A NEW SET OF THERMAL CONDUCTIVITY MEASUREMENTS

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ABSTRACT: A new set of thermal conductivity measurements collected over the course of one winter season in Glacier National Park, BC, Canada is introduced. Subsets of grain types are examined for empirical relationships between thermal conductivity and layer density. Further subsetting by moist or dry layers suggests that an empirical relationship between temperature and thermal conductivity is possible with either an expanded dataset or through a meta-study incorporating past studies of snow thermal conductivity.

KEYWORDS: thermal conductivity, snow, microstructure

1. INTRODUCTION

Thermal conductivity has long been recognized as an important physical parameter of the seasonal snow as it directly influences changes in crystal habit, size and bonding and thus affects everything from snowpack stability to heat exchange within climate models (e.g. Cook et al., 2008). Thermal conductivity is most simply described as the proportionality constant that relates a gradient (in this case the slope-normal gradient) to the heat flow. It may also be described by the 1D Fourier equation,

$$q = -k\frac{dT}{dz} \tag{1}$$

where *k* is the thermal conductivity. For scales of 10 cm to 1 m Equation 1 is a reasonable approximation to the bulk heat transport, but at the polycrystalline or grain scale the unequal distribution of pore space and effects of thermal pathways (tortuosity) through the ice lattice may complicate matters. Although models may treat thermal conductivity through the ice lattice and pore space separately, the bulk or *effective* thermal conductivity, k_{eff} is usually what is measured in field studies.

Thermal conductivity measurement techniques may be broadly classified as either Fourier-type, steady-state and transient-flow, or non-steady-state (NSS) (Sturm et al., 1997), with NSS techniques further classified as either short-time (Britsow et al., 1994) or long time approximations to the analytical solution. In the short-time case the contact resistance between the probe and medium must be known. Riche and Schneebeli (2010) found that contact resistance was strongly affected by the insertion of the needle probe and resulted in thermal conductivities of 2-3 times less than those measured using a guarded hot plate apparatus. In the long-time case after a certain transient period the rate of temperature increase becomes constant and no longer depends on the probe's thermal properties and the contact resistance. In this case the thermal conductivity (λ) may be found using the equation:

$$\lambda = \frac{Q}{4\pi\Delta T} ln\left(\frac{t_2}{t_1}\right) \tag{2}$$

Where $t_{1,2}$ are the start and end times of the linear heating, Q is the heating power and ΔT is the increase in temperature during the period of linear heating.

Studies dating back to at least 1886 (Sturm et al., 1997) have attempted to measure the thermal conductivity of snow. The techniques and accuracy are varied but in general most efforts prior to 1950 employed some form of Fourier analysis to derive the thermal conductivity of a bulk sample. In recent years advances in instrumentation have simplified the task of collecting thermal conductivity measurements in the field, with most recent field studies making use of heated needle probes.

Sturm et al. (1997) summarize 26 studies conducted between 1886 and 1991 in what remains the definitive compilation of snow thermal conductivity data. They note that although many studies have published relationships between density and thermal conductivity, the combined historical dataset shows no such relationship. Furthermore, the relationship between temperature and thermal conductivity was generally ignored in most studies. They and others (Arons, 1994) also emphasize the temperature dependence of the effective thermal conductivity of snow which, at least according to theory, becomes pronounced between -20 °C to 0 °C.

The same paper introduced a new set of measurements collected using an instrument similar to that

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used in the present study. Samples of refrozen grains had thermal conductivities of 0.095 W m^{-1} K^{-1} to 0.250 W m^{-1} K^{-1} for densities ranging from 314 kg m^{-3} to 496 kg m^{-3} though this group also had the largest standard deviation in thermal conductivity of all grain types.

Relationships between density and thermal conductivity based on grain type were also introduced: For 'density independent' snow types (depth hoar and other faceted types), the use of a single mean value was found to give the best fit to the measurements. For other types, both quadratic fits and maximum likelihood estimator were proposed. A follow-up study by Sturm et al. (2002) found good agreement with the above regressions when used to predict the thermal conductivity of layers classified by hand hardness and density.

Riche and Schneebeli (2010), in addition to evaluating the accuracy of short-time heated needle probes, used a guarded heat plate to measure thermal conductivities between 0.151 (ρ = 213 kg m^{-3}) and 0.185 W m^{-1} K^{-1} (ρ = 239 kg m^{-3}) for rounded grains.

Schneebeli and Sokratov (2004) applied vertical temperature gradients to sieved snow samples and used microtomography to track structural changes as they underwent metamorphism. They observed an initial sharp increase in thermal conductivity from approximately 0.35 to 0.55 W m^{-1} K^{-1} for samples with a constant density of 500 kg m^{-3} while lower density samples tended to remain constant around their initial value of 0.11 W m^{-1} K^{-1}.

Satyawali et al. (2008) applied high vertical temperature gradients (28 $^\circ$C m^{-1}) to sifted natural snow samples and monitored microstructural and thermophysical changes over a period of 4 weeks. They noted that the thermal conductivity in samples with an initial density of ρ = 180 kg m^{-3} increased more quickly during the 4 weeks and to ultimately higher values than another sample with initial density ρ = 320 kg m^{-3}. This increase in thermal conductivity coupled with only a small increase in density implies that the ice skeleton in low density snow may rearrange itself into effective pathways for heat conduction faster than similar snow of higher density. A similar conclusion was drawn by Sturm and Johnson (1992) with respect to depth hoar in a shallow, highly faceted snowpack. This relationship between initial density and rate of change of thermal conductivity is opposite that observed by Schneebeli and Sokratov (2004) and may be due to similar factors that led Sturm et al. (1997) to conclude that density is not a good predictor for thermal conductivity in faceted grain types. Calonne et al. (2011) and Greene (2007) also observed the formation of highly faceted grain types with no attendant change in density.

2. EQUIPMENT AND METHODS

A Hukseflux TP02 thermal non-steady-state thermal conductivity probe (Hukseflux, 2003) was used for all measurements in this study. The probe is designed to be used with the long-time approximation given in Equation 2. This means that incidences of poor contact between the probe and the sample will simply take longer to transition out of the zone of transient temperature increase. The manufacturer's stated accuracy at $20^\circ\mathrm{C}$ is $\pm$ (3% + 0.02) W m^{-1} K^{-1}. A correction during post-processing limits the error due to temperature to $\pm$ 0.02%, but measurements of low thermal conductivity will still have relatively high uncertainty. Morin et al. (2010) modeled heat flow around the TP02 and found that the area sampled extends approximately 3 cm radially from the probe.

Thermal conductivity was measured weekly at six study plots and during five cold lab experiments where a natural melt-freeze crust was subjected to strong vertical temperature gradients. At field sites, a test snow profile was used to describe qualitatively the snowpack structure and spatial variability over the scale of the pit wall (approximately 1 m horizontally). Once the complementary measurements were completed, the TP02 was inserted into the layer of interest for several minutes to allow it to reach thermal equilibrium with the surrounding snowpack. This was checked by comparing the TP02's thermistor temperature with the layer temperature previously measured as part of the snow profile.

Once the measurement was triggered the probe temperature was allowed to stabilize for an additional 100 seconds before starting a 100-second heating cycle. Similar procedures were used by Morin et al. (2010) and Domine et al. (2012). The probe tip temperature was monitored to ensure that the temperature increase did not exceed 1.0 $^\circ\mathrm{C}$. Occasional problems were encountered at low temperatures when the stiff probe cable made it difficult to prevent the probe from shifting out of the sample area. These measurements were always discarded. Excepting cases where the crust was too warm, a minimum of two valid measurements were attempted for each layer. Typically the layer above, layer below and one or more layers within the crust itself were sampled.

3. RESULTS

A total of 261 valid thermal conductivity measurements were recorded, predominantly in melt-freeze grain types but also in faceted (FC) and rounded (RG) grains. As with past studies the layer density and thermal conductivity were correlated in layers of rounded grains (R=0.78, $p \leq 0.05$) and also in weakly-faceted layers (R=0.78, $p \leq 0.05$). Figure 1 shows density plotted against thermal conductivity for all faceted layers. Equations (4) and (7) from Sturm et al. (1997) as well as Equation (12) from Calonne et al. (2011) are plotted for reference.

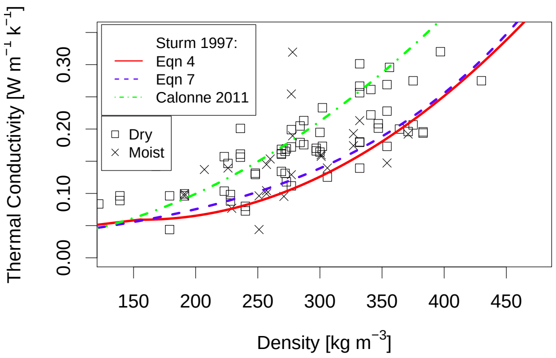

Figure 1: λ versus density for faceted (FC) grain types with outliers removed. Equations (4) and (7) from Sturm et al. (1997) and Equation (12) from Calonne et al. (2011) are plotted for reference.

The measurements from the present study are generally higher than the the equations from Sturm while the equation of Calonne offers a slightly better fit. The same relationship was evident when plotting thermal conductivity against density for subsets of rounded grains. The layers in the present study were up to 10 °C warmer than those sampled by Sturm and the layers classified as facets were only weakly faceted grains typically found in a transitional snowpack while Sturm's samples came from a shallow subarctic snowpack where the degree of faceting is usually much greater. A weak, but non-statistically significant positive linear relationship was found between temperature and thermal conductivity for the subset of faceted grains.

Subsets of melt-freeze forms had no statistically significant relationship between thermal conductivity and density but did exhibit a weak negative linear relationship between temperature and thermal conductivity. This latter result is suspect as the sample temperatures were clustered between -5 °C and 0 °C with only 8 measurements colder than -10 °C. Nevertheless this relationship bears further examination with a larger dataset.

When dry and moist layers were treated separately some stronger relationships between thermal conductivity and temperature emerged, as shows in Table 1.

Table 1: Correlations between thermal conductivity and layer temperature by treating dry and moist layers separately. All correlations are significant to $P \leq 0.05$.

Grain Type	Pearson R	# **Valid**
FC moist	0.71	26
FC dry	0.60	70
RG moist	0.77	9
MF dry	-0.49	62

This result is expected due to the contribution of free water to the K_{eff} but also illustrates a difficulty with relying on the 'glove test' (CAA, 2007) to determine the water content of snow. Despite the correlations in Table 1, temperature did not emerge as a significant predictor in linear or exponential predictive equations for any subsets of grain types.

4. CONCLUSIONS AND FUTURE WORK

This paper introduced a new set of thermal conductivity data collected over the course of one winter at fixed study sites and in a cold lab. The relationship between thermal conductivity and density for rounded and weakly faceted forms is similar to what has been found in past studies, but when compared with the empirical equations of Sturm et al. (1997) the values of thermal conductivity in the present study were typically higher. There is very likely a temperature dependence as the majority of the new measurements were made at warmer snowpack temperatures.

These new data suggest several worthwhile avenues to explore in future studies: 1) Dry and moist layers should be treated separately during analysis due to the increased presence of free water. In reality the change in actual water content is gradual but this distinction appears to be sufficient if precise measurements are not possible; 2) Empirical equations based on density alone do illuminate trends but they are not sufficient on their own as predictive equations. Other parameters, likely temperature, need to be incorporated. A meta-study incorporating the data of Sturm et al. (1997) and others offers the possibility that layer temperature would emerge as a significant predictor variable for thermal conductivity in snowpack models.

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