Relation of Temperature Gradient to Heat Transfer in Snow

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Abstract. Temperature distributions in snow, measured in the laboratory and the field are always used as a basis for the calculation of snow-heat conduction and water-vapor-diffusion characteristics. According to recently obtained experimental data temperature distributions are not linear even under steady conditions and thus do not fit into present theories of the simultaneous heat and mass-transfer mechanisms. The temperature distributions are related to the heat-transfer processes in a much more complicated way than is presently accepted. They must be the result of latent heat release in snow recrystallization that is superimposed on the balance between the evaporation and condensation processes, regulated by the specific surface area of the ice matrix, snow structure, and potentiality of the porous space for water-vapor transfer.

1 Previous Investigations

The quantities that today still chiefly characterize the snow conditions are the temperature and its gradient deduced from temperature measurements at several points; at the same time, these are the easiest to measure. They are used in almost any equation describing the processes of heat and mass transfer in snow and are included in any modeling of snow metamorphism.

The heat flux in snow is constructed by the heat conduction in the ice matrix, the heat transport by water-vapor flux and the heat transferred by air flux. The temperature distributions observed must be the result of the coexistence of these three terms [1]. For pure conduction a steady-state temperature distribution must be linear throughout homogeneous snow. When part of the heat is transported by water vapor (estimated to contribute up to 50% into the effective heat-conductivity coefficient of snow [2,3]), nonlinear temperature profiles can be expected. However, according to the presently accepted physical theory of simultaneous heat and mass transfer in snow, the water-vapor flux can only change the profile by less than 2% from the linear one [4]. Presence of air convection changes the temperature distribution tremendously [5]; it becomes the main mechanism of the temperature-profile construction [4].

There exist more than a dozen models of simultaneous heat and mass transfer in snow and snow recrystallization. The main difference between most of them is the presentation of the snow structure: de Quervain [6] tried to consider the set of ice plates parallel or perpendicular to the direction of heat and mass transfer. Sommerfeld [7] constructed his "branch grain theory" of crystal growth, where evaporated material condensed on specific grains further away from a heat source. Gubler [8] designed a model which included interparticle structures. Adams and Sato [1,3] considered the relation of heat conduction to microstructure, interpreting snow crystals as ice spheres. Successful modeling was also done without involving stereological properties of snow [9]. Of course each model was a simplification of the real natural processes, and a combination of different factors included and different assumptions made, usually resulted in achieving quite a good agreement between modeled and observed data.

The above mentioned and other published models used the same physical interpretation of the mass-transfer phenomenon, described in [10]. The temperature of the ice matrix and the porous air were equated for each point of a snow sequence, and supersaturation (or non-saturation) in the snow was accepted to be smaller than the diffusion driving density difference [8]. These assumptions, coupled with the fact that (except in [9]) the volumetric heat production related to the non-zero density balance in the snow was omitted from the heat-transfer equations, indeed resulting in almost linear steady-state modeled temperature distributions.

The tomographic reconstruction from optical interferometric data on ice-crystal growth in supercooled water [11] and in air [12] showed temperature gradients up to 500°C m^{-1} around growing crystals over distances in the order of the crystal size. Under conditions always called "isothermal" the temperature of the ice was up to 2°C higher than the temperature in the surrounding pore space. This raised doubt in the validity of equating the ice matrix and the porous air temperatures when constructing the heat-transfer or snow-metamorphism models. More than this, these temperature gradients are of the same order as the gradients commonly applied to snow in known heat and mass-transfer experiments. That is why usage of the water-vapor concentration close to its saturated value can also not be correct.

It is traditionally stated that the intensity of the water-vapor transfer depends on the temperature gradient. However experimental data did not reveal a relation between these two characteristics [13]. The relationship found was a dependence of the water-vapor flux on the water-vapor-concentration gradient, related primarily to the temperature and secondarily to the temperature gradient. Finding a stronger water-vapor-flux dependence on the temperature than could be expected from the theoretical model [14] also supports this.

The quasi-steady-state temperature distributions actually observed [15] were always far from linear. As the obtained data could hardly be explained on the basis of the above sited interpretation of heat and mass–flux coexistence, additional experiments were done to find which processes could form such non-linear behavior.

2 Present Experimental Results

Heat and mass fluxes in the snow were produced by keeping opposite faces of 0.1 m long snow samples under different temperatures. The temperature was measured on the central axis parallel to the direction of the heat and mass fluxes. A more detailed description of the experimental apparatus and the results of crystal-size determination are given in [16]. The temperature distributions were accepted to represent quasi-steady-state conditions after the temperature change with time was no longer visible within the accuracy of the present measurements (±0.1°C). The results shown here are a combination of the data obtained before and partly shown in [17] (19 snow samples) and results of recently performed experiments (17 snow and glass bead samples).

The thin lines on the following figures are the linear temperature distributions, which could be expected in the case that the heat was transferred by conduction only. Bars represent the range of the temperature varying during steady-state conditions, corresponding to the temperature regulation in the experimental set–up and not changing shape of the graphs.

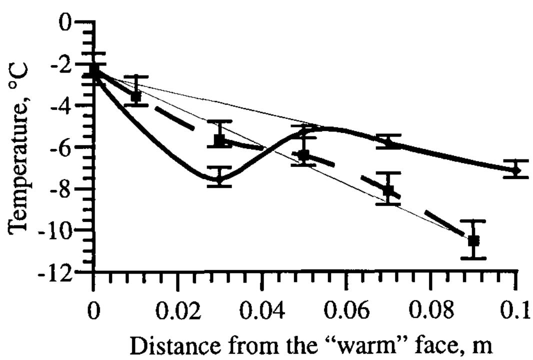

Fig. 1. Quasi-steady-state temperature distributions in snow samples with horizontal heat and mass fluxes; natural compacted (*dashed line*) and sifted (*solid line*) snow

Fig. 1 shows examples of the quasi-steady state temperature distributions obtained with horizontally produced heat and mass fluxes in a sample made from naturally compacted snow (snow density 325 kgm^{-3}), and when naturally compacted snow was sifted through a wire net for sample preparation (in this case the snow density became 458 kgm^{-3} and the crystal size range 1.11–8.34 × 10^{-4} m). The non-linearity (concave to the "warm" face) is present in both samples, but in sifted snow the temperature gradient in the central part of the sample was opposite to those applied externally.

Fig. 2 shows examples of the quasi-steady state temperature distributions in two similar snow samples made from sifted new snow (snow density 290 kgm^{-3}, crystal size range 1.1–6.8 × 10^{-4} m) with vertically produced heat and mass fluxes. The character of the temperature distributions is similar – a

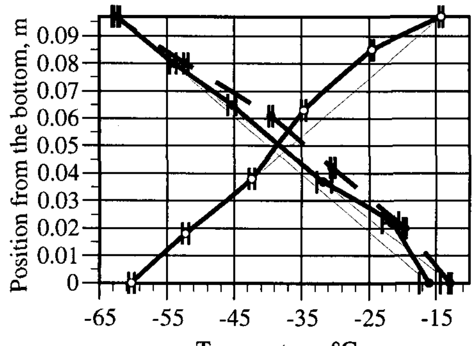

Fig. 2. Quasi-steady-state temperature distributions in snow (*solid lines*) and steady state temperature distribution in glass bead samples (*dashed line*) with vertical heat and mass fluxes; ○ – downward, • – upward fluxes

non-linear profile is formed in the part of the snow sample with temperatures higher than −40 to −30°C, and the distributions are almost linear in the colder parts of the samples. This must be related to the maximum possible water-vapor concentration in the porous space, decreasing with the temperature decrease. However in the snow samples with "upward heat flux" the temperature distributions in the "warm" parts were convex to the "warm" face, which required other mechanisms of the water-vapor transfer than in the snow samples with "horizontal" and "downward" heat flux. The dashed line presents the temperature distribution with upward heat flux produced in a sample made from glass beads ($1.2–2.0 \times 10^{-3}$ m grain size) in the same temperature range. A considerable difference from linearity is seen throughout the whole sample, not restricted to the "warm" part as in the snow sample. It ought to be noted that the downward heat flux formed a linear temperature distribution in the glass bead sample.

Fig. 3 shows an example of temperature distribution in a sample from the same snow as used for the snow samples shown in Fig. 2, but with smaller

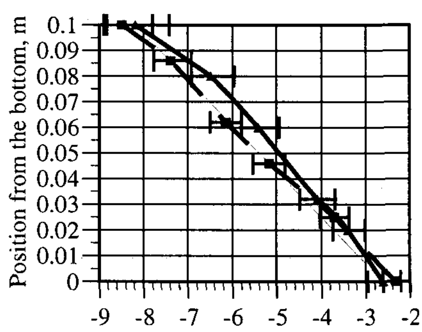

Fig. 3. Quasi-steady state temperature distribution in snow (*solid line*) and steady state temperature distribution in glass bead samples (*dashed line*) with vertical upward heat and mass fluxes

applied temperature difference. A convex temperature distribution was also formed; the whole temperature range corresponded to the "warm" part of the temperature distributions in Fig. 2. The dashed line shows an almost linear temperature distribution found in the glass bead sample under the same conditions.

3 Conclusions

These results of our experimental work drive us to conclude that the simultaneous heat and mass transfer modeled on the basis of presently used theoretical treatments of the phenomenon [4] are not able to explain the experimentally observed quasi-steady state temperature distributions in snow.

It is possible that the temperature measured in the snow is the temperature of the ice grains contacting a thermocouple – higher in zones where condensation prevails [11,12], and lower than the temperature of the porous air in zones where evaporation prevails. However, in this case the attempts to relate the observed to the theoretically expected temperature distributions need assumptions other than presently accepted for modeling the process. More than this, the temperature of grains with different size can also be different, and the actual "temperature range" in each "point" of the measurement can be broader, the wider the crystal size range is.

When relating the observed non-linearity of temperature distributions to alternations of evaporation and condensation processes [15], it can be concluded that the latent heat release had higher impact on the observed temperature distributions in case of sifted snow, characterized by wider range of crystal sizes and higher specific surface area of the ice matrix, and thus possibly more active process of mass exchange between neighboring grains, i.e. recrystallization. The non-linearity shows a clear dependence on the temperature; this means that it is related to the water vapor in the porous space formed by the recrystallization process.

In low density snow and when the heat flux is upward, the temperature distributions could be affected by convection superimposed on the prevailing evaporation and condensation zoning (Fig. 2). But under our experimental conditions the convection more likely enforced not air but only water-vapor transport (Fig. 3).

All the above considerations lead to the conclusion that the measured temperature gradients do not represent the amount of heat and water vapor transferred in snow even under quasi-steady state conditions. The temperature distributions in snow are the result of the mass and energy exchange between neighboring grains, regulated on the one hand by the specific surface area of the ice matrix, the crystal size range, the snow porosity and the tortuosity, limiting the amount of water vapor transferred by the externally applied temperature gradient; and decreasing, on the other hand, with decreasing temperature.

As the source of the water-vapor transfer consists mostly of material evaporated from the surface of the grains, it can be expected that the activity of snow metamorphism should also primarily correlate to temperature and only secondarily to the temperature gradient that is present in snow, which is in agreement with our experimental results shown in [16].

Acknowledgments: The work was partly supported by the Japan Science and Technology Agency through JST and JISTEC.

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(Received 14 Feb. 1999, accepted 15 May 1999)