PERMEABILITY AND CAPILLARY STRUCTURE OF CHINESE WOODS

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ABSTRACT

Axial permeability measurements of Chinese spruce, pine, and birch were made over a range of average pressure from 1.6 to 54 cm Hg. Linear plots of permeability vs. reciprocal mean pressure were obtained for spruce and pine in agreement with the Klinkenberg equation. Pit-opening radii were calculated from the intercepts and slopes, and the number of openings per cm^2 of cross section were determined based on an assumed pit-membrane thickness of 0.1 μm. The plot of permeability vs. reciprocal mean pressure of the birch was curvilinear, indicating the presence of two conductances in series, which were assumed to be vessels and perforation plates. The calculated vessel radius and vessel concentration were in good agreement with data presented by Cheng (1980).

Keywords: Permeability, capillary structure, Chinese woods, pine, birch, spruce.

INTRODUCTION

Permeability is important in many wood-utilization processes in which fluids are introduced or removed such as pulping, wood-preservation treatments, impregnation with monomers in the production of wood-polymer composites, and drying. The permeability of wood depends on the interconnection of the tracheid or vessel lumens by pit membranes or perforation plates. Permeability may be very low if the pit membranes are encrusted or occluded, if the pits are aspirated, or if the vessels of a hardwood are plugged with tyloses.

The size of pit-membrane openings has been measured with the electron microscope by Côté and Krahmer (1962), Côté et al. (1964), and Thomas and Nicholas (1966). It has also been measured from electro-osmotic flow data by Stamm (1932), from the bubble point by Stamm (1935), Stamm and Wagner (1961), Yao and Stamm (1967), and Siau et al. (1981), from the filtration of aqueous suspension of particles of known size by Liese (1965), and Megraw (1967), and from measurements of gas permeability using the Adzumi equation by Sebastian et al. (1965), Comstock (1967), and Siau et al. (1981). Petty and Preston (1969) and Petty (1970) have observed a curvilinear relationship between permeability and reciprocal mean pressure rather than a linear relationship as predicted by the Adzumi or Klinkenberg equations. This was attributed to the effect of two conductances in series, which may be assumed to represent the tracheids and pit openings of a softwood or the vessel lumens and perforation plates or intervessel pits of a hardwood. The results so obtained may be used to calculate

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radii and the number of conductive openings as explained by Siau et al. (1981) and Siau (1984).

The purpose of this research was to use permeability measurements to calculate anatomical dimensions of the woods of spruce (*Picea jezoensis*), pine (*Pinus koraensis*), and birch (*Betula platyphilla*), which were grown in the People's Republic of China.

PROCEDURE

Logs of 30 cm diameter of the three species were cut approximately 1.3 m above the ground. Ten rectangular specimens of heartwood 2 cm × 2 cm × 10 cm and two cylindrical specimens 5 cm in diameter and 1.2 to 2.8 cm long were prepared from each species, with the latter dimensions in the axial direction. The cylindrical specimens were side-coated with silicone rubber sealant (G. E. RTV-112) and were vacuum-dried at 50 C to constant weight. The permeabilities of the rectangular specimens were measured by three methods: (1) the rising-water method (Siau 1969, 1971), (2) the falling-water method, and (3) the rotameter method (Siau 1971). The former two methods measure air flow by water displacement and the latter by means of a calibrated rotameter. Measurements were made at an average pressure of approximately 0.5 atm in methods (1) and (3) because the upstream end of the specimen was at one atm, while the downstream end was connected to a vacuum pump. In the falling-water method (2), the pressure differential was obtained from the water column, which was less than 100 cm long. Therefore the downstream pressure was slightly less than one atm, resulting in an average pressure of approximately one atm. Since the permeabilities determined by the falling-water method were measured at a higher average pressure, lower permeability values would be expected because of a smaller fraction of Knudsen or molecular slip flow.

The permeabilities of the cylindrical coated specimens were measured, using an apparatus designed by Petty and Preston (1969) and described by Siau (1984). Relatively small pressure differentials from 0.036 to 7.6 cm Hg were used with the lower values measured using an oil manometer and the larger with a mercury manometer. Reciprocal mean pressures were in the range of 1.4 to 48 atm^{-1}, corresponding to average pressures from 54 cm Hg down to 1.6 cm Hg.

THEORY

When both viscous and Knudsen flow are present within a minute capillary, a linear relationship exists between permeability and reciprocal mean pressure, which is characterized by the Klinkenberg equation as:

$$K_g = K + Kb/\bar{p} \tag{1}$$

where K_g = specific gas permeability, K = specific permeability at $1/\bar{p}$ = zero, Kb = slope of the plot of K_g vs. $1/\bar{p}$, where $\bar{p}$ = mean pressure.

Frequently woods of low permeability obey Eq. (1) because nearly all of the resistance to flow is due to the pit openings. The intercept K represents the viscous component of the flow, which is proportional to the fourth power of the capillary radius (r^4). The second term, $Kb/\bar{p}$, represents Knudsen diffusion and is proportional to r^3. Therefore the capillary radius may be calculated by dividing the former by the latter. When the constants are evaluated based on air permeability at 20 C, the radius may be calculated as

$$r = 0.40 \times 10^{-4} \text{ atm cm (intercept/slope)}$$

where r is expressed in cm and the pressure in atm.

Petty (1970) has found a curvilinear relationship between permeability and reciprocal mean pressure for many woods, particularly those of higher permeability. This was attributed to two conductances 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 equation resulting in the relationship:

$$K_g = \frac{(A + l/\bar{p})(B + m/\bar{p})}{(l + m)/\bar{p} + A + B} \tag{2}$$

where A and B are the two intercepts and l and m the corresponding slopes of the Klinkenberg plots representing the two conductances.

If A and l are assigned to the larger radius, representing the tracheid or vessel lumen, this radius may be calculated as

$$r_l = 0.40 \times 10^{-4} \text{ atm cm } (A/l) \tag{3}$$

where r_l = larger radius, cm.

The uncorrected small radius (r_2) corresponding to the pit openings or perforation plates may then be calculated as

$$r_2 \text{ (uncorrected)} = 0.40 \times 10^{-4} \text{ atm cm (B/m)} \tag{4}$$

Two corrections must be applied to r_2: (1) the Couette correction to the viscous term to account for end resistance and (2) the Clausing factor for reduced Knudsen diffusion in a short capillary. These may be combined in the following overall correction factor (Siau 1984):

$$\frac{L/r + 1.2}{1.33L/r + 2.67} \tag{5}$$

where L/r = ratio of length to radius of the capillary when L/r is less than 1.5.

The number of conductive pit openings per unit area may be calculated from B by converting this value to the equivalent permeability by a multiplying factor equal to the thickness of the pit membrane divided by the length of the path through the tracheid lumen. The Comstock model for softwoods is assumed (Siau 1984). The parallel-uniform-capillary model results in the following equation, which was solved for n_p, the number of conductive pit openings per cm^2 of cross-sectional area.

$$K_{Lp} = \frac{BL_p}{L_t(1 - \alpha)} = \frac{n_p \pi r_2^4}{8} \tag{6}$$

where K_{Lp} = true intercept specific permeability of the pit openings, cm^2 (1 cm^2 = 1.013×10^8 darcy for air), B = intercept conductance, cm^2, L_p = thickness of pit

TABLE 1. *Average axial permeabilities and coefficients of variation (CV) of groups of 10 each of rectangular specimens of spruce, pine, and birch, measured by three methods. In all cases, the permeabilities measured by the falling-water method were lower than those by the rising-water and rotameter methods because the latter were measured at a lower average pressure. A statistical "t" test indicated that the results of the rising-water and rotameter methods were not significantly different but that both these were significantly higher than the results of the falling-water method for the spruce and pine specimens. Permeabilities are expressed in darcys.*

		Method		
Species		Rising water	Falling water	Rotameter
Spruce	Average perm.	0.043	0.019	0.045
	CV	0.26	0.19	0.18
Pine	Average perm.	0.12	0.059	0.12
	CV	0.14	0.074	0.064
Birch	Average perm.	18.1	16.7	16.9
	CV	0.20	0.49	0.19

membrane, L_t = length of tracheid, α = fraction of overlap of tracheids assumed equal to 0.3.

The length of the tracheids was assumed to be 3,770 μm for spruce and 3,060 μm for pine (Cheng 1980). L_p was assumed to be 0.1 μm (Petty 1970).

The number of conductive tracheids or vessels per cm^2 of cross-sectional area (n_{tc}) may be calculated directly from A, which is assumed equal to the permeability because the length of the flow path through the pit membranes is negligible compared with that through the lumens.

$$A = \frac{n_{tc}\pi r_1^4}{8}$$

where A is expressed in cm^2.

RESULTS

The average permeabilities and coefficients of variation of the rectangular specimens of the three species are presented in Table 1. The lower values obtained for the spruce and pine by the falling-water method were attributed to the higher average pressure in accordance with Eq. (1). Statistical calculations based on the "t" test indicated that these differences were significant. However, the results for birch were statistically the same by all three methods although, as expected, the average for the falling-water method was the lowest. This greater uniformity of the birch may be explained by the large vessel diameter and the resulting low initial slope of the plot of permeability vs. $1/\bar{p}$. From Fig. 2 it is clear that there is a relatively smaller decrease in the permeability of birch between average pressures of 0.5 atm and 1.0 atm.

The permeabilities of the cylindrical specimens of spruce and pine measured with the Petty apparatus are illustrated in Fig. 1. The data were first analyzed in accordance with Eq. (2) as two series conductances by means of a gradient-search program (Zellnick et al. 1962). The values of A obtained for both woods exceeded B by factors greater than 2,000. Therefore the effect of B and *l* on the slope of the plot was negligible, and it was concluded that both these plots obeyed the linear

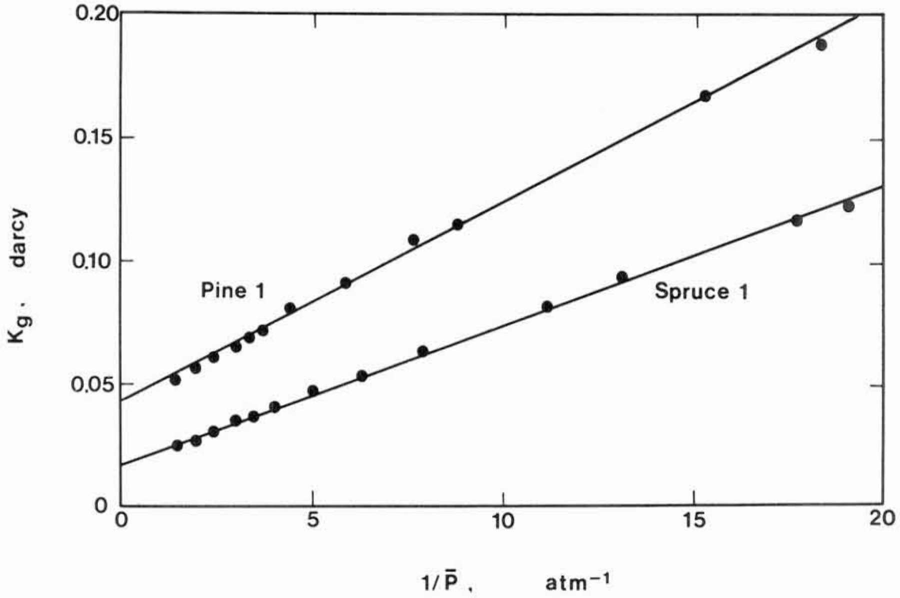

FIG. 1. Specific axial gas permeability, darcy, vs. reciprocal mean pressure, atm^{-1}, for specimens spruce 1 and pine 1. For spruce 1 the intercept permeability was 0.017 darcy and the slope, 0.0055 darcy atm; for pine 1 the intercept permeability was 0.042 darcy and the slope, 0.0080 darcy atm.

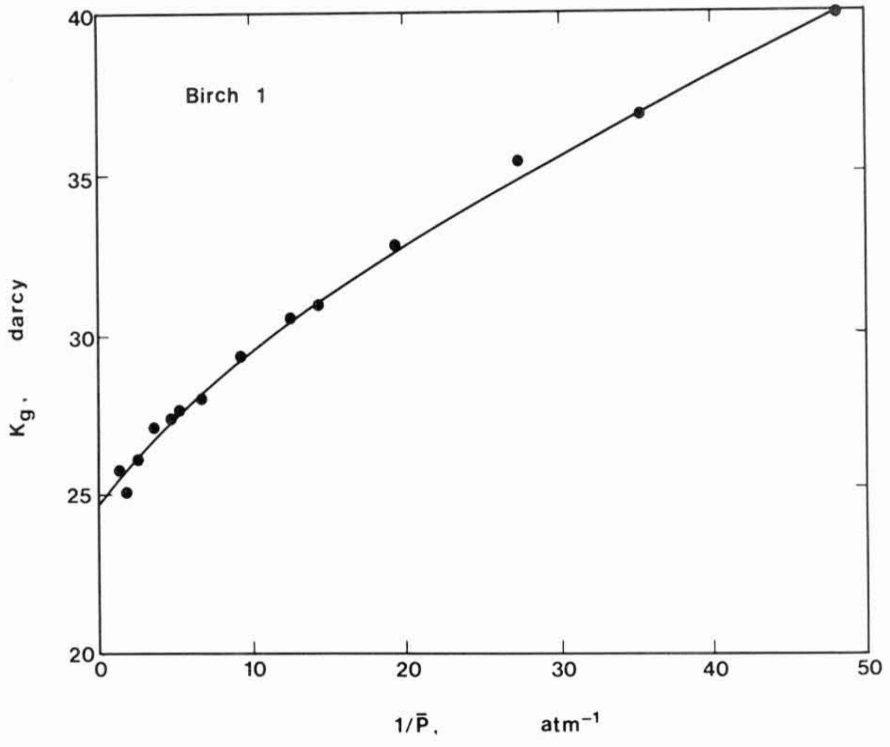

FIG. 2. Specific axial gas permeability, darcy, vs. reciprocal mean pressure, atm^{-1}, for the specimen birch 1. The intercept permeability was 24.6 darcy. The intercept conductances and slopes were: A = 32.7 darcy, l = 0.219 darcy atm, B = 100.0 darcy, and m = 9.15 darcy atm.

TABLE 2. *Dimensions of anatomical features of Chinese woods based on permeability measurements and on data presented by Cheng (1980). Linear dimensions in μm.*

Species	Spruce		Pine		Birch
Tracheid or vessel radius (r_1) (Cheng 1980)	16.25		17.5		57.5
Tracheids/cm^2 = ¼$r_1{}^2$	94,700		81,600		
Vessels/cm$_2$ (Cheng 1980)					800–1,100
Specimen no.	1	2	1	2	1
Vessel radius (r_1) (Eq. 3)					59.8
r_2 (Eqs. 4, 5)	0.61	0.48	0.95	0.98	2.01
Pit openings/cm^2 (n_p) (Eq. 6)	1,218	3,105	605	533	
Vessels/cm^2 (Eq. 7)					645
Intercept permeability (K_g), darcy	0.017	0.018	0.042	0.043	24.6
A, darcy					32.7
l, darcy atm					0.219
B, darcy	0.017	0.018	0.042	0.043	100.0
m, darcy atm	0.0055	0.0068	0.0080	0.0079	9.15

Klinkenberg equation (Eq. 1), and they were analyzed on this basis. Thus it was only possible to calculate r_2 and n_p for spruce and pine and these are given in Table 2. The values of r_2 were 0.61 and 0.95 μm for spruce 1 and pine 1 (Eqs. 4 and 5). The number of conductive pit openings per cm^2 of cross section (n_p) was calculated from Eq. (6), yielding values of 1,218/cm^2 for spruce 1 and 605/cm^2 for pine 1. The number of tracheids per cm^2 was calculated as ¼ $r_1{}^2$ using values of r_1 of 1.63×10^{-3} cm for spruce and 1.75×10^{-3} cm for pine (Cheng 1980). This yielded 94,700/cm^2 for spruce and 81,600/cm^2 for pine.

The calculated values of n_p of 1,218/cm^2 and 605/cm^2 were relatively small because of the large pit openings (0.61 and 0.95 μm) and the low permeabilities (Eq. 6). The large calculated radii may be attributed to the r^4 dependency on the permeability, which accentuates the effect of a relatively small number of openings at the upper end of the distribution of radii. The calculation is based on the uniform-parallel-circular-capillary model while pit membranes contain a wide distribution of sizes. Therefore, in reality, the true number of pit openings could be much larger than n_p.

Sebastian et al. (1965) conducted a similar study with white spruce wood (*Picea glauca*) sapwood and heartwood. They also found a linear relationship between permeability and reciprocal mean pressure (or specific flow rate vs. mean pressure) in accordance with the Adzumi equation. They calculated mean values of r_2 of 1.25 μm for sapwood and 2.3 μm for heartwood. These compare with our uncorrected values of 1.29 μm and 1.01 μm for spruce 1 and 2. They attributed the higher radii in heartwood and longer specimens to the chanelling of flow into a relatively small number of larger openings. Measurements by Sebastian et al. (1965) with the TEM yielded values for sapwood that were one-half and for heartwood, one-fourth, the calculated values. Values of n_p calculated from these results varied from a maximum of 62,000/cm^2 for sapwood down to 1.8/cm^2 for heartwood, giving values both higher and lower than those measured for spruce and pine in this investigation. Petty and Preston (1969), on the other hand, measured pit-opening radii of 0.74 to 0.98 for sapwood and 0.20 μm to 0.26 μm for heartwood of Sitka spruce (*Picea sitchensis*).

Reference to Fig. 2 indicates that the plot of permeability vs. $1/\bar{p}$ for birch is curvilinear, and therefore the analysis was based on Eq. (2). The values of A and l were used to calculate an r_1 of 59.8 μm, which was assumed to represent the vessel radius. This is in reasonable agreement with 57.5 μm given by Cheng (1980). The number of conductive vessels per cm^2 from Eq. (7) (n_t) is 645/cm^2 compared with 800 to 1,100/cm^2 given by Cheng (1980). The value of r_2 calculated from B and m from Eq. (4) is 2.01 μm, which was interpreted as the size of the opening in the scalariform perforation plates between the vessel elements.

Petty (1978) measured the axial permeability of the wood of birch (*Betula pubescens*) and also found a curvilinear relationship between permeability and reciprocal pressure. The length of the specimens was 1.5 to 3 cm which was less than the length of the vessels. Analysis of two conductances yielded a value of r_1 of 29.5 μm, which was in exact agreement with their microscopically measured value. The calculated concentration of vessels on the cross section was 5,700/cm^2 which was less than their measured value of 7,330/cm^2. The small radius (r_2) was calculated as 1.46 μm as a short capillary or 2.54 μm as a long capillary. This was interpreted as the opening between the scalariform perforation plates. In a later study Petty (1981) made similar measurements on the wood of *Acer pseudoplatinus* but with a length exceeding that of the vessels (20 cm). In this case, a vessel radius of 22.3 μm was calculated for air-dried wood compared with a measured value of 21.3 μm. The concentration of vessels on the cross section was 3,790/cm^2 compared with a measured value of 8,100/cm^2. The calculated small radius (r_2) was 0.090 μm, which was assumed to be the pores of the intervessel pits. It is interesting to note that the calculated vessel concentration was lower than that based on microscopic measurements in all these investigations.

The measurement of gas permeability over a wide range of pressures provides an effective tool for the determination of capillary dimensions in wood, particularly when a curvilinear relationship between permeability and reciprocal pressure is obtained. Such investigations are valuable in elucidation of the relationship between anatomical structure and flow properties.

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