clear that the plots of superficial specific permeability against the reciprocal mean pressure, were independent of the flow rates used over the entire range of flow rates of each specimen groups except red oak heartwood. For red oak heartwood, Figure 16 shows that the permeability coefficient at any given constant mean pressure decreased with the increased flow rates after the used flow rates were above 19.57 cm\(^3\)/s. Since the experiments indicated the evidence of nonlinear air flow in red oak heartwood, another three more flow rates were added to this specimen group in order to obtain more data for the subsequent evaluation of slip flow. All the three added flow rates were below 19.57 cm\(^3\)/s, namely, 15.33, 11.77, and 8.02 cm\(^3\)/s (Figure 18). Therefore, 30 more runs were added to the red oak heartwood specimen group, resulting to a total of 230 runs of permeability measurements at the second phase of the experimental procedure as described in Section 3.3.2.

It is interesting to note that the effect of flow rates on the relationship between superficial specific permeability and reciprocal mean pressure for all the ten specimens within each specimen group was of the same trend. Therefore, the superficial specific permeability at the mean pressure of 0.5x10\(^5\) Pa was also taken in order to make a direct comparison of the permeability values at different flow rates.

Table 4 summarizes the superficial specific permeability values at the mean pressure of 0.5x10\(^5\) Pa for the tested specimen groups at various different flow rates. From these numbers, it
Figure 16  Plot of superficial specific permeability, $K_{gs}$ ($\mu m^3/\mu m$), versus reciprocal mean pressure, $1/P$ ($Pa^{-1} \times 10^5$) at various flow rates ($cm^3/s$), for one typical specimen of red oak heartwood (ROH) and red alder heartwood (RAH). ■44.52, ▲36.12, □29.33, ▼27.87, ◀22.47, ●19.57, ×15.33, ◇9.85, +8.18.
Figure 17  Plot of superficial specific permeability, $K_{\text{gs}}$ ($\mu$m$^3$/µm), versus reciprocal mean pressure, $1/P$ (Pa$^{-1}$x10$^5$) at various flow rates (cm$^3$/s), for one typical specimen of ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS). ▴19.57, ▲15.73, □11.77, ▼8.02, ◊4.0, ●1.75, ×1.38, ◢1.02, +0.67, △0.33.
Figure 18  Plot of superficial specific permeability, $K_{gs}$ ($\mu$m$^3$/μm), versus reciprocal mean pressure, $1/P$ (Pa$^{-1}$x10$^5$) under 8 different flow rates (cm$^3$/s), for one typical specimen of red oak heartwood (ROH). □ 44.52, ▲ 36.12, □ 27.87, ▼ 19.57, ○ 15.33, ● 11.77, × 9.85, ◊ 8.02.
Table 4: Superficial specific permeability at mean pressure of $0.5 \times 10^5$ Pa for four different species at various flow rates. The coefficients of variation as % in parenthesis.

<table>
<thead>
<tr>
<th>Species</th>
<th>$Q$ (cm$^3$/s)</th>
<th>$K_{sp}$ (μm$^3$/μm)</th>
<th>Species</th>
<th>$Q$ (cm$^3$/s)</th>
<th>$K_{sp}$ (μm$^3$/μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red oak heartwood</td>
<td>44.52</td>
<td>18.005 (30.1)</td>
<td>Red alder heartwood</td>
<td>36.12</td>
<td>8.512 (24.1)</td>
</tr>
<tr>
<td></td>
<td>36.12</td>
<td>18.942 (29.4)</td>
<td></td>
<td>29.33</td>
<td>8.581 (24.3)</td>
</tr>
<tr>
<td></td>
<td>27.87</td>
<td>20.191 (27.9)</td>
<td></td>
<td>22.47</td>
<td>8.514 (24.5)</td>
</tr>
<tr>
<td></td>
<td>19.57</td>
<td>21.971 (27.1)</td>
<td></td>
<td>15.33</td>
<td>8.534 (24.5)</td>
</tr>
<tr>
<td></td>
<td>15.33</td>
<td>21.962 (27.4)</td>
<td></td>
<td>8.18</td>
<td>8.525 (24.8)</td>
</tr>
<tr>
<td></td>
<td>11.77</td>
<td>22.008 (27.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.85</td>
<td>21.933 (27.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.02</td>
<td>22.066 (27.0)</td>
<td>Ponderosa pine sapwood</td>
<td>11.77</td>
<td>0.670 (40.1)</td>
</tr>
<tr>
<td>Ponderosa pine sapwood</td>
<td>15.73</td>
<td>0.670 (40.1)</td>
<td>Douglas-fir sapwood</td>
<td>1.75</td>
<td>0.103 (22.9)</td>
</tr>
<tr>
<td></td>
<td>11.77</td>
<td>0.670 (40.1)</td>
<td></td>
<td>1.02</td>
<td>0.102 (21.6)</td>
</tr>
<tr>
<td></td>
<td>8.02</td>
<td>0.672 (38.8)</td>
<td></td>
<td>0.67</td>
<td>0.102 (22.3)</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>0.668 (40.3)</td>
<td></td>
<td>0.33</td>
<td>0.102 (20.3)</td>
</tr>
</tbody>
</table>

is obvious that the permeability value at the mean pressure of $0.5 \times 10^5$ Pa is almost the same for all the flow rates used in red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood. However, in the red oak specimen group, the permeability value at the mean pressure of $0.5 \times 10^5$ Pa was almost the same for all the flow rates used up to 19.57 cm$^3$/s, and then was reduced with further increase of the flow rates.

A paired t-test was also used to analyse these differences of the permeability values at the mean pressure of $0.5 \times 10^5$ Pa among various flow rates (Tables 5 and 6). Table 5 shows that
Table 5: Comparison of $K_{ps}$ at mean pressure of $0.5 \times 10^5$ Pa for various flow rates of two hardwoods. The probability level of paired t-test in parenthesis.

<table>
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<tr>
<th>Species</th>
<th>Q(cm$^3$/s)</th>
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<th>9.85</th>
<th>11.77</th>
<th>15.33</th>
<th>19.57</th>
<th>27.87</th>
<th>36.12</th>
<th>44.52</th>
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<td>Red oak</td>
<td>8.02</td>
<td>0.133</td>
<td>0.058</td>
<td>0.104</td>
<td>0.095</td>
<td>1.875</td>
<td>3.124</td>
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<tr>
<td></td>
<td></td>
<td>(0.079)</td>
<td>(0.609)</td>
<td>(0.300)</td>
<td>(0.302)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
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</tr>
<tr>
<td>heart-wood</td>
<td>9.85</td>
<td>-0.076</td>
<td>-0.029</td>
<td>-0.038</td>
<td>1.742</td>
<td>2.991</td>
<td>3.928</td>
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<tr>
<td></td>
<td></td>
<td>(0.531)</td>
<td>(0.786)</td>
<td>(0.669)</td>
<td>(0.000)</td>
<td>(0.000)</td>
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<tr>
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<td>11.77</td>
<td>0.046</td>
<td>0.037</td>
<td>1.817</td>
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<td></td>
<td>44.52</td>
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<th>22.47</th>
<th>29.33</th>
<th>36.12</th>
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<td>Red alder</td>
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<td>0.011</td>
<td>-0.056</td>
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<td>(0.164)</td>
<td>(0.573)</td>
<td>(0.826)</td>
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<td>heart-wood</td>
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<td>(0.645)</td>
<td>(0.651)</td>
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Table 6: Comparison of $K_{av}$ at mean pressure of $0.5 \times 10^5$ Pa for various flow rates of two softwoods. The probability level of paired t test in parenthesis.

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<th>Species</th>
<th>Q(cm$^3$/s)</th>
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<th>11.77</th>
<th>15.73</th>
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<td>Ponderosa pine</td>
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<td>-0.002</td>
<td>-0.002</td>
<td>0.003</td>
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<td></td>
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<td></td>
<td></td>
<td>(0.801)</td>
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<tr>
<td>sapwood</td>
<td>8.02</td>
<td>0.002</td>
<td>0.002</td>
<td>0.007</td>
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<td>(0.758)</td>
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<td>19.57</td>
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<td>(0.255)</td>
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<th>1.02</th>
<th>1.38</th>
<th>1.75</th>
</tr>
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<tbody>
<tr>
<td>Douglas-fir</td>
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<td>0.000</td>
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<td>-0.001</td>
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<td>sapwood</td>
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<td>(0.867)</td>
<td>(0.795)</td>
<td>(0.771)</td>
<td>(0.286)</td>
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<tr>
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<td>0.67</td>
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<td>(0.689)</td>
<td>(0.903)</td>
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<tr>
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<td>1.02</td>
<td>0.000</td>
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<td>-0.001</td>
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<td>(0.068)</td>
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<tr>
<td></td>
<td>1.38</td>
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<td>-0.001</td>
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<td></td>
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<td></td>
<td>1.75</td>
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</tr>
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</table>

beyond a flow rate of 19.57 cm$^3$/s, there is significant difference of measured permeabilities between various pairs at different flow rates for red oak heartwood. Tables 5 and 6 also show that there is no significant difference of measured permeabilities between various pairs at five different flow rates for red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood.

Therefore, it was concluded that over the entire range of measured flow rates for the specimen of
red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood in this study, their permeability values were independent of the flow rates used. However, for red oak heartwood, there was a significant decrease of permeability values with the increase of flow rates when flow rates was above 19.57 cm³/s, thus indicated the presence of nonlinear air flow components.

4.2.2 Detection of nonlinear flow according to the relationship between Q and ΔP

Adzumi's Eq.(14) for gas flow, shows a linear relationship between pressure gradients or pressure drop and flow rates at a constant mean pressure. Therefore, the relationship between ΔP and Q at a mean pressure of $0.5 \times 10^5$ Pa can also be used as the detection of nonlinear flow for the tested specimens.

Figures 19 and 20 show the data of one specimen from each group obtained over the entire region of flow rates. Careful inspection of these two figures indicates that except for the specimen from red oak heartwood, the straight lines are the only reasonable relationship of the data based on the relationship between ΔP and Q at a mean pressure of $0.5 \times 10^5$ Pa. However, for the red oak specimen shown in Figure 19, it is demonstrated that a linear dependence of the pressure drop on the flow rate stops to exist when the used flow rates were above 19.57 cm³/s. It is obvious that the experimental points departure from the dotted straight line resulted in an increase of pressure drop relative to that predicted by a linear relationship alone. It is also observed that the data obtained under lower flow rates, could be described by a linear dependence of the pressure drop on the flow rate at a constant mean pressure.

Figures 21 through 24 show the relationship between pressure drop and flow rate at a mean pressure of $0.5 \times 10^5$ Pa, based on the data from all the specimens. Except for Figure 21,
Figure 19  Relation between pressure drop and flow rate at a constant mean pressure of 0.5x10^5 Pa for one typical specimen of red oak heartwood (ROH) and red alder heartwood (RAH).
Figure 20  Relation between pressure drop and flow rate at a constant mean pressure of 0.5x10^5 Pa for one typical specimen of ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS).
Figure 21  Relation between pressure drop and flow rate at a constant mean pressure of $0.5 \times 10^5$ Pa for all specimens of red oak heartwood (ROH) under its 5 lower flow rates.
Figure 22  Relation between pressure drop and flow rate at a constant mean pressure of 0.5x10^5 Pa for all specimens of red alder heartwood (RAH) within its entire range of flow rates.
Figure 23  Relation between pressure drop and flow rate at a constant mean pressure of 0.5x10^5 Pa for all specimens of ponderosa pine sapwood (PPS) within its entire range of flow rates.
Figure 24  Relation between pressure drop and flow rate at a constant mean pressure of 0.5x10^5 Pa for all specimens of Douglas-fir sapwood (DFS) within its entire range of flow rates.
which was obtained in the flow region from a flow rate of 8.02 to 19.57 cm³/s for red oak heartwood, Figures 22, 23, and 24 were attained over the entire region of flow rates for red alder heartwood, ponderosa pine and Douglas-fir sapwood, respectively. The solid lines appearing in Figures 21 to 24 are straight lines through the origin of the coordinates that have been fitted to the data. These figures show that in no case is there evidence of systematic deviations of the data from the respective lines. Furthermore, the correlation coefficient for each regression line is in the range of 0.999 to 0.9999 in Figure 21, 0.9992 to 0.9999 in Figure 22, 0.9991 to 0.9999 in Figure 23, and 0.9983 to 0.9999 in Figure 24. Thus, the linear relationship between pressure drop and flow rate at a constant mean pressure in accordance with Eq.(14), is experimentally supported. Based on the results of the relationship between pressure drop and flow rates as described above, it may be concluded now that within the region of lower flow rates (Q≤19.57 cm³/s) for red oak heartwood, and within the entire range of flow rates which can be achieved in this study for the other three specimen groups, the pressure drop exhibits a linear relationship with the flow rate at a constant mean pressure. Thus the possibility of nonlinear flow developing in the specimen is excluded.

As is demonstrated in Figure 19, when the flow rate used is above 19.57 cm³/s for red oak heartwood, significant departures from the linear relationship between pressure drop and flow rate occur. This implies the presence of nonlinear flow within the specimen. That is, when the higher flow rates are used for this specimen group, an expression for relationship between pressure drop and flow rate at a constant mean pressure may involve both a linear and a quadratic dependence of the pressure drop on the flow rate, in accordance with Eq.(25). Therefore, the validity of Eq.(25) was examined here even though only three experimental data points were available for
each specimen in this research. In order for Eq.(25) to reduce to the linear form, the flow rate must be divided throughout the equation. Thus the pressure drop to flow rate ratio \((\Delta P/Q)\) is a linear function of the flow rate \((Q)\) at a constant mean pressure.

Figure 25 illustrates this linear relationship where the solid straight lines for all ten specimens appearing in the figure have fitted to the experimental data quite well. The correlation coefficients of regression lines ranged from 0.978 to 1. Thus Eq.(25) in which both a linear and a quadratic dependence of the pressure drop on the flow rate are involved, is experimentally supported. In other words, these results strongly suggest that, when the flow rate used is above 19.57 cm\(^3\)/s for the red oak heartwood specimens, the pressure drop at a given constant mean pressure is represented as the sum of two terms—one linear and the other quadratic in the flow rate.

It has been established above that both permeability measurement and pressure-flow rate-relationship methods for the detection of nonlinear air flow in wood achieved the same results. For red alder heartwood, ponderosa pine and Douglas-fir sapwood, within the entire range of respective flow rates used, the superficial specific permeability at the mean pressure of 0.5\(\times\)10\(^5\) Pa is independent of the flow rates, and Adzumi's equation (Eq.(14)) is a valid description of the pressure drop-flow rate relation at a given mean pressure of 0.5\(\times\)10\(^5\) Pa, thus indicating the existence of linear flow components only within the specimen for these specimen groups. For red oak heartwood, when the lower flow rates are used \((Q < 19.57 \text{ cm}^3/\text{s})\), the test results for the detection of nonlinear air flow are exactly the same as the specimen groups just mentioned above. However, for the case where the flow rates used are above 19.57 cm\(^3\)/s, the superficial specific permeability at the mean pressure of 0.5\(\times\)10\(^5\) Pa decreases with the increase of the flow rates, and
Figure 25  Relation between pressure drop to flow rate ratio and flow rate at a constant mean pressure of $0.5 \times 10^5$ Pa for all specimens of red oak heartwood (ROH) at the flow rates above $19.57 \text{cm}^3/\text{s}$. 

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the expression equation of pressure drop and flow rate at a given mean pressure of $0.5 \times 10^5$ Pa involves both a linear and quadratic dependence of the pressure drop on the flow rate, thus demonstrating the presence of the nonlinear flow components in the specimen.

In this study, nonlinear air flow phenomena was only found in the higher permeability species at higher flow rates. This was in agreement with the results reported by Wiley and Choong (1975), Choong et al. (1988), and Perng (1980b). Wiley and Choong (1975) found that the plots of $K_n$ versus $1/P$ in several hardwoods and softwoods were generally lower and with somewhat steeper slopes at $1.36 \times 10^4$ Pa (= 102 mm-Hg) compared to $6.665 \times 10^3$ Pa (= 50 mm-Hg) pressure drop, and the effect of pressure drop became more pronounced in the higher permeability range. At the same time, they also found that the effect of pressure drop was negligible for woods with nitrogen permeability coefficients less than $0.2 \mu m^3/\mu m$.

Later, Choong et al. (1988) confirmed their initial findings by permeability measurements on seven hardwood species. They reported that the plots of nitrogen permeability as a function of the reciprocal mean pressure indicated the reduction of the former with the pressure drop. Furthermore, in order to show the dependency of nitrogen permeability on pressure drop, they generated the plots of permeability versus pressure drop at constant mean pressure $P = 1.05 \times 10^5$ Pa and $2.0 \times 10^5$ Pa. These indicated that the curves remained horizontal up to some critical value of pressure drop, and then began to drop sharply with an increase in pressure drop. Meanwhile, they also found that at low permeability (below $1 \mu m^3/\mu m$), the curves of permeability versus pressure drop appeared nearly horizontal, thus indicating no apparent effect of pressure drop.

When Perng (1980b) studied the effect of specimen's length on the permeability coefficient, he also found that when permeability was above $2 \mu m^3/\mu m$ and samples had lengths
within the critical range, both flow rate and permeability decreased abruptly with decreasing sample length. He attributed this phenomenon to the influence of turbulence and nonlinear laminar flow in terms of the plot of flow rate against pressure drop.

On the other hand, the opposite results on nonlinear flow in wood were reported by Kuroda and Siau (1988). They reported that the air permeability of low permeability species such as loblolly pine, Douglas-fir and white spruce was dependent on flow rate, and the permeability was found to be decreasing with flow rate. They reported this phenomenon as evidence of the onset of either turbulent or nonlinear laminar flow. However, no evidence was found of nonlinear laminar flow in specimens of high permeability species such as paper birch and basswood.

Actually, the fact that nonlinear flow more likely occurs for the higher permeability species at higher flow rates has more reasonable explanations. According to Eq.(22) for liquid flow or Eq.(25) for gas flow, the nonlinear flow component is proportional to the square of flow rates. The higher the flow rate, the greater the contribution of nonlinear flow component to the total pressure drop. For example, for the specimen of ROH-14-13 in this study, the pressure drop due to nonlinear flow took up approximately 19% of the total pressure drop at the flow rate of 27.87 cm$^3$/s, while approximately 28% at the flow rate of 44.52 cm$^3$/s under a constant mean pressure of 0.5x10$^5$ Pa. For the lower permeability species, it is very difficult to reach a higher flow rate through the specimen. Even in higher permeability species, if the lower flow rate is used, the pressure drop due to nonlinear flow at these flow rates may be small enough to be negligible compared with the total pressure drop.

In summary, the following may be concluded from the above results of nonlinear flow detection in wood:
1. Non-Darcian flow due to nonlinear flow seems existed only in highly permeable red oak heartwood at higher flow rates.

2. For red alder heartwood, ponderosa pine and Douglas-fir sapwood, over the experimental range, both methods for the detection of nonlinear air flow indicate the existence of linear flow components only within the specimen. Permeability measurement method indicates that the superficial specific permeability at the mean pressure of 0.5x10^5 Pa is independent of the flow rates. Pressure-flow rate-relationship method indicates that Adzumi’s equation is a valid description of the pressure drop-flow rate relation at a given mean pressure of 0.5x10^5 Pa.

3. For red oak heartwood, when the lower flow rates are used (Q ≤ 19.57 cm³/s), the test results are exactly the same as other three specimen groups, indicating only existence of linear air flow within the specimen. When the flow rates used are above 19.57 cm³/s, the permeability measurement method indicates that the superficial specific permeability at the mean pressure of 0.5x10^5 Pa decreases with the increase of the flow rates, and the pressure-flow rate-relationship method indicates that the expression equation of pressure drop and flow rate at a given mean pressure of 0.5x10^5 Pa involves both a linear and quadratic dependence of the pressure drop on the flow rate. Therefore, the presence of the nonlinear flow components in the red oak heartwood specimen at higher flow rates was supported experimentally.

4.3 Evaluation of slip flow

As it was pointed out in Section 3.3, the evaluation of non-Darcian flow due to slip flow
could be determined following the detection of nonlinear flow in wood. To this end, for the specimens from red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, that showed no evidence of nonlinear flow over the entire range of flow rates with the experimental facility developed for the present research, data points from 5 different flow rates (i.e., 5 runs) for each specimen could be added together (about 45 points) and then used to evaluate slip flow within the tested specimen based on Klinkenberg’s equation or Petty’s model. For the red oak heartwood specimen group exhibiting the presence of nonlinear flow at the flow rates above 19.57 cm$^3$/s, the data points obtained from 5 lower flow rates could then be added together (about 45 points) and used to test and evaluate slip flow components within each specimen.

4.3.1 Detection of slip flow in wood

Similarly to the detection of nonlinear flow in wood discussed above, both the permeability measurement method and the flow rate-pressure-relationship method can be employed as the detection of non-Darcian air flow due to slip flow. If there is only Darcian air flow in wood, the former method based on Klinkenberg’s equation should show no relationship between superficial specific permeability and reciprocal mean pressure. That is, the slope of straight line representing the relationship between the superficial specific permeability and the reciprocal mean pressure as expressed by Klinkenberg’s equation, should be zero. The latter one based on flow rate-pressure-relationship must show that, the straight line representing the relationship between the specific flow rate ($QLP/\Delta P$) and the mean pressure ($\bar{P}$) as expressed by Adzumi’s equation (Eq.(14)) should pass through the origin of the coordinates.

Re-inspection of Figures 16 and 17 clearly indicates that the superficial specific
permeability is the function of reciprocal mean pressure for all the specimen groups. Thus, the existence of slip flow in studied species is experimentally confirmed by the permeability measurement method.

In order to examine the validity of Adzumi’s equation (Eq.(14)), numerical values of the grouping variable QLP/AP (i.e., specific flow rate) must be calculated from the experimental measurements. To do this, one of nine data points at each constant flow rate was taken from the experimental measurements. In this study, for convenience, that was done by taking the first point measured at each flow rate (or run) for each specimen.

As described previously (Section 3.3.1), the first point of each run in this study was measured at the maximum pressure drop and minimum mean pressure under a constant flow rate, thus it has the highest slip flow contribution, as presented in Figures 26 through 29. The specific flow rate is plotted as the ordinate variable, while mean pressure is the abscissa. Since five different flow rates were available for the test of non-Darcian flow due to slip flow for each specimen group in this study, five data points appeared in these plots for each specimen.

Figures 26 through 29 show that the straight line representing the relationship between the specific flow rate and the mean pressure for each specimen of all the four specimen groups, does not pass through the origin of the coordinates, rather it has an intercept. This vertical intercept actually correspond to the value of slip flow contribution in accordance with Adzumi’s equation (Eq.(14)). The correlation coefficient for the straight lines is in the range of 0.996 to 0.9998, 0.9977 to 0.9997, 0.9933 to 0.9995, and 0.997 to 0.9997 in Figures 26, 27, 28, and 29, respectively, so that the relationship between the specific flow rate and the mean pressure in accordance with Adzumi’s equation is experimentally supported. Since both methods for the
Figure 26  Relationship between the specific flow rate and the mean pressure for all the specimens of red oak heartwood (ROH).
Figure 27  Relationship between the specific flow rate and the mean pressure for all the specimens of red alder heartwood (RAH).
Figure 28  Relationship between the specific flow rate and the mean pressure for all the specimens of ponderosa pine sapwood (PPS).
Figure 29  Relationship between the specific flow rate and the mean pressure for all the specimens of Douglas-fir sapwood (DFS).
detection of slip flow in wood indicate that the slip air flow exists in all the studied specimen
groups, further detailed evaluation based on the viscous-slip flow model was carried out.

4.3.2 Evaluation of viscous-slip flow model in wood

As described in Section 2.3.3, the combination of viscous and slip flow components into
the total gas flow through wood can be expressed exactly by Adzumi’s equation (Eq. (14)), or
Klinkenberg’s equation (Eq. (18)). In this study, the Klinkenberg’s equation was employed to fit
the experimental data of air permeability measurements from the specimen in which both viscous
and slip flow components were included. As discussed previously, there is no significant effect of
flow rates on the permeability for red alder heartwood, ponderosa pine and Douglas-fir sapwood
within their entire range of 5 different flow rates, as well for the red oak heartwoods when five
lower flow rates were used. In this case, the permeability measurements under each of 5 different
flow rates could be added together, and thus approximately 45 experimental data were available
to fit Klinkenberg’s equation for each specimen in this study.

Reference to Figures 16 through 18 indicates that the plot of superficial specific
permeability ($K_{gs}$) versus reciprocal mean pressure ($1/P$) is linear for all the specimen groups
studied. These linear plots indicate that there was no significant presence of high and low
conductances in series as indicated in Petty’s model. Therefore, the experimental data from each
specimen were analysed in accordance with the linear Klinkenberg’s equation (Eq.(18)).

The correlation coefficients between superficial specific permeability ($K_{gs}$) and reciprocal
mean pressure ($1/P$) were in the range of 0.888-0.989, 0.964-0.988, 0.973-0.994, and 0.985-
0.997 for red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir
sapwood, respectively. By comparing them to the critical value of correlation coefficient in a table of multiple correlation coefficient (Kozak 1966), the test indicates that all these regression equations are significant at the probability level of 0.01.

The samples, the intercepts ($K_g$) and the slopes ($K_{gb}$) of their regression equations, together with the slip flow constant ($b$), the ratio of superficial specific permeability to true permeability at mean pressure of $0.5 \times 10^5$ Pa ($K_{g_s}/K_g$), and the average radii ($r$) and number ($n$) of effective openings calculated from the regression equations are summarized in Tables 7 and 8. The plots of superficial specific permeability versus reciprocal mean pressure with the corresponding regression line for one sample of each specimen groups are illustrated in Figures 30 and 31.

As described previously, the intercept of Klinkenberg’s equation represents the specific permeability or true gas permeability. This intercept permeability could be used to compare with the value of liquid permeability since it does not include the slip flow components and it is only a function of the wood structure. In this study, the true permeability of red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood was 20.91, 7.05, 0.51 and 0.068 $\mu m^3/\mu m$, respectively. This indicates an extremely wide range in the permeability values for woods of four different species, with a ratio of 308:1. The permeability value reported here is in good agreement with the one in the table of wood permeability classifications given by Siau (1995).

The magnitude of slip flow components for different species can also be evaluated from the Klinkenberg’s equation. From Tables 7 and 8, the average ratio of the superficial specific permeability at $0.5 \times 10^5$ Pa mean pressure to the true permeability was 1.047, 1.204, 1.292, and
Table 7: Summary of the evaluation based on the Klinkenberg's equation for red oak heartwood (ROH) and red alder heartwood (RAH).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$K_p$ (μm²/μm)</th>
<th>$K_p$ x $10^{-5}$ (μm²Pa)</th>
<th>$b x 10^{-5}$ (Pa)</th>
<th>$K_p/K_s$ (μm)</th>
<th>$r$ (per cm²)</th>
<th>$nx 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROH-14-4</td>
<td>24.466</td>
<td>0.5529</td>
<td>0.0226</td>
<td>1.045</td>
<td>17.700</td>
<td>0.0635</td>
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<td>ROH-14-7</td>
<td>30.308</td>
<td>0.7837</td>
<td>0.0259</td>
<td>1.052</td>
<td>15.469</td>
<td>0.1348</td>
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<td>ROH-14-8</td>
<td>22.113</td>
<td>0.5643</td>
<td>0.0255</td>
<td>1.051</td>
<td>15.675</td>
<td>0.0933</td>
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<tr>
<td>ROH-14-9</td>
<td>28.582</td>
<td>0.6801</td>
<td>0.0238</td>
<td>1.048</td>
<td>16.810</td>
<td>0.0912</td>
</tr>
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<td>0.3136</td>
<td>0.0217</td>
<td>1.043</td>
<td>18.450</td>
<td>0.0318</td>
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<td>ROH-14-13</td>
<td>19.569</td>
<td>0.3741</td>
<td>0.0191</td>
<td>1.038</td>
<td>20.924</td>
<td>0.026</td>
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<td>1.052</td>
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<td>ROH-14-16</td>
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<td>ROH-14-17</td>
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<td>0.0245</td>
<td>1.049</td>
<td>16.300</td>
<td>0.0568</td>
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<tr>
<td>ROH-14-18</td>
<td>18.066</td>
<td>0.4639</td>
<td>0.0257</td>
<td>1.051</td>
<td>15.577</td>
<td>0.0782</td>
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<td>Average</td>
<td>20.915</td>
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<td>17.432</td>
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<tr>
<td>STD</td>
<td>5.604</td>
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<td>0.006</td>
<td>2.331</td>
<td>0.0348</td>
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<tr>
<td>RAH-10-1</td>
<td>8.8517</td>
<td>0.7994</td>
<td>0.0903</td>
<td>1.181</td>
<td>4.429</td>
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<td>RAH-10-2</td>
<td>8.9794</td>
<td>0.9443</td>
<td>0.1052</td>
<td>1.210</td>
<td>3.804</td>
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<td>RAH-10-3</td>
<td>4.2695</td>
<td>0.4944</td>
<td>0.1158</td>
<td>1.232</td>
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<td>0.0903</td>
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<td>RAH-10-6</td>
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<td>1.232</td>
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<td>RAH-10-7</td>
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<td>0.1104</td>
<td>1.221</td>
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<td>RAH-10-10</td>
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<td>4.093</td>
<td>5.1726</td>
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<td>RAH-10-11</td>
<td>7.8461</td>
<td>0.7468</td>
<td>0.0952</td>
<td>1.190</td>
<td>4.203</td>
<td>6.4088</td>
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<td>RAH-10-12</td>
<td>8.1015</td>
<td>0.7413</td>
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<td>STD</td>
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<td>0.021</td>
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Table 8: Summary of the evaluation based on the Klinkenberg's equation for ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$K_b$ (μm$^3$/μm)</th>
<th>$K_b$ x 10$^{-5}$ (μm$^3$Pa)</th>
<th>$b$ x 10$^{-5}$ (Pa)</th>
<th>$K_{gr}/K_b$ (μm)</th>
<th>$r$ (per cm$^2$)</th>
<th>nx10$^{-6}$</th>
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<td>PPS-6-7</td>
<td>0.6109</td>
<td>0.0452</td>
<td>0.0740</td>
<td>1.148</td>
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<td>PPS-6-8</td>
<td>0.4332</td>
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<td>PPS-6-10</td>
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<td>0.7796</td>
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<td>Average</td>
<td>0.0681</td>
<td>0.2652</td>
<td>1.530</td>
<td>1.552</td>
<td>3.616</td>
<td></td>
</tr>
<tr>
<td>STD</td>
<td>0.0175</td>
<td>0.0488</td>
<td>0.098</td>
<td>0.271</td>
<td>2.270</td>
<td></td>
</tr>
</tbody>
</table>
Figure 30  Regression line of superficial specific permeability, $K_{gs}$ ($\mu m^3/\mu m$), against reciprocal mean pressure, $1/P$ (Pa$^{-1}\times 10^{-5}$), for one typical specimen of red oak heartwood (ROH) measured at 5 lower flow rates and red alder heartwood (RAH) measured at entire range of 5 different flow rates.
Figure 31  Regression line of superficial specific permeability, $K_s$ ($\mu$m$^3$/µm), against reciprocal mean pressure, $1/P$ ($Pa^{-1} \times 10^{-5}$), for one typical specimen of ponderosa pine sapwood (PPS) and Douglas-fir sapwood (DFS) measured at the entire range of 5 different flow rates.
1.53 for red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood, respectively. In other words, the average percentage of slip flow components at one-half atmospheric pressure of mean pressure was 4.7, 20.4, 29.2, and 53 percent for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. This ranking is similar to that found with other woods.

Comstock (1967) reported a ratio \( \frac{K_s}{K_g} \) of 1.6 for eastern hemlock calculated at one atmospheric pressure of mean pressure. Kumar (1979) also plotted the superficial specific permeability against the reciprocal mean pressure for 7 hardwoods and calculated the contribution of slip flow in each species. He found that for two highly permeable species, viz. horse chestnut \((Aesculus indica)\) and udal \((Sterculia villosa)\), with slip free permeability of 11.21 and 17.18 \(\mu m^3/\mu m\) respectively, the calculated slip flow component was only 1.3 and 1.2% respectively. In safed siris \((Albizia procera)\) and toon \((Toona ciliata)\), with fairly high true permeability of 1.56 and 1.99 \(\mu m^3/\mu m\) respectively, the observed slip flow component was 12 and 9.8% respectively. In kaim \((Mitragyna parvifolia)\), kokko \((Albizia lebbek)\) and maharukh \((Ailanthus excelsa)\), with low permeability of 0.021 to 0.31 \(\mu m^3/\mu m\), slip flow component formed quite a significant percentage of the viscous flow (18 to 37%). Perng (1981a) reported that the average percentage of slip flow of the total specific flow rates calculated at one-half atmospheric pressure of mean pressure was 36.5% for spruce wood, 12.91, 15.78, 19.08, and 20.43% for beech, sugar maple, white ash, and yellow birch respectively, whereas it was only 4.8% for red oak.

Bao and Lu (1993) calculated both ratio of superficial specific permeability to true permeability \(\frac{K_s}{K_g}\) and percentage of slip flow component for Chinese spruce and pine. The observed ratio \(\frac{K_s}{K_g}\) and percentage of slip flow contribution were 1.69 and 69% for Chinese
spruce with true permeability of 0.0177 \( \mu m^3/\mu m^2 \), and 1.376 and 37.6% for Chinese pine with true permeability of 0.0423 \( \mu m^3/\mu m^2 \), respectively.

The magnitude of the slip flow effect may be also examined by the slip flow constant \( b \). In the specimen groups studied here, the slip flow constant \( b \) was highest (0.265\( \times 10^5 \)Pa) for Douglas-fir sapwood, higher (0.146\( \times 10^5 \)Pa) for ponderosa pine sapwood, lower (0.102\( \times 10^5 \)Pa) for red alder heartwood, and lowest (0.023\( \times 10^5 \)Pa) for red oak heartwood. The slip flow constant reported here is in close agreement with the results of Perng (1980a) and Bao and Lu (1993) as well. Perng (1980a) reported that the slip flow constant was 0.289\( \times 10^5 \)Pa in red spruce sapwood, which was close to the value of Douglas-fir sapwood in this study, and 0.108\( \times 10^5 \)Pa in yellow birch, which was almost the same as the value of red alder heartwood for this study. Bao and Lu (1993) found that the slip flow constant for Chinese spruce and pine were 0.356\( \times 10^5 \)Pa and 0.197\( \times 10^5 \)Pa, respectively. Perng et al. (1985) reported that the slip flow constant for trembling aspen (\textit{Populus tremloides} Michx.) was highest in the core (0.3\( \times 10^5 \)Pa), lower in the heartwood (0.09\( \times 10^5 \)Pa), and lowest in the sapwood (0.04\( \times 10^5 \)Pa).

The results of this study, together with other reported results discussed above, confirmed that slip flow is dependent on the permeability of wood. The magnitude of the slip flow effect increases with decreasing permeability of the wood, since slip flow is inversely proportional to the radius of the capillary according to Eq.(17). The higher the permeability, the larger the effective opening size of the capillaries in the flow path. At large effective openings, the flow is primarily viscous, whereas with smaller effective openings, slip flow predominates.

The small percentage of slip flow components in red oak heartwood may indicate that the most flow was through the open vessels in the early wood and the rest was through the small
latewood vessels or other small effective openings (Perng 1981b). The fairly high slip components in red alder heartwood indicates that the vessel flow path must be partly obstructed so that the effective openings are reduced (Kumar 1981). This slip flow may be attributed to the presence of scalariform perforation plates with 15 plus thin bars in red alder (Panshin and de Zeeuw 1980). The large component of slip flow observed in softwoods is generally attributed to the pit openings which are in series and connected with tracheids.

One of the main advantages of using a gas as measuring fluid is that the average pore size in wood can be estimated. As discussed previously, the Adzumi’s equation (Eq.(14)) depicting viscous flow and slip flow components, can be rearranged in two ways to permit calculation of the average effective pore radius \( r \) by dividing the viscous term (proportional to \( r^4 \)) by the slip flow term (proportional to \( r^3 \)). In the first method, the equation is rearranged with the specific flow rate \( QLP/\Delta P \) as the dependent variable and the mean pressure \( \bar{P} \) as the independent variable. The radius can then be calculated by dividing the slope of the linear plot of specific flow rate versus mean pressure by the intercept. In the second method, the Adzumi’s equation is rearranged with permeability as the dependent variable and the reciprocal mean pressure as the independent variable. The equation rearranged in this way is actually the Klinkenberg’s equation (Eq.(18)). Thus, the radius can be calculated by dividing the intercept of the linear Klinkenberg’s plot by slope as expressed by Eq.(20). In this study, the second method was employed as the evaluation of average effective openings in wood, and the number of effective openings was calculated as well according to Eq.(7).

The radius as well as the number of the effective openings were calculated from all specimens and given in the Tables 7 and 8. The radius of average effective openings \( r \) and the
number of effective openings per cm² of cross section (n) were 17.432 μm and 0.066x10⁶ per cm²,
3.955 μm and 7.5x10⁶ per cm², 2.972 μm and 3.3x10⁶ per cm², and 1.552 μm and 3.6x10⁶ per
cm² for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir
sapwood, respectively. These values are very close to the ones reported by Perng (1981a,b). He
obtained the values of r and n as 26.127 and 0.253x10⁶, 6.314 and 3.06x10⁶, 3.372 and
14.77x10⁶, 2.373 and 7.11x10⁶, and 2.106 μm and 55.6x10⁶ per cm² for red oak, American beech,
sugar maple, white ash, and yellow birch, respectively. He also calculated the average value of r
and n for three spruce woods as 1.111 μm and 2.115x10⁶ per cm². Since the number of effective
openings was mathematically obtained from the values of the radius of openings and the true
permeability, only the values of r in this study were compared with other previous results as
below.

Sebastian et al. (1965) calculated an mean radius of 1.255μm for white spruce sapwood.
Comstock (1967) found the radius of 0.38-0.76 μm and 0.382-1.36 μm for eastern hemlock
heartwood and sapwood respectively. Petty and Preston (1969) reported radii of 0.74-0.98 for
sapwood and 0.20-0.26 μm for heartwood of sitka spruce (Picea sitchensis (Bong.) Carr.). Bao
et al. (1986) also found a linear relationship between permeability and reciprocal mean pressure
for two Chinese softwoods. They calculated mean values of r of 0.54 μm as a short capillary or
1.15 μm as a long capillary for spruce and 0.96 μm as a short capillary or 2.14 μm as a long
capillary for pine. Wiedenbeck et al. (1990) obtained a mean radius of 1.5 μm for sapwood of
lodgepole pine (Pinus contorta Dougl.). Obviously, the values of r for the two softwoods in this
study are quite reasonable compared with these previous results.

It is generally believed that all of the flow through softwoods is through the tracheids
which are interconnected by bordered pit pairs. The pit openings are much more smaller than the tracheid lumens and are therefore assumed to provide all of the resistance to flow. Therefore, the radius of effective openings calculated from gas flow measurements for softwoods are always referred to as the radius of effective pit openings. Siau (1995) summarized all the previous results on the measurement of pit opening size, and stated that, microscopic measurements and indirect determinations from gas flow and from capillary measurements indicate that softwood pit openings have effective diameters between 0.02 and 8 µm. Furthermore, he pointed out that, the larger values are usually obtained from flow measurements and may indicate the size of the aperture rather than the openings in the margo. It is obvious that, all the values of radius of effective pit openings for different softwoods from previous results cited above, together with the values for ponderosa pine sapwood and Douglas-fir sapwood in this study, are within the range of softwood pit openings given by Siau (1995).

The interpretation of the values of effective openings size in hardwoods is more complicated than softwoods. Petty (1978) found a curvilinear plot of permeability versus reciprocal mean pressure for birch wood with the specimens of 15 to 30 mm in length. The values of the large and small radii were then calculated from Eq.(21). Analysis of two conductances yielded a value of \( r_1 \) of 29.5 µm, and \( r_2 \) of 1.46 µm as a short capillary or 2.54 µm as a long capillary. The large value \( (r_1) \) was interpreted as the vessel lumina and the small one \( (r_2) \) as the opening between the scalariform perforation plates. In a later study Petty (1981) made similar measurements on the wood of sycamore. In this case, the calculated large values for vessel radius were 29.2 µm for solvent dried wood and 22.3 µm for air dried wood. The radius of small component, calculated for long and short capillaries, respectively, was 0.21 µm and 0.094 µm for
solvent dried wood and 0.16 μm and 0.073 μm for air dried wood. This small radius was assumed to be the pores of the intervessel pits.

Siau et al. (1981) also observed a curvilinear relationship between permeability and reciprocal mean pressure for basswood and sugar maple. The calculated large radii were 32.9, 64.7μm and the small radii (calculated as the short capillaries) were 0.17, 0.34μm for basswood and sugar maple, respectively. They interpreted the large radii as the vessels, and the small radii as the intervessel pits. As discussed earlier, Bao et al. (1986) reported linear plots of permeability versus the reciprocal mean pressure for Chinese spruce and pine, but the plot of permeability versus the reciprocal mean pressure for Chinese birch was curvilinear. The large radius was calculated as 59.8μm. The small radius was estimated as 2.01μm as a short capillary or 4.4μm as a long capillary. They explained the presence of high and low conductances in series in birch, as the result of the vessels and the openings in the scalariform perforation plates between them. However, Perng (1981b) did not explain the values of r calculated for several hardwoods. He considered this theoretical circular shaped effective openings as the average radius of several structure components such as the perforation plates, tyloses, other deposits, fibres and parenchyma cells.

In this study, the radius of effective openings in red oak heartwood (17.432μm) could be assumed to represent the vessel lumina since it has simple perforation plates, and a 3.955μm value for the effective openings in red alder heartwood could be expected for the openings between the scalariform perforation plates.

It should be pointed out that the Adzumi’s equation or Klinkenberg’s equation, which make it possible to evaluate the size and the number of effective openings in wood from gas flow
measurement, is based on the uniform-circular-parallel-capillary model, a rather idealized concept of the actual structure of wood. In reality, the pit openings in softwoods and the perforation plates in hardwoods are short, multishaped and tortuous, which does not fit the model requirements. It would be unrealistic, therefore, to assume much in the way of real agreement between the sizes estimated on the basis of the model and the actual physical dimensions of the openings in wood. It would seem realistic, however, to assume that for a given species, the relative sizes and number of openings could be estimated with reasonable order of magnitude from gas flow data.

It should also be pointed out that some researchers (Petty 1981, Siau et al. 1981, Bao et al. 1986) considered the pit openings in softwoods and perforation plates in hardwoods as the short capillaries, and then made the overall correction which include both the Couette correction and the Clausing factor (Siau 1995) for the values of r calculated from gas flow measurements. However, in this study, such kind of correction for the short capillaries was not carried out, since as discussed above, the calculation of effective openings provides only an estimate of order of magnitude rather than precise answers of its physical dimensions because of the discrepancies between the wood structure and the model on which the flow equations are based.

From the information obtained in this section, the following conclusions may be drawn:

1. Non-Darcian flow due to slip flow seems common in both softwoods and hardwoods. Both permeability measurement and pressure-flow rate-relationship methods for the detection of slip flow in wood indicate that the slip air flow exists in all the studied specimen groups.

2. The true permeability of red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood was 20.91, 7.05, 0.51 and 0.068 μm³/μm, respectively.
The average ratio of the superficial specific permeability at 0.5x10^5 Pa mean pressure to the true permeability was 1.047, 1.204, 1.292, and 1.53 for red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood, respectively. The slip flow constant b was highest (0.265x10^5 Pa) for Douglas-fir sapwood, higher (0.146x10^5 Pa) for ponderosa pine sapwood, lower (0.102x10^5 Pa) for red alder heartwood, and lowest (0.023x10^5 Pa) for red oak heartwood.

3. The slip flow in wood is dependent on the permeability of wood. The magnitude of slip flow increases with decreasing permeability of the wood.

4. The radius of average effective openings (r) and the number of effective openings per cm^2 of cross section (n), were 17.432 μm and 0.066x10^6 per cm^2, 3.955 μm and 7.5x10^6 per cm^2, 2.972 μm and 3.3x10^6 per cm^2, and 1.552 μm and 3.6x10^6 per cm^2 for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively.

5. The radius of effective openings obtained for two softwoods could be referred to as the radius of effective pit openings. The radius of effective openings calculated for red oak heartwood could be assumed to represent the vessel lumina, and the value of radius of effective openings calculated for red alder heartwood could be interpreted for the openings between the scalariform perforation plates.

4.4 Separation of the nonlinear laminar from turbulent flow

As described in Section 2.3, it is generally expected that true turbulent flow is unlikely in any of the capillaries in most wood species because the critical Reynolds’ number (around 2,300)
for transition from laminar to turbulent flow is much higher than that which can be achieved in most woods. However, the nonlinear laminar flow due to kinetic-energy losses at a low Reynolds’ number could occur in wood. Since in the case of nonlinear laminar flow, the pressure drop is proportional to the square of flow rate, which is approximately the case also in turbulent flow, it is difficult to distinguish the nonlinear laminar flow from turbulent flow by measuring the relationship between the pressure drop and the flow rate. In order to make the two distinguishable, the Reynolds’ number has to be calculated. In this study, the existence of nonlinear flow in the red oak heartwood at the flow rates higher than 19.57 cm$^3$/s has already been shown. By considering the highest flow rate value ($Q_{\text{max}} = 44.52$ cm$^3$/s) used for this specimen group, and the radius and the number of effective opening obtained by analysing the Klinkenberg’s plot as described above, the Reynolds’ number of one capillary can be evaluated based on Eq. (9) with $Q = Q_{\text{max}}/nA$ replacing $Q$ in Eq. (9). This way, the calculated Reynolds’ number for the ten specimens of red oak heartwood, ranged from 0.263 to 1.05 with an average of 0.61. This could be considered as a good agreement with the results reported by other researchers (Collins 1961, Scheidegger 1975, Siau and Petty 1979, Kuroda and Siau 1988, Siau 1995).

Collins (1961) states that in curved tubes and other porous media where the flow paths are tortuous, the transition from laminar to nonlinear flow is gradual and may occur between Reynolds’ number 1 to 10. Scheidegger (1974) cited several references in which nonlinear flow had been observed at Reynolds’ numbers between 0.1 and 75 in various nonhomogeneous porous materials. Siau and Petty (1979) suggested that nonlinear flow may occur in wood at Reynolds’ number in the region of 0.1 to 10 according to the results obtained for air flow through short, straight circular capillaries. Kuroda and Siau (1988) reported the evidence of nonlinear flow in
three softwoods with corresponding Reynolds’ numbers between 0.41 and 1.62. Furthermore, Siau (1995) states that the onset of nonlinear flow in wood can occur at Reynolds’ numbers between 1 and 16 based on the size of pit openings and the assumption where fluids enter pit openings.

It is apparent from the above results cited from other researchers that the critical Reynolds' number above which nonlinear flow is believed to occur, is much lower for porous media where the curved and short flow paths are included, than for long, straight tubes (where it is around 2,300). The only conclusion that can be drawn is that this nonlinear flow is not turbulent flow at all, but an expression of nonlinear laminar flow, and that the breakdown of Darcy's law at high flow rates is thus primarily due to the emergence of inertial effects in laminar flow (Scheidegger 1974). Furthermore, from these results it must be expected that there is no such thing as a "universal" Reynolds' number in porous media at which nonlinear laminar flow would set in, since the critical Reynolds' number for the emergence of nonlinear laminar flow due to kinetic-energy losses in curved or short capillaries, is very much affected by the curvature of the capillaries.

On the basis of the results reported previously and obtained in this study, it may be concluded that the nonlinear flow found in red oak heartwood at higher flow rates here is probably nonlinear laminar flow due to the kinetic-energy losses occurred in the curved openings.
5.0 Summary and Conclusions

The purpose of this thesis research was to better understand the mechanisms of gas flow in wood, and especially the phenomenon of non-Darcian air flow. Specifically, the objectives were to evaluate the non-Darcian air flow due to (1) specimen length; (2) nonlinear flow; (3) slip flow in wood, through a systematic investigation of the air flow phenomena in two softwoods and two hardwoods. Throughout the thesis, the hypothesis that Darcy’s law is not of universal application to gas flow in wood was shown to be true.

Other general conclusions drawn from the thesis research are summarized below:

1. Non-Darcian behaviour due to specimen length seems common in the studied species. In the experimental range of specimen lengths, there is an existence of a certain length above which the permeability values are nearly identical for the various lengths of the tested species. These specimen lengths were found to be 140, 100, 60 and 40 mm for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. This indicates that an approximately uniformity of wood structure can be obtained for these species by the use of the respective specimen lengths mentioned above. When the specimen length is below a critical value for the different species described above, permeability increases drastically with decreasing specimen length. The higher the air permeability of a species, the greater is the specimen length above which permeability values remain almost constant for various specimen lengths. When the specimen length is above a critical value for the different species described above, the pressure drop caused by end effects due to the shape and condition of the specimen entrance is negligible.

2. Both permeability measurement and pressure-flow rate-relationship methods for the detection of nonlinear air flow in wood resulted in the same results. For red alder heartwood,
ponderosa pine and Douglas-fir sapwood, throughout the entire measured range of respective flow rates, the superficial specific permeability at the mean pressure of $0.5 \times 10^5$ Pa is independent of the flow rates, and Adzumi's equation is a valid description of the pressure drop-flow rate relation at a given mean pressure of $0.5 \times 10^5$ Pa, thus indicate the existence of linear flow components only within the specimen for these specimen groups. For red oak heartwood, when the lower flow rates are used ($Q < 19.57 \text{ cm}^3/\text{s}$), the test results for the detection of nonlinear air flow are exactly the same as the specimen groups just mentioned above. However, for the case where the flow rates used are above $19.57 \text{ cm}^3/\text{s}$, the superficial specific permeability at the mean pressure of $0.5 \times 10^5$ Pa decreases with the increase of the flow rates, and the expression equation of pressure drop and flow rate at a given mean pressure of $0.5 \times 10^5$ Pa involves both a linear and quadratic dependence of the pressure drop on the flow rate, thus demonstrating the presence of the nonlinear flow components in the specimen. The calculated value of Reynolds' number in the range of 0.263 to 1.05 further suggests that the nonlinear flow found in the red oak heartwood at higher flow rates in this study is probably nonlinear laminar flow due to the kinetic-energy losses occurred in the curved openings.

3. Both permeability measurement and pressure-flow rate-relationship methods for the detection of slip flow in wood indicate that the slip air flow exists in all the studied specimen groups. Further evaluation based on the viscous-slip flow model yielded the following useful information. The true permeability of red oak heartwood, red alder heartwood, ponderosa pine sapwood and Douglas-fir sapwood was 20.91, 7.05, 0.51 and 0.068 $\mu\text{m}^3/\mu\text{m}$, respectively. The average ratio of the superficial specific permeability at $0.5 \times 10^5$ Pa mean pressure to the true permeability was 1.047, 1.204, 1.292, and 1.53 for red oak heartwood, red alder heartwood,
ponderosa pine sapwood and Douglas-fir sapwood, respectively. The slip flow constant b was highest (0.265×10^5 Pa) for Douglas-fir sapwood, higher (0.146×10^5 Pa) for ponderosa pine sapwood, lower (0.102×10^5 Pa) for red alder heartwood, and lowest (0.023×10^5 Pa) for red oak heartwood. These values reported above confirm that slip flow is dependent on the permeability of wood, and its magnitude increases with decreasing permeability of the wood. The radius of average effective openings (r) and the number of effective openings per cm^2 of cross section (n), which were calculated from Klinkenberg's equation, were 17.432 μm and 0.066×10^6 per cm^2, 3.955 μm and 7.5×10^6 per cm^2, 2.972 μm and 3.3×10^6 per cm^2, and 1.552 μm and 3.6×10^6 per cm^2 for red oak heartwood, red alder heartwood, ponderosa pine sapwood, and Douglas-fir sapwood, respectively. The radius of effective openings obtained for two softwoods could be referred to as the radius of effective pit openings. The radius of effective openings calculated for red oak heartwood could be assumed to represent the vessel lumina, and the value of radius of effective openings calculated for red alder heartwood could be interpreted for the openings between the scalariform perforation plates.
6.0 Recommendations

The equipment used in this investigation was designed to study gas flow in wood under a vacuum system. This restriction provided for a limited range of pressure drops and flow rates for investigating the gas flow behaviour in wood. In order to obtain a higher pressure drop across the specimen and then a wider range of flow rates in wood, especially for a low permeability species, a high pressure system flow measurement should be used.

More investigations should be carried out for red oak heartwood in the nonlinear laminar flow region. In this study, only three flow rates were available to analyse the relationship between the pressure drop to flow rate ratio and the flow rate. Further study should include more experimental points taken within this nonlinear laminar flow region, and therefore, a solid regression equation in which both a linear and a quadratic dependence of the pressure drop on the flow rate are involved, could be experimentally developed.

Since the flow measurement with a gas can provide an estimate of order of magnitude for some anatomical structures in wood, it would be better to combine an microscopic study to relate the information regarding the anatomical structures from gas flow measurements to the actual anatomical structure of the wood.
Literature Cited


Kozak, A. 1966. Multiple correlation coefficient tables up to 100 independent variables. Research Notes, No. 57. Faculty of Forestry, University of British Columbia.


Symbols and Abbreviations

A  cross-sectional area of the specimen
A_e  effective conducting area of the specimen
b  slip flow constant
d  positive exponential coefficient
DFS  Douglas-fir sapwood
e  slope of high conductance in Petty's model
E  intercept of high conductance in Petty's model
f  slope of low conductance in Petty's model
F  intercept of low conductance in Petty's model
K  specific permeability
K_g  specific permeability for gas in the absence of slip flow or true permeability
K_sp  superficial specific permeability for gas
K_l  specific permeability for liquid
L  specimen length in the flow direction
L'  corrected length for the short capillary
m  coefficient for kinetic-energy and end-effect losses
m_k  coefficient for kinetic-energy losses
m_e  coefficient for and end-effect losses
M_w  molecular weight
n  number of openings or capillaries per unit cross-sectional area
N  number of openings or capillaries in parallel
P  pressure at which the flow rate is measured

\( P_{atm} \)  atmospheric pressure

\( P_1 \)  downstream pressure

\( P_2 \)  upstream pressure

\( \bar{P} \)  arithmetic average of \( P_2 \) and \( P_1 \)

\( \Delta P \)  pressure drop across the specimen

\( \Delta P_1 \)  closed manometer reading on the vacuum side

\( \Delta P_2 \)  open manometer reading on the air side

\( \Delta P_e \)  pressure drop due to end effects

\( \Delta P_f \)  pressure drop caused by friction

\( \Delta P_k \)  pressure drop caused by kinetic-energy losses

PPS  ponderosa pine sapwood

\( Q \)  volumetric flow rate

\( \bar{Q} \)  volumetric flow rate at \( \bar{P} \)

r  radius of openings or capillaries

R  universal gas constant

RAH  red alder heartwood

\( R_e \)  Reynolds’ number

\( R_e' \)  critical Reynolds’ number of turbulence

\( R_e'' \)  critical Reynolds’ number of nonlinear laminar flow

ROH  red oak heartwood

s  slip-flow factor

125
STD  standard deviation

T  temperature in Kelvin

v  average flow velocity

V  available void volume

w  fraction of all conducting tracheids at a depth of 1 cm

**Greek Letters**

\(\lambda\)  mean free path

\(\mu\)  viscosity of the fluid

\(\rho\)  density of the fluid

\(\Phi\)  porosity or void area of the specimen’s cross section

\(\phi\)  Adzumi constant