THE DARCY PERMEABILITY OF FINE-GRAINED COMPACT SNOW

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ABSTRACT

The intrinsic permeabilities of snow from four natural snow layers and two samples of artificial snow ranged from 1.9×10^{-9} to 3.3×10^{-11} m^2. These measurements form an envelope on the low side of Shimizu's (1970) measurements. The new measurements may indicate an experimental bias in previous measurements of the permeability of snow such that the reported average permeabilities are approximately a factor of two too high. For natural snow, the permeability averages 1.0×10^{-9} m^2 with a standard deviation of 5.4×10^{-10} (coefficient of variation = .54). The Carmen constant squared (proportional to the permeability) averages 1.21 with a standard deviation of 0.36 (coefficient of variation = .30), implying that the porosity and the specific surface explain some of the variation in the permeability of natural snow, but that other textural properties may be important.

INTRODUCTION

Accurate estimates of snow permeability have become important recently because of dry deposition of gaseous pollutants to snow. The extremely large ice surface area in snow (Sommerfeld, 1987) can adsorb large amounts of gaseous pollutants. The acquisition and exchange of such pollutants depends on the air permeability of the snow. Furthermore, the Darcy permeability enters as an important term in modeling water flow through snow (Colbeck and Davidson, 1973).

Also, convection in the snowpack, if it occurs, would be important in the transport of gaseous pollutants. Several estimates of the importance of convection in snow covers (Akitaya, 1974; Klever, 1985; Palm and Tveitereid, 1979; Powers *et al.*, 1985) give conflicting results. Akitaya (1974) and Powers *et al.* (1985), calculated that convection is likely at temperature gradients commonly found in snowpacks. In a series of careful experiments, however, Akitaya (1974) was unable to produce convection in natural snow, although he was able to produce it under extreme gradients using an artificial snow of very high permeability. Powers *et al.* (1985) claimed to have observed convection, but the scatter in their data makes the claim questionable. Neither Akitaya nor Powers *et al.* measured the permeability of their samples. Akitaya used the measurements of Shimizu (1970) to estimate it. Powers *et al.* used a Kozeny-Carmen approximation (Kraus *et al.*, 1953) for their estimate. They speculated that part of their scatter might have been due to this estimate. Both methods are of questionable accuracy. In each case the specific surface area was estimated from an estimated grain size, an inexact procedure that involves subjective judgements. Also, the Kozeny-Carmen approximation is questionable at high porosities and with highly non-spherical particles.

Permeability measurements show such large scatter that the permeability of a particular sample may deviate from average measurements by more than an order of magnitude. Bader (1939) shows a scatter of about two orders of magnitude, and Keeler (1968) shows a similar range. Martinelli (1971) shows about an order of magnitude range with significantly lower permeabilities than other workers. Shimizu (1970) shows a range intermediate between Bader (1939) and Martinelli (1971). Denoth *et al.* (1979) give a range from 2.5 $X10^{-8}$ to 6.6 $X10^{-11}$ m^2. Their permeabilities averaged about half the values calculated using Shimizu's (1970) relationship for permeability (K_0) as a function of nominal grain size (d_0) and snow specific gravity (ρ_s),

$$(1) \qquad K_0 = 0.077\, d_0^2\, e^{-7.8\, \rho_s}.$$

It therefore seemed apparent to us that there is need for careful measurements on well defined snow.

SNOW SAMPLE PREPARATION

We performed two of our measurements on a type of artificial snow whose texture could be well specified in terms of grain size for comparison with Shimizu's (1970) measurements, and in terms of stereological parameters (Perla *et al.*, 1986). It was produced according to the technique of Sommerfeld and Freeman (1988). Water droplets from a sonic nebulizer were allowed to fall into liquid nitrogen. The frequency of the nebulizer was chosen to produce droplets with a mean radius of about 100μ. Perla (1978) calculated that ice particles of 100μ radius and larger would not change size appreciably in a few weeks. The particles were sieved to eliminate particles larger than about 250μ radius. They were packed into cylindrical glass tubes 250 mm long by 12.7 mm radius. The insides of the tubes were lined with a thin layer of ice to insure adhesion between the walls and the ice spheres. Tubes were packed to a density of about 580 kg m^{-3} to achieve uniformity. At lower densities, cracks and inhomogenieties could be observed in the surface sections (see below). The sample tubes were allowed to sinter for 800 to 900 hours at about -10° C to eliminate small radii of curvature. This helped to decrease the variation in size and to eliminate changes in texture during the course of the measurements.

Two natural snow samples were collected from each of four different layers exposed in a pit wall. The samplers were made from PVC tubing that was 52 mm inside diameter and 0.3 m long. The samples were stored for several days at -15° C before the measurements were made. The snow was observed to be very well adhered to the tube walls.

APPARATUS

A schematic diagram of the apparatus is shown in Figure 1.

Gas Flow

The air supply was a tank of carrier grade artificial air regulated at 15 PSI. The flow rate was controlled by electro-mechanical flow controllers. For the artificial snow, the flow transducers and valves had ranges of 0 - 10, 0 - 30, and 0 - 1000 SCCM, producing filter velocities up to .33 m sec^{-1} These spanned the ranges used by Shimizu (1970) and Martinelli (1971). Factory calibration specifies an accuracy of ± 1.0 % of full scale. Bubble flow meter calibrations were well within the factory specifications. Flows appeared stable and reproducible to better than ± 0.1 % of full scale. A flow controller with a range of 0 to 800 SCCM was used for the natural snow measurements.

Pressure Measurement

The pressure measurements for these experiments were performed using the same gage used by Martinelli (1971); an Equibar Type 120, capacitance pressure gage. It was calibrated at Colorado State University just prior to the experiments. Pressure

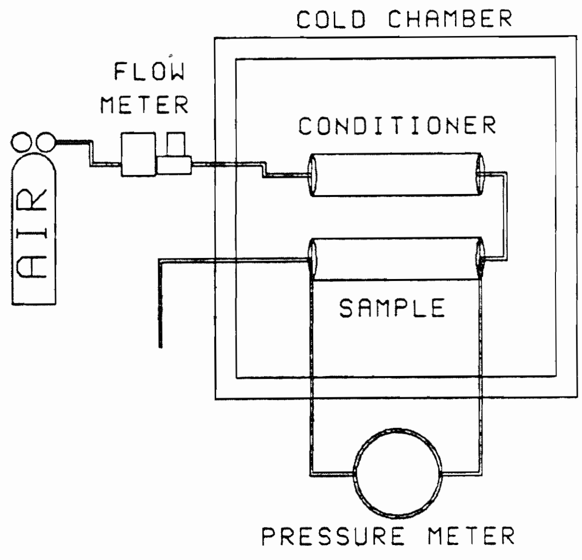

Figure 1 Schematic of the apparatus

indications were within ± 1.0 % of the true pressure. Because pressure differentials measured by Martinelli (1971) and by other workers differed by more than an order of magnitude, the pressures were checked using two Schaevitz Model P3061 differential pressure gages, one with a range 0 - 2 in. H_2O and the other 0 - 50 in. H_2O. These also had factory calibrations with ± 1.0 % total (combined scatter and nonlinearity) accuracy. The two types of gages agreed well within the specified accuracy.

<u>Sample Holder</u>

The sample holder was similar to that used by Sommerfeld and Lamb (1986). The main difference between it and those used by previous workers is that it included a conditioning tube containing snow similar to the experimental sample. This arrangement insured that the air flowing through the experimental sample was at the equilibrium temperature and humidity for the test sample, preventing any sublimation or deposition of water vapor.

DARCY PERMEABILITY

Figure 2 shows raw data plots of the measurements of two different artificial samples. Notice that the curvature at the higher flow rates is opposite that expected from the onset of turbulent flow. This is an artifact of the use of a mass flow meter. At the higher flow rates, the pressure in the sample tube increases. The mass density of the gas increases and the ratio of the filter velocity to the mass flow rate decreases to compensate. If corrections are not made for this effect, it would be possible to obtain a straight line relationship between mass flow rate and pressure differential well into the turbulent flow regime. The range in which the false linearity existed would depend on the configuration of the system. We corrected for this effect.

The slopes of the curves show that the permeabilities were within 5% (± 2.5%) of each other. This reproducibility between samples is considerably better than achieved by previous workers. It should be emphasized that for each sample, the flow rate was cycled from zero to 1000 SCCM and back down in 10% increments using all three flow monitors. No hysteresis was found, although the 0 - 30 SCCM controller was found to be sluggish in part of its range during the first experiment, producing the sawtooth pattern in the insert in Figure 2. The problem was cured in the next experiment by replacing the controller. Notice that apart from this problem, the transistion between flow controllers does not cause appreciable steps in the data, which indicated high precision and stability in the system. The volume flow rates were determined from the mass flow rates, the barometric pressure, and the temperature of the experiments.

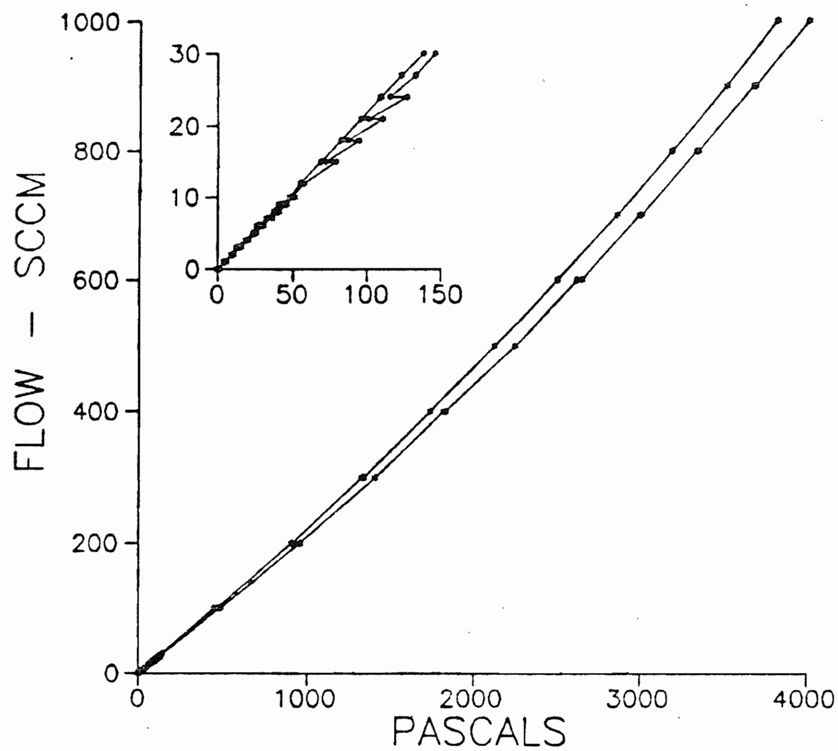

Figure 2 Pressure drop across the sample cylinder versus the mass flow rate for artificial snow.

The measurements on the natural snow samples were performed in a similar apparatus that accommodated the larger sample tubes. Measurements were performed at 800, 400, and 200 SCCM (mass flow rate), with the volume flow rates calculated from the barometric pressure and the temperature of the experiments. An average of three measurements at the lowest flow rate were used in the calculations.

TABLE 1. Results of the Measurements

Sample No.	Snow Type*	Point Density	Snow Density	Specific Surface	Permeability	Carmen Constant
		ρ_p	ρ_s	$S_v.mm^{-1}$	K_0 m^2	k^2
1A	IIA1	.208	.191	9.2	1.5×10^{-9}	2.02
1B	"	.239	.219	9.6	5.8×10^{-10}	0.97
2A	IIA1	.195	.178	8.1	1.5×10^{-9}	1.53
2B	"	.182	.167	6.5	1.9×10^{-9}	1.18
3A	IIA1	.326	.298	7.6	7.4×10^{-10}	1.12
3B	"	.345	.316	8.3	5.4×10^{-10}	1.05
4A	IIA2	.402	.368	8.6	3.0×10^{-10}	0.83
4B	"	.334	.306	6.2	9.2×10^{-10}	0.96
	Mean - natural snow			8.0	1.0×10^{-9}	1.21
	Standard deviation			1.1	5.4×10^{-10}	0.36
X1		.672	.616	25.7	3.3×10^{-11}	4.94
X2		.598	.548	27.2	3.5×10^{-11}	3.20
		Mean - all samples			8.2×10^{-10}	1.78
		Standard deviation			6.2×10^{-10}	1.25

*Sommerfeld and LaChapelle, 1970

Martinelli (1971) reported anomalous behavior at low flow rates and pressure differentials. We did not observe such anomalies. From the action of the pressure gage at low pressure differentials, we conclude that Martinelli's anamolous readings may have been due to pressure changes in the building caused by wind pumping. We observed pressure fluctuations in our measurements when a corridor door adjacent to the laboratory was opened. Results of the measurements are given in Table 1 and plotted in Figure 3 with Shimizu's (1970) results.

MEASUREMENTS OF TEXTURAL PARAMETERS.

Stereological parameters were measured by the method of Perla *et al.* (1986). The important features for this paper are the point density, and the surface area per unit volume (Table 1).

COMPARISON WITH OTHER MEASUREMENTS

Figure 3 shows our measurements and those of Shimizu (1970). Notice that our measurements form a lower envelope to the other measurements. Exact comparisons among

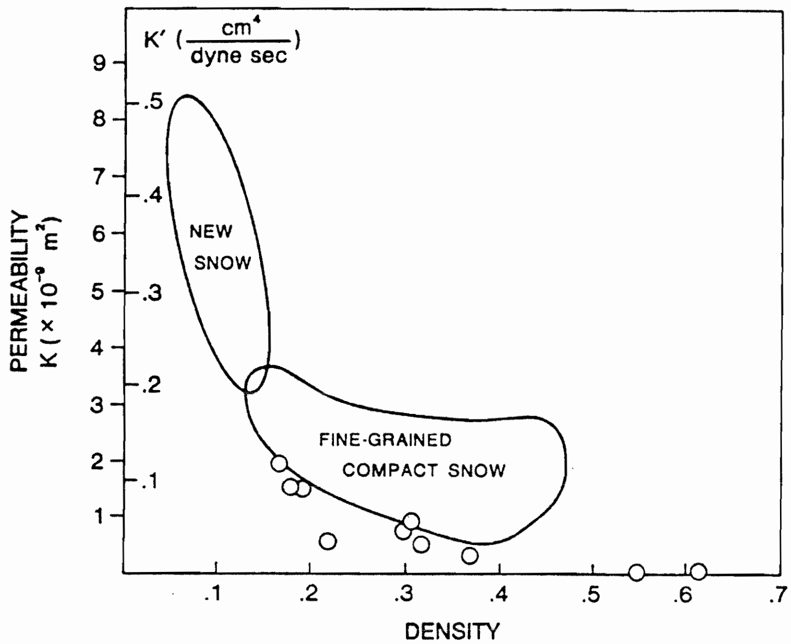

Figure 3 Comparison of the permeabilities reported here (○) and Shimizu (1970).

different permeability measurements on natural snow are not possible because of the difficulty in characterizing the snow that was used by previous workers. However, we can compare our measurements on artificial snow with Shimizu's (1970) relationship (equation 1) because our grain size is well specified. We estimated our mean grain diameter from the specific surface area (S_V, Table 1), to be

$$d_0 = \frac{6}{S_V} = 0.23 \text{ mm},$$

which is in good agreement with our original sphere diameter of 0.2 mm. Averaging the two artificial snow experiments, Shimizu's (1970) relationship gives

$$K_0 = 4.3 \times 10^{-11} \text{ m}^2$$

which again is in good agreement with our average of 3.4×10^{-11}

Adamson (1982) gives a type of Kozeny-Carmen equation,

$$K_0 = \frac{k^2 (1 - \rho_p)^3}{8 S_v^2} , \qquad (2)$$

where ρ_p is the point density. Table 1 lists the Carmen constant squared (k^2) calculated from our data. Kraus *et al.* (1953) give $k = 5.0$ ($k^2 = 25$) for randomly pored media. The theory was developed for glass spheres of uniform diameter. It does not appear that the Kozeny-Carmen theory explains the permeability of snow very well. In the case of the natural snow, the permeabilities would have to be about a factor of 10 higher to raise the k to 5.0. Such a high permeability would be out of the range of all the measurements but those of Bader (1939).

DISCUSSION

Shimizu (1970) explained the fact that his measurements averaged much lower than Bader's (1939) by sample damage along the sample tube wall in Bader's (1939) apparatus. Shimizu avoided that problem by designing a double vessel permeometer. However, we do not find his explanation compelling for two reasons: (1) Sample tubes of the type used by Bader compress the sample in the vicinity of the wall, and elastic rebound tends to press the snow to the wall (F. W. Smith, pers. comm.). This has also been our experience in using tube samplers. (2) Martinelli (1971) used a sample tube similar to Bader's (1939) and his permeabilities averaged significantly lower than Shimizu's (1970). We note, instead, that the average permeabilities seem to be a function of flow rate. Martinelli's flow rates were lower than Shimizu's and Keeler's which were lower than Bader's. In addition, the scatter appears to correlate with flow rate.

An explanation for such an effect would be the sublimation of preferred channels through the sample by dry air drawn through the sample. The higher the flow rate, the greater the sample damage. Kuroiwa (1968) used kerosene and measured lower permeabilities than others using dry air.

Our experiments minimized any sublimation problem by providing air that had been conditioned to the same humidity and temperature as the test sample. The permeabilities we measured were similar to the lowest measured by Shimizu (1970) and Martinelli (1971). In fact, the bulk of Shimizu's (1970) measurements, about 30 out of 42, lie near the lower range of his measurements (Figure 4). Decreasing the estimated permeabilities in

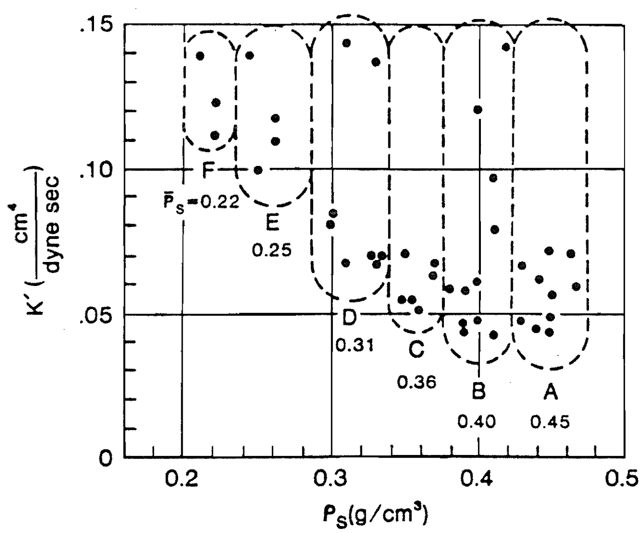

Figure 4 Permeability versus density reproduced from Shimizu (1970).

Akitaya's (1970) calculations by a factor of two would result in better agreement between his experiments and his calculations. A factor of two decrease in permeabilities calculated from Shimizu's relationship would also agree better with Denoth *et al.* (1979).

CONCLUSIONS

The measurements presented here indicate that some air permeabilities of snow measured previously may be high. A possible explanation is that dry air eroded channels of easy flow in some of the samples. Our apparatus was specifically designed to prevent such erosion. Erosion of easy flow channels would be a more severe problem with measurements on lower density snow. Our data are in better agreement with Shimizu's (1970) measurements at higher densities than at lower. It thus appears that the lowest values measured by previous workers may be more correct than their mean values. If this is the case, convection in snowpacks is less common than previously thought.

It is difficult to make accurate comparisons among permeability measurements because of the difficulty in characterizing the snow. It appears that stereological measurements may be necessary to make very accurate comparisons. We suggest that the specific surface area of the sample is one important parameter. For these samples of natural snow, the Kozeny-Carmen theory makes some improvement in the scatter of the data but, is unable to completely explain the permeability of snow. The coefficient of variation of the natural snow permeabilities is 0.54 while that of k^2 (proportional to the permeability) is 0.30. Application of the Kozeny-Carmen theory does not improve the coefficient of variation (0.76 vs. 0.70) when the artificial snow data are included. Also, the Carmen constants (k) calculated from these results are considerably lower than the value given by Kraus *et al.* (1953). These results indicate that textural parameters other than porosity and specific surface area are also important in determining the permeability of snow.

The specific surface area that we measured in our natural snow averaged 8.0 mm^{-1} with a standard deviation of 1.1. These measurements did not span the full range of snow types but the range of specific surface areas is relatively small. Snow with complex crystal shapes that have a higher surface area per crystal tend to be lower density; they have fewer crystals per volume than snow with simpler crystal shapes.

It also appears that much of the scatter in previous data may have been the result of experimental technique. If further measurements on natural snow continue to give the relatively low scatter shown here, perhaps a simple phenomenological relationship between permeability and density would be sufficient for many applications where great accuracy is not required.

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