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Permeability Measurements on New and Equitemperature Snow

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Measurements of the air permeability were performed on snow from six horizons within a snowpack at the Glacier Lakes Ecosystems Experiment Site in southeastern Wyoming. The snow was new or equitemperature snow, with densities (ρ_s) ranging between 0.134 and 0.367 Mg m^{-3}. The specific surface area of ice in each sample was measured stereologically. Intrinsic permeabilities (K_0) calculated from these data ranged from 3.0×10^{-10} to 3.1×10^{-9} m^2. The data fitted the equation $K_0 = 1.096 \times 10^{-8} e^{-9.57\rho_s}$, with a standard deviation of 2.8×10^{-10} m^2. A dimensionally correct relationship between permeability and specific surface area did not fit our data as well as a simple density relationship. The small scatter reported is attributed to careful selection of undamaged samples and the prevention of sample sublimation during the measurements.

Introduction

During the month of February, between 46 and 53% of the land area of the northern hemisphere is snow covered [*Barry*, 1992]. Continental snowpacks act as chemical reservoirs; pollutants can accumulate in the pack over the entire winter and are released during a relatively short spring melt period. Interactions between the snow and the atmosphere can change the quantities of different chemical species stored in the snow. In addition, snow can retain chemical species to be incorporated into major ice sheets and large glaciers. The record of atmospheric chemistry preserved in this way is important in understanding the past history of the atmosphere [*Dibb et al.*, 1991; *Bales and Dibb*, 1992].

Processes that may be important in the acquisition and redistribution of impurities in snowpacks include wind pumping [*Clarke et al.*, 1987; *Colbeck*, 1989; *Clarke and Waddington*, 1992; *Albert and McGilvary*, 1992]; convection [*Akitaya*, 1974; *Palm and Tveitereid*, 1979; *Klever*, 1985; *Powers et al.*, 1985; *Brun et al.*, 1987; *Sturm and Johnson* 1991]; and melt water flow [*Colbeck and Davidson*, 1973]. Accurate quantification of these processes require accurate permeability information.

The intrinsic permeability (K_0) is

$$Q = K_0 A(\Delta P/L\ \mu_f) \quad (1)$$

where Q is the volumetric discharge (cubic meters per second), K_0 is the intrinsic permeability (square meters), A is the cross-sectional area (square meters), $\Delta P/L$ is the pressure gradient (pascals per meter), and μ_f is the dynamic viscosity of the fluid (kilograms per meter per second) [*Friedman and Sanders*, 1978].

It is uncertain whether or not convection is common in snow at normal earth surface conditions. Calculated Rayleigh numbers have exceeded those thought critical for convection in snow [*Nield*, 1968] and in laboratory and field experiments [*Akitaya*, 1974; *Brun et al.*, 1978] but convection was not observed. Field experiments by *Sturm and Johnson* [1991] indicate that extreme thermal gradients are necessary for even intermittent convection.

Considerable scatter in previous measurements of air permeability have made accurate estimates difficult and constitute a major source of uncertainty in estimating Rayleigh numbers for snow. *Bader* [1954] showed a range of about 10^3 for snow of density 0.3 Mg m^{-3}. *Keeler*'s [1969] data indicate a range of about half of *Bader*'s [1954]. *Shimizu* [1970] and *Martinelli* [1971] show a range of about a factor of four at the same density. *Shimizu* [1970], whose work seems the most careful and complete, related the air permeability to snow density (ρ_s) and grain size (d_0) for a limited type of snow which he characterized as fine-grained compact:

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

Regressions we performed using his data showed that the data fits were significantly improved by the inclusion of d_0^2, as opposed to a simple density relationship.

Akitaya [1974] failed to observe convection when he used (2) to calculate Rayleigh numbers which were above critical for convection in snow. *Denoth et al.* [1979] estimated permeabilities from water flow. His results showed large scatter but averaged about half the permeabilities predicted by *Shimizu*'s [1970] equation from Denoth's densities and grain sizes. These results seem to indicate that the permeabilities given by (2) are higher than the true permeabilities for the snows they studied.

The measurement of permeability is prone to systematic errors which tend to cause spuriously high permeabilities. The first type of error is physical damage caused by sample handling. This can be in the form of cracks or disaggregation caused by insertion of the sample tube, or separation of the sample from the sample tube wall because of settling or elevated temperatures.

Sommerfeld and Rocchio [1989] also pointed out that when different air permeability data are compared, the scatter and the average values seem to be a function of air flow rate. They speculated that dry air might erode preferential channels in some samples, increasing the experimental error and causing the reported permeabilities to average too

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high. A third source of systematic error is that erosion would have a more serious effect along flow paths involving sample damage, exacerbating any damage effects. The fact that these sources of error are systematic means that accuracy may not be improved by larger sample numbers if such systematic errors are large.

Shimizu [1970] recognized two types of systematic errors; sample damage and erosion. His permeability apparatus was designed to decrease the effect of damage along sample walls but not damage within the body of the sample. He addressed the erosion problem by measuring the permeability of a single sample during a 10-hour period. However, this experiment was not conclusive because (1) The temperature was low and the humidity was high in his laboratory when this experiment was conducted, reducing the amount of erosion that might occur, and (2) the snow he used was relatively high in density (0.42 Mg m^{-3}) and may not have been sensitive to channel erosion. The permeability measured in this experiment was near the low end of his measurements, grouped with the majority of his measurements in this density range. A sceptical interpretation of this experiment is that when erosion was shown not to be a problem, the permeability measurement was low.

Grain size estimates such as used by *Shimizu* [1970] are based on subjective judgments [*Perla and Sommerfeld*, 1986] and thus introduce additional inaccuracies in comparisons among different types of snow. While *Shimizu* [1970] determined the cross-sectional ice area objectively, from the snow density, the number of grains appearing in a section was estimated by a more subjective counting technique: "a complicated-shaped grain having m remarkable constrictions was counted as $m + 1$ grains." Comparisons between objective stereological measurements of mean intercept lengths of snow samples [*Sommerfeld*, 1983] and *Shimizu*'s [1970] diameter estimates show that errors of 30–50% in subjective mean diameter estimates are easily possible. The subjective nature of the grain size estimates also make it difficult to compare different sets of measurements. On the other hand, subjective measurements have been shown to be consistent. They may be precise even if they are inaccurate, with the result that an analysis like *Shimizu*'s [1970] can be internally consistent.

Shimizu's [1970] grain size estimates should be related to specific surface area S_v (ice surface area per unit snow volume); a stereological parameter that can be measured accurately [*Underwood*, 1970] and relatively easily with computer technology available since Shimizu performed his measurements. K_0 can be related to the porosity and the specific surface area of a porous bed by a Carmen-Kozeny equation [*Adamson*, 1982]

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

where ρ_p is the point density (1 − the void fraction) and k is the Carmen-Kozeny constant. For uniform spherical grains, $1/S_v^2$ and d_0^2 are related in a simple way [*Underwood*, 1970].

We present a new set of permeability measurements here which are not entirely in agreement with those of *Shimizu* [1970]. We also measured the specific surface area of each of our samples using a section plane method [*Perla*, 1982] and classified each snow sample using *Sommerfeld and LaChapelle* [1970] in an attempt to provide a more complete description of the snow.

TABLE 1. Snow Samples Reported in This Study

Sample No.	Type	Stereological Density, mg m^{-3}	In situ Density, mg m^{-3}	K_o, m^2	S_v, mm^{-1}	k^2
A	IIA.1	0.191	0.225	1.50E−09	9.2	2.04
1B	IIA.1	0.219	0.217	5.82E−10	9.6	0.97
2A	IIA.1	0.179	0.177	1.53E−09	8.1	1.54
2B	IIA.1	0.167	0.182	1.93E−09	6.4	1.15
3A	nd	0.299	nd	7.43E−10	7.6	1.12
3B	nd	0.316	nd	5.35E−10	8.3	1.05
4A	IIA.2	0.367	0.307	3.00E−10	8.6	0.83
4B	IIA.2	0.306	0.305	8.40E−10	6.2	0.87
7	IB	0.152	0.149	2.62E−09	7.6	2.09
8	IB	0.134	0.146	3.07E−09	8.5	2.85
10	IB	0.150	0.160	2.62E−09	6.3	1.42
11	IB	0.174	0.139	2.57E−09	7.0	1.89
12	IB	0.136	0.140	3.08E−09	6.8	1.85
14	IB	0.168	0.130	2.65E−09	6.7	1.74
2C	IIB.1	0.311	0.329	1.08E−09	6.8	1.38

Type from *Sommerfeld and LaChapelle* [1970]. IB, new snow, wind blown; IIA.1, equitemperature, decreasing grain size, beginning; IIA.2, equitemperature, decreasing grain size, advanced; IIB.1, equitemperature, increasing grain size, beginning; and nd, not determined.

METHODS

Snow samples were collected from six distinct horizons within snowpits dug at the Glacier Lakes watershed in the Snowy Range National Forest, Wyoming, during the winters of 1988–1989 and 1989–1990. In situ snow densities were obtained from the pit wall for each horizon at the time of sample collection by weighting the samples.

A total of 47 snow cores were collected. Corers of the size we used compress the snow about 3% radially [*Work et al.*, 1965] and slow elastic rebound causes the snow to press against the corer walls after several minutes (F. W. Smith, unpublished data, 1980). However, disaggregation along the corer wall, which can occur with large grained or fragile snow, or settlement during transportation can defeat this process. Fifteen of the cores survived handling and transportation to the laboratory. This low rate of sample recovery (32%) has not been reported by other workers. Damage included cracks caused by corer insertion, settlement away from the corer walls caused by transportation, and sample shrinkage away from the walls caused by above freezing temperatures. Cracks caused by corer insertion were generally not apparent until the sample was removed from the corer for section plane preparation. If the sample separated or macroscopic cracks were visible at this point, the sample was discarded. Gaps along the wall were sometimes detected by visual examination. In addition, samples which slid easily from the corer, indicating lack of wall adhesion, were discarded. Cracks in the samples and gaps along the corer walls would give anomalously high permeabilities and exacerbate erosion problems. Two cores each of four horizons were collected on February 24, 1989, six from a single horizon on January 17, 1990, and one from a horizon on January 11, 1990. Table 1 lists the snow type, the stereological density (point density times the density of ice), and the in situ (gravimetric) densities for the samples.

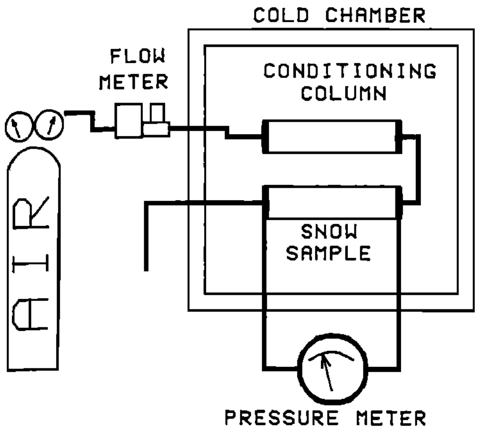

Fig. 1. Schematic of the permeability apparatus.

The pressure measurements for this study were performed using an Equibar Type 123 differential capacitance pressure gage (the same gage used by Martinelli). It was calibrated to an accuracy of better than 1% by the Colorado State University Engineering Research Center prior to the experiments. The flow meter had a factory specified accuracy of ±1%, which was verified using a bubble flow meter. The entire apparatus is shown schematically in Figure 1. It is described in detail in the works by *Sommerfeld and Rocchio* [1989] and *Rocchio* [1990]. The unique feature of the apparatus is the conditioning column. It was filled with snow similar to that in the sample column to ensure that the air flowing through the apparatus was at the equilibrium temperature and humidity for the test sample. This design prevented the erosion of preferential air flow channels through the snow sample and assured that sublimation or deposition of water vapor did not occur during permeability measurements. We previously determined that a flow rate of 200 SCCM (cm^{-3} per minute at standard temperature and pressure) with corresponding filter velocity of 1.6 mm s^{-1}, was in the laminar flow range [*Sommerfeld and Rocchio*, 1989].

The method for section plane preparation developed by *Perla* [1982] was used for our experiments. For specific surface area and point density measurements within single snow core samples, each core was divided into three sections and surface sections were prepared for each division. A total of 45 sample sections were photographed and analyzed to determine specific surface areas and point densities.

IMAGEPRO [*Media Cybernetics*, 1989], a commercially available software package, was used to convert the snow section photographs into the digital images necessary for use in the stereological analysis. The contrast and brightness levels of the video camera were manually adjusted to obtain the best discrimination between the ice grains and the matrix. Two stereological parameters, point density and surface area per unit volume, were measured using a program developed by *Perla* [1989].

RESULTS

Intrinsic permeabilities K_0 were calculated using (1). The volume flow rates were calculated from the mass flow rates, the ambient barometric pressure, and the temperature of the experiment chamber. Three measurements taken at 200 SCCM were averaged. These values were also used in the calculation of the Carmen-Kozeny constant (equation (5)).

The permeabilities ranged between a low of 0.3×10^{-9} and a high of 3.1×10^{-9} m^2 for snow densities between 0.13 Mg/m^3 and 0.37 Mg/m^3 (Table 1). These values are in very good agreement with the lowest of *Shimizu*'s [1970] permeabilities (Figure 2). The seven samples taken from a single horizon (numbers 7–14) had permeabilities within about 10%, indicating excellent reproducibility in samples of the same snow.

Snow densities calculated from the point density measurements obtained from the stereological analysis compared well with the in situ density measurements (see Table 1). Snow density which is plotted against permeability in Figure 2 was calculated by multiplying the point density by the density of ice.

The specific surface areas ranged from a high of 9.6 mm^{-1} to a low of 6.2 mm^{-1}. The corresponding permeabilities were 5.8×10^{-10} m^{-2} and 8.4×10^{-10} m^{-2}, which were not the lowest or highest permeabilities. The population variance of the specific surface areas was 1.05. The K^2 values obtained using our specific surface area measurements ranged from 2.8 to 0.8 (see Table 1). *Kraus et al.* [1953] give $k^2 = 25$ for "randomly pored media."

To provide an estimate of core homogeneity, densities within the cores were analyzed stereologically. Analysis showed that 84% of the variance was due to intersample variance, 5% due to location of the core section within the sample, and 11% from measurements within each core section. The conclusion from these comparisons is that each core was very homogeneous.

DISCUSSION

The snow densities in this study ranged from 0.37 to 0.13 Mg m^{-3}. In addition, two samples of artificial snow with snow densities of 0.548 Mg m^{-3} and 0.616 Mg m^{-3} and corresponding permeabilities of 3.5×10^{-11} m^{-2} and 3.3×10^{-11} m^{-2} [*Sommerfeld and Rocchio*, 1989] were used in determining the empirical relationship between permeability and snow density (Figure 2). The following relationship was obtained from an exponential regression on the data:

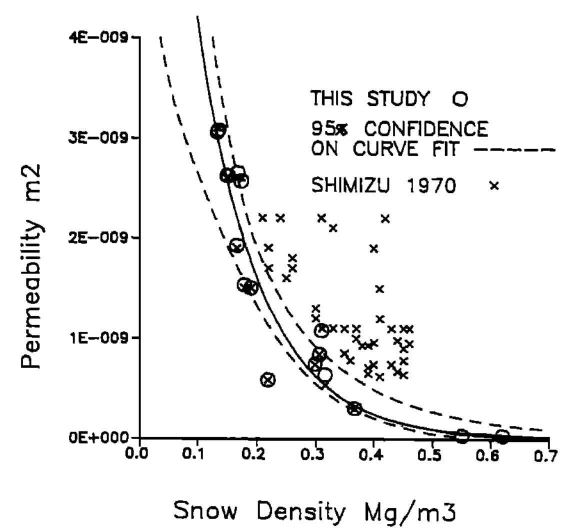

Fig. 2. Data from *Shimizu* [1970]. Solid curve is (4), and the dashed curves indicate the 95% confidence interval on that curve.

$$K_0 = 1.096 \times 10^{-8} e^{-9.57\rho_s} \tag{4}$$

The standard deviation was $\pm 2.8 \times 10^{-10}$ m^2. This curve is shown in Figure 2 along with its 95% confidence interval.

The low scatter in our permeability results tends to confirm the validity of the measurement method and apparatus design. Excellent reproducibility is indicated by the small spread in measurements from the same horizon (numbers 7–14, Table 1). The use of a conditioning column minimized the problem of sublimation of preferred channels through the snow cores by dry air. Care taken to eliminate damaged samples and to select homogeneous snow contributed to the small scatter in the data.

Shimizu [1970] related grain surface (d_0^2) to permeability. While exact comparison between his determinations of d_0 and our specific surface area measurement is not possible, they both estimate essentially the same parameter and therefore should show similar trends.

Our average density was 0.22 Mg m^{-3} and our average specific surface area was 7.6 mm^{-1}. The equivalent sphere diameter for a snow made of uniform spheres with the same density and specific surface area is 0.2 mm. This compares with *Shimizu*'s [1970] average of about 0.4 mm for the same density. As was discussed above, visual estimates of grain number generally result in lower numbers and thus larger grain size estimates than objective measurements because a large number of very small grain sections tend to be ignored.

We had hoped that by using specific surface area instead of a derived equivalent grain diameter, we would improve on *Shimizu*'s [1970] d_0^2 textural relationship. We have only one case that can be compared to *Shimizu* [1970]. Our four samples, 2C, 3A, 3B, and 4B would be classified as fine grain compact snow with an average density of 0.31 Mg m^{-3}. A regression on log K_0 versus $1/S_v$ shows a slope of 1.8 (R^2 = 0.56). This result is in general agreement with the regressions we performed to data taken from *Shimizu*'s [1970] Figure 15 for both for both slope (1.22 to 2.04) and R^2 (0.32 to 0.88). This result is consistent with *Shimizu*'s [1970] choice of a square relationship with grain size which is also dimensionally correct.

To test the importance of S_v in our data (without the two artificial samples) we obtained the following relationship:

$$K_0 S_v^2 = 0.65 e^{-10.15\rho_s}, \qquad R^2 = 0.785 \tag{5}$$

Shimizu [1970] proposed an approximation to Brinkman's relationship [*Scheidegger*, 1960]:

$$K_0/d_0^2 = 0.56 e^{-11.5\rho_s} \tag{6}$$

This is very similar to (5), providing some theoretical support for our result.

However, for a fit to density only (without the data on artificial snow), we obtained

$$K_0 = 1.36 \times 10^{-8} e^{-10.97\rho_s}, \qquad R^2 = 0.893 \tag{7}$$

Comparing (5) and (7) shows that S_v may not be as important a parameter in determining the permeability of natural snow we studied as we originally thought, at least in our data.

We attribute this result to the small range in specific surface areas among our samples. The small range among the snow types we studied has a relatively simple explanation. Complex crystals associated with new snow have more surface area per crystal, lower densities, and therefore fewer crystals per volume. The opposite is true of older snow with simple crystal shapes, which have higher densities, less surface area per crystal, and more crystals per volume. This effect can also be seen in Figure 3 where snow density and surface area per gram are seen to be highly correlated. Low-density snow has a high surface area per gram but a small number of grams per volume, while the opposite is true of high-density snow. The net result is to decrease the range of specific surface areas in equitemperature snow of different densities.

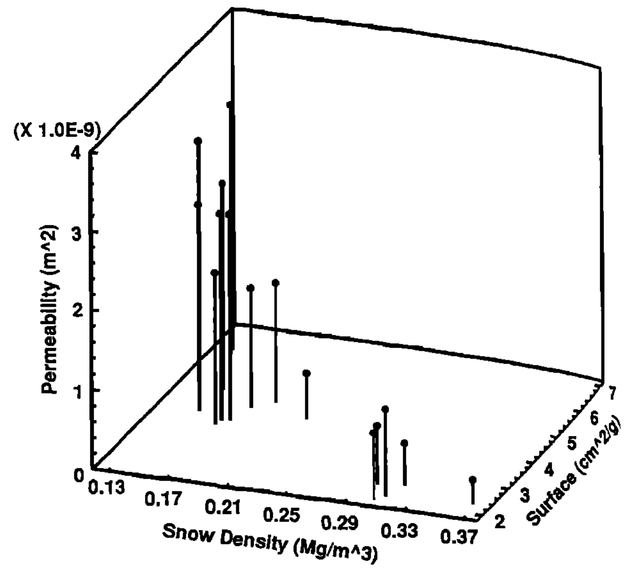

Fig. 3. Permeability, density, and surface area per gram for the samples.

While specific surface area must have an influence on permeability, we conclude that the effect is small for the snow we studied because of the density correlation described above and is masked by other sources of scatter in the measurements. These could include differences in tortuosity and grain form factors among the samples, undetected inhomogeneities, and undetected sample damage.

Our negative result with regard to surface area calls into question *Shimizu*'s [1970] relationship between permeability and grain size. However, because of our small number of samples and limited range of specific surface areas, we do not think we have a definitive test, but merely wish to call attention to a potential problem. We note that other permeability measurements presented by *Shimizu* [1970] are not consistent with the data he used to determine (2). Also, the use of our lower permeabilities in calculating Rayleigh numbers would lead to a prediction more consistent with the results of experiments [*Akitaya*, 1970; *Brun et al.*, 1987]. On the other hand, our density range of 0.13–0.37 averages significantly lower than the 0.22–0.45 Mg m^{-3} that *Shimizu* [1970] used to determine his relationship. It is possible that the types of snow used for the two different sets of measurements were not comparable.

It does not appear that the Carmen-Kozeny theory (equation (5)) models the permeability of natural snow satisfactorily. Our determinations of k^2 ranged over more than a factor of 3 and were all considerably lower than the theoretical value of 25. For natural snow the permeabilities would have to be about a factor of 10 higher to raise the value of k^2

to 25. Such high permeabilities would be above *Shimizu*'s [1970] highest measurements for the types of snow we studied. Since the most likely sources of error in these measurements are systematic and give spuriously high values, values higher than those measured by *Shimizu* [1970] seem very unlikely. Furthermore, we did not find any relationship between the k^2 calculated from our experimental data and the snow texture as classified in Table 1. While *Shimizu*'s [1970] d_0^2 term is similar to the S_v^2 term in (5), the exponential density terms in his (2) and our (4) give different relationship between density and permeability than does the $(1 - \rho)^3$ term in (5). Thus neither *Shimizu*'s [1970] data nor ours supports the Carman-Kozeny model.

CONCLUSIONS

Our results show that a simple permeability–snow density relationship (equation (4)) fits our data better than one including a dimensionally correct specific surface area parameter. Snow density is a convenient parameter because of its ease of measurement both in the lab and in the field. The snow types and the density range we studied span those commonly found in continental snowpacks at the start of melt and generally make up the bulk of such snowpacks.

We choose to make detailed comparisons between our results and those of *Shimizu*'s [1970] because we think his are the most careful and complete measurements available in the literature.

However, our results are in disagreement with those of *Shimizu* [1970] on two important points. Our permeability at any density averages about half of *Shimizu*'s [1970] average, and we did not find convincing evidence of a specific surface area effect on the permeability that would correspond to *Shimizu*'s [1970] grain diameter relationship. Three different hypotheses could explain this discrepancy. First, our data are too limited in snow type to show a specific surface area relationship. If this is true, it raises the encouraging possibility that snow types identifiable in the field could be used with density measurements to make estimates of permeability. Second *Shimizu*'s [1970] data contain systematic errors. Third, our data accidently contained only low-permeability samples.

Further study of the relationship of permeability and density including a greater range of snow types and a greater range of specific surface areas is indicated. Different sampling techniques will be necessary to sample snow types such as very new snow and depth hoar without physical damage to the samples. Perhaps such studies will help clarify the relationship between permeability and parameters other than density which should exist but appeared to be masked in our data. Equation (5) is very close to *Shimizu*'s [1970] approximation to Brinkman's [*Scheidegger*, 1960] theoretical relationship (6). This indicates that a theory derived from Brinkman's arguments might be applicable to snow permeability.

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