DIRECTIONAL PERMEABILITY OF SOFTWOODS[1]

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ABSTRACT

It is well known that the permeability of wood varies markedly in the three structural directions, but a satisfactory explanation for the magnitude of variation has not been offered. Based on available gas permeability data, the ratio of longitudinal to tangential permeability varies from 520 to 81,600, and the longitudinal to radial ratio varies from 15 to 547,000. Two hypothetical models of wood structure were analyzed to determine their usefulness in explaining the difference between longitudinal and tangential permeability. The closest approximation to published data was found by assuming that wood cells have tapered ends that overlap on the radial surfaces and that contain pits only on these tapered ends. For a fiber length to width ratio of 100, the model predicts permeability ratios of 10,000 and 22,500 for fiber overlaps of one-half and one-fourth of a fiber length.

Wood is a highly anisotropic material, and permeability probably varies more with structural direction than any other property. Ratios of longitudinal to transverse permeability as high as 10^6 have been observed in some species. This large anisotropy in fluid permeability must be due to the structural shape and arrangement of the wood cells, and probably relates also to cell function in the living tree. Because longitudinal tracheids function as vertical conduits for sap, they are naturally quite permeable in the direction in which fluids must flow. Because of the manner in which tracheids overlap and the location of the intertracheid openings on the radial walls, fluids can flow tangentially through the same openings that permit longitudinal flow. This suggests that longitudinal and tangential permeability should be closely related. Rays perform the specialized function of translocating water and food between the cambium and the inner sapwood. Their requirements are only remotely related to the requirements placed on longitudinal tracheids. Because of this, there is little reason to expect a close relationship between longitudinal and radial permeability.

This report presents the results of analyses of hypothetical models of wood structure with the objective of explaining the magnitude of the difference between longitudinal and tangential permeability.

DATA AND ASSUMPTIONS

Although results of many studies of the permeability of wood have been reported, most of them do not contain quantitative data on permeability in the different structural directions. Some early studies (Erickson et al. 1938 and Sutherland et al. 1934) were made using water and other liquids, but the data generated are not reliable indicators of the true permeability values because of the problems of falling rate of flow with time and the dependence of the apparent permeability on pressure. These problems do not occur in gas permeability measurements. Therefore, available gas permeability values for dry wood are considered to be more reliable indicators for determining the relationships between longitudinal and transverse permeabilities. Since Comstock (1967) has shown that permeability values measured with gases and liquids are closely related, the relationships can be considered generally applicable.

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TABLE 1. *Gas permeability of several softwood species in the three structural directions*

Species	Moisture content	Source of data	Permeability: Longi-tudinal	Permeability: Tangen-tial	Permeability: Radial	Permeability ratios: Longi-tudinal/tangen-tial	Permeability ratios: Longi-tudinal/radial	Permeability ratios: Tangen-tial/radial
	%		*Darcys*	*Darcys* $\times 10^4$	*Darcys* $\times 10^4$			
Pine (sapwood)	9	Osnach	30.2	3.7	21.0	81,600	14,400	0.176
Pine (heartwood)	9	Osnach	1.88	0.79	3.6	23,800	5,200	0.219
Corsican pine (heartwood)	–	Smith	1.53	12.7	256.	1,200	60	0.049
Southern pine (sapwood)	14	Choong	2.15	3.	113.	7,200	190	0.027
Southern pine (heartwood)	14	Choong	0.039	<0.5	26.	>780	15	<0.019
Fir (sapwood)	9	Osnach	0.90	0.13	0.8	69,200	11,200	0.163
Fir (heartwood)	9	Osnach	0.045	0.017	0.153	26,500	2,900	0.111
Douglas-fir (heartwood)	–	Smith	0.018	0.015	0.00055	12,000	327,000	27.3
Spruce (sapwood)	9	Osnach	0.58	0.079	0.76	73,400	7,600	0.104
Spruce (heartwood)	9	Osnach	0.003	0.0012	0.013	25,000	2.300	0.092
Sitka spruce (heartwood)	–	Smith	0.082	0.037	0.0015	22,200	547,000	24.7
Redwood (sapwood)	14	Choong	14.2	125.	4.	1,100	35,500	31.3
Redwood (heartwood)	1	Resch	4.8	0.64	<0.25	75,000	>192,000	>2.56
Redwood (heartwood) (extracted)	1	Resch	11.2	4.6	6.35	24,300	17,600	0.725
Redwood (heartwood)	14	Choong	5.45	6.	4.	9,100	13,600	1.5
Eastern red cedar (sapwood)	14	Choong	1.65	20.	2.	820	8.250	10.0
Eastern red cedar (heartwood)	14	Choong	1.05	20.	14.	520	750	1.43

Table 1 contains data from several investigations on the gas permeability of several coniferous species in the longitudinal, tangential, and radial directions. These data show the wide range of permeability observed in a given direction as well as the great differences between directions. The column headed "permeability ratios," shows substantial variations in the ratios of longitudinal to tangenital permeability, (K_L/K_T), but the range is not nearly as large as that observed for the longitudinal to radial permeability (K_L/K_R) ratio. The K_L/K_T ratio varies from 520 to 81,600, whereas K_L/K_R varies from 15 to 547,000, a range two orders of magnitude broader than for K_L/K_T. The Table 1 data show a rather poor relationship between radial and tangential permeability.

Least-squares regressions of log tangential

TABLE 2. *Correlation coefficients for the logarithmic relationships between permeability in the three directions*

Relationship	Correlation coefficient (R squared)	Significance level	Regression equations
Longitudinal/ tangential	0.7543	0.99	$\log K_T = -3.959 + 1.154 \log K_L$
Longitudinal/ radial	0.6040	0.95	$\log K_R = -3.784 + 1.171 \log K_L$
Tangential/ radial	0.5907	0.95	$\log K_R = 0.149 + 0.872 \log K_T$

permeability on log longitudinal permeability and the other two combinations were calculated. Table 2 lists the correlation coefficients for the logarithmic relationships. The longitudinal-tangential relationship is somewhat better than the longitudinal-radial or tangential-radial relationship. Thus the available data seem to support the hypothesis that longitudinal and tangential permeability are controlled by the same factors and are somewhat closely related, but the radial permeability is controlled independently and is not closely related to either longitudinal or tangential permeability.

In attempting to explain the relationship between longitudinal and tangential permeability, certain assumptions about the wood structure and the factors controlling flow through wood have been made:

1. Wood cellular structure is homogeneous; i.e. ray cells and earlywood-latewood differences are ignored.
2. Flow is through the cell cavity-pit system, and the pits offer the only significant resistance to flow.
3. Cells are square in cross section.
4. Pits are of uniform size and located only on the radial walls of the cells.
5. A sufficient number of cells are traversed so that end effects can be ignored.

If assumption 2 is valid, then a very simple expression can be written for the relationship of longitudinal to transverse permeability, which is derived as follows: Permeability, K, is directly proportional to the number of pits conducting in parallel per unit area, N_P, and inversely proportional to the number of pits traversed in series per unit length, N_S.

$$K = C(N_P/N_S) \tag{1}$$

C is a constant. If longitudinal and tangential permeability are designated by adding subscripts L and T, then:

$$\frac{K_L}{K_T} = \frac{N_{PL} \cdot N_{ST}}{N_{SL} \cdot N_{PT}}. \tag{2}$$

The quantities for the number of series and parallel pits depend on further assumptions about the wood structure. Other assumptions must be made about the shape of the tracheids, location and distribution of pits, and the nature of cell overlap. Two models were constructed with slightly different assumptions regarding these characteristics.

Model I (Fig. 1)

Assumptions:

A. Tracheids are long rectangular boxes with imperforate ends.
B. Pits are uniformly distributed on the radial walls of the tracheids.
C. Tracheids overlap adjacent tracheids over half of their length.

Figure 1 is a three-dimensional drawing of this model. The arrows designate a longitudinal flow path and a tangential flow path. Inspection of the model will permit estimation of the values for use in equation 2 in terms of the length and width of the tracheids.

Consider first the number of effective parallel pits per unit area for longitudinal flow. It is apparent if we look into the

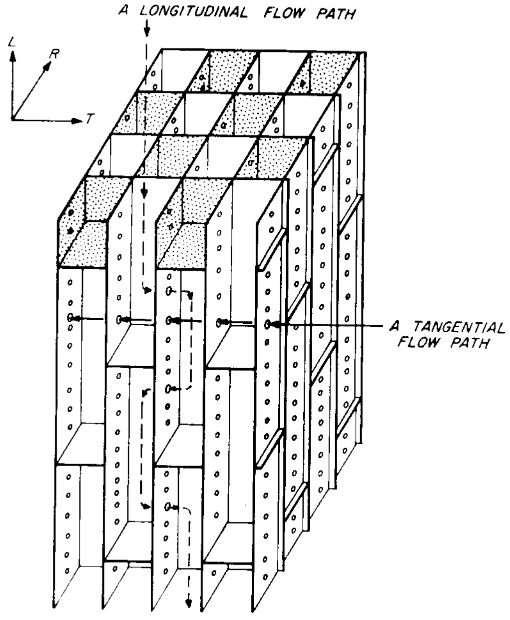

FIG. 1. Schematic drawing of Model I. Dashed line represents a longitudinal flow path. Solid line represents a tangential flow path. Unshaded tracheids are the effective entry tracheids for longitudinal flow.

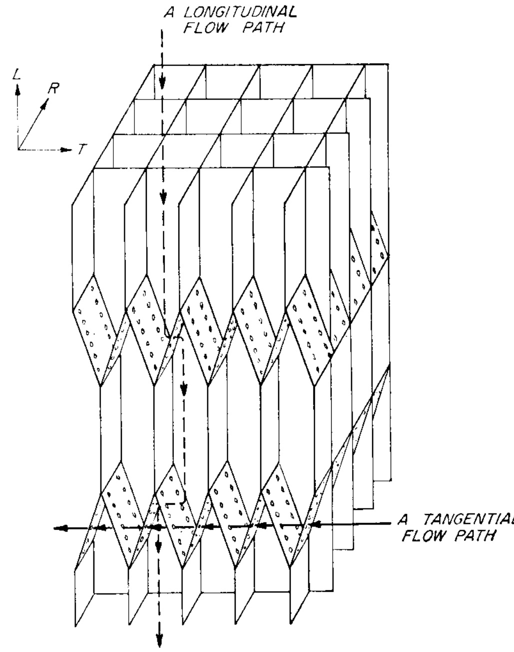

FIG. 2. Schematic drawing of Model II. Dashed line represents a longitudinal flow path. Solid line represents a tangential flow path.

model in the direction of flow, that the effective pits are those connecting exposed tracheids to unexposed tracheids. One half of the exposed tracheids will overlap unexposed tracheids, and one half of the pores per tracheid will be connected to those unexposed tracheids. Thus the number of effective pores per tracheid will be one-fourth the total number of pores per tracheid; i.e. $n_t/4$. The number of tracheids per unit area for longitudinal flow, N_{AL}, will be:

$$N_{AL} = 1/w^2,$$

where w is the width of a single tracheid.

$$\therefore N_{PL} = n_t/4w^2.$$

The number of pores in series per unit length, N_{SL}, depends on the number of tracheid walls crossed per unit length, and since two walls must be traversed to travel one tracheid length,

$$N_{SL} = 2/f,$$

where f is the tracheid length.

For tangential flow the effective number of pores per unit area will be

$$N_{PT} = n_t/2fw$$

and the number traversed in series per unit length will be

$$N_{ST} = 1/w.$$

The ratio of longitudinal to tangential permeability predicted is then

$$K_L/K_T = \tfrac{1}{4}(f/w)^2.$$

The ratio of tracheid length to width is usually about 100, which yields a predicted permeability ratio of 2500.

Model II (Fig. 2)

Assumptions:

A. Tracheids have tapered ends that overlap on the radial surfaces, but not on the tangential surfaces.
B. Pits are uniformly distributed on the overlapping portion, but lacking elsewhere.

TABLE 3. *Calculated and observed ratios of longitudinal/tangential permeability*

Species	Tracheid length[a]	Tracheid width[a]	Permeability ratios: Model I	Model II: $a = 0.5$	Model II: $a = 0.25$	Observed
	Millimeter	*Micrometer*				
Southern pine (sapwood)	4.62	40	3,600	14,300	32,200	7,200
Douglas-fir (heartwood)	3.40	40	1,800	7,200	16,300	12,000
Sitka spruce (heartwood)	5.35	40	4,500	17,900	40,300	22,200
Redwood (sapwood)	6.60	58	3,200	12,900	29,100	1,100
Redwood (heartwood)	6.60	58	3,200	12,900	29,100	9,100–75,000
Redwood (extracted, heartwood)	6.60	58	3,200	12,900	29,100	24,300
Eastern red cedar (sapwood)	2.15	25	1,850	7,400	16,600	820
Eastern red cedar (heartwood)	2.15	25	1,850	7,400	16,600	520

[a] Average values from Panshin et al. (1964)

This model is diagrammed in Fig. 2. One immediately apparent characteristic is that the differential permeability will depend on the relative length of the overlapping portions. The fraction of the tracheid length overlapping at the end is designated α. The maximum α would be 0.5, and total overlap for both ends would be 2α.

The expressions for the number of series and paralled flow paths, using the same nomenclature as for Model I, are:

$$N_{PL} = \left(\frac{n_t}{2}\right)\left(\frac{1}{w^2}\right)$$

$$N_{SL} = \frac{1}{f(1-\alpha)}$$

$$N_{PT} = \frac{n_t}{4}\,\frac{1}{wf(1-\alpha)}$$

$$N_{ST} = 2/w.$$

This gives a permeability ratio of:

$$K_L/K_T = \frac{4[f(1-\alpha)]^2}{w^2}.$$

Since α can vary from zero to 0.5, K_L/K_T can vary from 10,000 to 40,000 for an f/w ratio of 100. This is higher than Model I by an order of magnitude, which illustrates the sensitivity of the permeability ratio to the structure of the wood cells.

Comparisons of the observed and calculated values of K_L/K_T are shown in Table 3. The fiber length and width values are taken from Panshin et al. (1964) and represent only species averages. The calculated values are not always in close numerical agreement with measured values, but then measured values do not always agree either. For example, comparing the values for redwood reveals a range in measured values of about 70 times. This is probably related in part, at least, to differences in the experimental techniques used by the investigators. The length of the permeability samples can have a substantial effect on the permeability values if they are of the order of 1–2 fiber lengths or shorter. Transverse values are particularly sensitive to grain orientation and the method of delineating the flow area. Unfortunately, the techniques used by most of the investigators were not detailed in their reports.

The low permeability ratios for eastern red cedar and redwood sapwood appear to have plausible explanations. In redwood sapwood, which is quite permeable, the assumption that pits offer the only significant resistance to flow is almost certainly not valid. Lumen resistance is a significant factor in longitudinal flow through highly permeable sapwood, which has the effect of lowering the K_L/K_T ratio. Eastern red cedar is characterized by numerous intercellular spaces (Panshin et al. 1964), which might be responsible for the low permeability ratio for this species.

The theoretical and experimental relationships between longitudinal and tangential permeability, assuming a constant fiber length-width ratio of 100, are shown in Fig. 3. All of the data in Table 1 were used in calculating the experimental line. Model II appears to fit the data best with a value of α between 0.5 and 0.25.

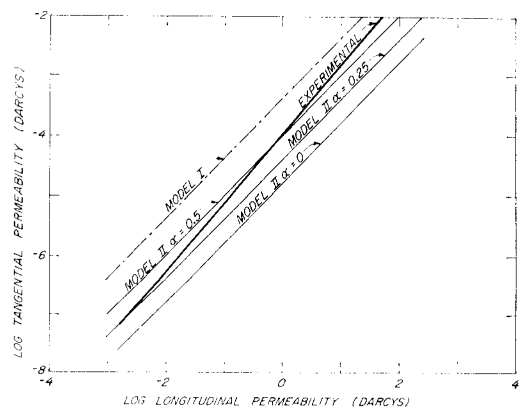

FIG. 3. Logarithmic plot of tangential vs. longitudinal permeability of all available data along with the relationships predicted by the models.

DISCUSSION

It is obvious that the models presented do not represent actual wood structure in some respects. Model I does not account for the tapered ends of the cells, and Model II does not consider the actual distribution of pits on the cell walls. Although most pits on real cells are located on the tapered ends, some are located on the nonoverlapping portion also, which would aid only tangential flow, thus reducing the calculated permeability ratio. Another difference between the models and actual wood structure concerns the uniformity of size and distribution of pits. They are neither uniform in pore size nor uniformly distributed in wood. Other things could be mentioned, but the point is that although the ratio must by nature be quite variable and dependent on many factors, a reasonable approximation to the experimental data is obtained by assuming a cell with tapered ends which overlaps adjacent tracheids from one-fourth to one-half of the cell length. For a fiber length/width ratio of 100, the predicted permeability ratio is between 22,500 and 10,000. This is about 100 times the value quoted by Stamm (1964), which seems to be widely used.

The extremely high ratio of longitudinal to transverse permeability is something that should be considered in processes involving the flow of fluids in wood. Hudson (1968) has taken advantage of this difference and the high permeability of green sapwood in developing a method of treating green poles of great length by forcing a treating fluid longitudinally through the wood. Incising is another treatment aimed at utilizing the larger longitudinal permeability to obtain good preservative treatment. Drying processes, where temperatures in excess of the boiling point are employed, undoubtedly involve substantial longitudinal flow of moisture because of the high pressures generated inside the wood.

In most practical situations there are no true tangential or true radial surfaces. Almost any board or veneer sheet will have longitudinal grain at some angle to its face. Thus there will be a longitudinal component of flow perpendicular to a board face, which may completely overshadow true tangential or radial flow, even though the slope of grain is very small.

REFERENCES

CHOONG, E. T., AND P. J. FOGG. 1968. Moisture movement in six wood species. Forest Prod. J., **18**(5): 66–70.

COMSTOCK, G. L. 1967. Longitudinal permeability of wood to gases and nonswelling liquids. Forest Prod. J., **17**(10): 41–46.

ERICKSON, H. D., H. SCHMITZ, AND R. A. GORTNER. 1938. Directional permeability of seasoned wood to water and some factors which affect it. J. Agr. Res., **56**(10): 711–746.

HUDSON, M. S. 1968. New process for longitudinal treatment of wood. Forest Prod. J., **18**(3): 31–35.

OSNACH, N. A. 1961. The permeability of wood. Derev. Prom., **10**(3): 11–13. (Transl. by Canada Dept. of Forestry & Rural Develop., #99).

PANSHIN, A. J., C. DEZEEUW, AND H. P. BROWN. 1964. Textbook of wood technology, Vol. I. McGraw-Hill, N.Y. 643 p.

RESCH, H., AND B. A. ECKLUND. 1964. Permeability of wood—exemplified by measurements on redwood. Forest Prod. J., **14**(5): 199–206.

SMITH, D. N. 1963. The permeability of wood to liquids and gases. Paper presented at Fifth FAO Conf. on Wood Technology, Madison, Wisconsin, Sept. 1963.

STAMM, A. J. 1964. Wood and cellulose science. Ronald Press Company, N.Y.

SUTHERLAND, J. H., H. W. JOHNSTON, AND O. MAASS. 1934. Further investigation of the penetration of liquids into wood, Canadian J. Res., **10**: 36–72.

KOLOSVÁRY, G., and T. CZVIKOVSZKY. 1969. Making wood-plastic combinations by chemical radiation methods. I. Theoretical considerations. *Holztechnologie* 10(2): 44–48 (G.gre). Possible wood improvements via vinyl monomer impregnation and radiation curing are discussed. Monomers used were vinyl acetate, styrene, vinyl chloride, methyl methacrylate, olefine, acrylic nitrile, the mixtures of them, and polyesters. (A)

KOLOSVÁRY, G., and T. CZVIKOVSZKY. 1969. Making wood-plastic combinations by chemical radiation methods. II. Practical application. *Holztechnologie* 10(2): 104–108 (G.gre). The present paper gives a detailed survey of the possibilities of wood improvement by vinyl monomer impregnation and radiation curing. Monomers studied are vinyl acetate, styrene, vinyl chloride, methyl methacrylate, olefine, acrylic nitrile, the mixtures of them, and polyesters. (R.E.)

MÜLLER, H. 1969. Drying-technical and power-economical tests with a "large-room dryer" (Grossraumtrockner). *Holztechnologie* 10(2): 80–84 (G.gre). The prototype of a large-room dryer is illustrated. Test results of air velocity and temperature, and for sawn hardwoods and softwoods are included. Evaluation of dried wood and power consumption demonstrates the advantages of the dryer. (R.E.)

CRZECZYŃSKI, T., and J. BAUZA. 1969. Properties of hardboards produced by the wet process and by the dry process. *Holztechnologie* 10(2): 109–112 (G.gre). Comparison is made between the properties of hardboards of nominal thicknesses of 3.2 and 5.0 mm produced by the dry process in France, Japan, and Turkey, and the quality of wet-process board produced in Poland. French and Japanese production is superior to Turkish or Polish. (R.E.)

FISCHER, R. 1969. Contribution about the problems with producing sawn timber. *Holztechnologie* 10(2): 84–88 (G.gre). With conventional methods of log conversion, an end to further economies development can be expected. This can be overcome if the relations between log and product can be favorably influenced. (A)

BÖHME, P., and S. KARGER. 1969. Concentration of the important material parameters characterizing decorative laminated materials for surface coating of wood-based material. *Holztechnologie* 10(2): 130–136. Criteria are given for promoting use of decorative laminates for coating wood-base materials. Ten different types of particleboards and 19 types of laminates are characterized. Comparison with the criteria permits choice of suitable materials and optimum conditions. (A)