博士（地球環境科学）　セルゲイ　A　ソクラトフ

学 位 論 文 題 名

Experimental study on the heat and water vapor transport in snow

（雪の熱および水蒸気輸送に関する実験的研究）

学位論文内容の要旨

The heat and water vapor transfer in snow under applied temperature gradients has been studied for a long time in the research fields glaciology to study these processes as ground-atmosphere interactions during winter time, recrystallization of snow related with snow avalanches formation and so on. The main purpose of these investigations was to obtain the heat conductivity and water vapor diffusion coefficient in snow which could be included into any snow-related models used in environmental studies.

However experimental results obtained by most of previous investigators gave values of water vapor diffusion coefficient about 5 times higher than diffusion coefficient in air (2.2 $\times 10^{-5}$ $m^2 \cdot s^{-1}$). Several explanations for this result were offered but none of them could fully explain it. This situation forced us to carry out this systematic study in attempt to understand the interaction between water vapor flux in porous space and heat conduction in ice matrix.

The experimental set-up consisted of thermoinsulated snow samples with uniform density of cross section 18 cm $\times$ 18 cm and lengths 10 ~ 40 cm situated horizontally or vertically. The temperature difference from 4 to 12 ℃ was applied to opposite faces of snow samples and as a result we could have wide range of temperature gradients inside snow samples. The applied temperature difference was kept for a long time (from 3 to 24 days) during which period temperature distribution inside snow samples was measured in 2 cm interval and every 10 minutes. The temperature changed rapidly from initially uniform temperature for the first 12 ~ 48 hours in dependence on sample length and after then it was steady at all positions of measurements. After the experimental run the snow samples were cut perpendicularly to the direction of heat and mass transfer in slabs with thickness of about 1 cm, and mass measurements of these slabs gave density redistributions in snow as a result of built heat and mass transfer.

As an addition to the heat and mass transfer experiments the author carried out experiments on CO_2 diffusion in snow. This was done by applying CO_2 concentration difference on opposite faces of snow samples (7 cm length, 5 cm diameter) without applying temperature gradients. Same snow was used for these experiments and the obtained data could be used for comparing CO_2 diffusion without heat flux influence with the water vapor transfer characteristics.

The obtained steady state temperature distributions were not linear as they could be

in media with uniform heat conductivity. Attempts to calculate effective heat conductivity of snow gave very large range of values, which could not be explained by neither difference in snow density nor the temperature dependence of heat conductivity of ice. Detailed analyses of temperature distribution revealed that they represented waves around convex to the warm ends curves. The waves appeared immediately after the sudden heating of one face of snow sample and remained at the same position till the end of each experimental run. The lengths of these waves were from 3 to 8 cm and the waves could be recognized through whole the sample length (5 ~ 6 waves per 30 cm sample). As similar waves were found in horizontal, vertical fluxes upward and vertical fluxes downward snow samples they could not be a result of convection developed inside snow.

The explanation of wave formation could be as follows: Sudden temperature increase on one face of snow sample forms heat flux into the snow sample. As heat conductivity of ice grains is much higher than that of porous air the result of such ice grain heating could be evaporation from the grains surfaces. However the formation of temperature gradient in porous space together with the water vapor concentration gradient produces the water vapor flux in the same direction. At some distance from the heat source the water vapor concentration in porous space could become supersaturated, and condensation could take place resulting in latent heat release causing temperature waves. It can be also suggested that when such condensation zone is the heat source for the next wave in the general direction of heat transfer we could have the same mechanism for formation of further waves through the sample length. The process of water vapor-ice reaction proceeds under steady state conditions also.

Similar waves were recognized in the density distributions measured after each run. Based of the wave positions in the samples from the temperature data, the density change could be correlated to any recognized wave. Indeed, it was possible to note in density distributions that each wave was related with the decrease and increase of density.

Thus, it was possible to calculate water vapor flux from density change in evaporation and condensation zones inside a wave. Several waves which were recognized both in the temperature and density distributions were used for water vapor diffusion coefficient calculations. The obtained values were from 0.9 to 1.8 $\times 10^{-5}$ $m^2 \cdot s^{-1}$ — smaller than water vapor diffusion coefficient in air and thus in good agreement with theoretical values. The difference with previous works was in using of local temperature gradients inside noted waves. It means that the discovery of the new phenomenon of wave formation in temperature and density distributions has explained why the previously obtained diffusion coefficients were not in agreement with theoretical considerations.

The CO_2 experimental data gave tortuosity of snow, which was used in the water vapor flux calculations ($\approx$ 1.73). Including this value into obtained diffusion coefficients we could reconfirm the model of Giddings & LaChapelle (1962) and we have proposed a new parameter, "diffusion enhancement factor", to explain the complex heat and water vapor transport mechanism in snow under applied temperature gradient. Summarizing the new obtained data it can be concluded that the temperature distributions in snow under applied temperature gradients have wavy patterns. The waves are formed by alternation of evaporation-condensation zones. As stated in the theory of Giddings & LaChapelle, the porosity effect of snow is canceled by increased temperature gradient in porous space, but tortuosity can play very important role in water vapor diffusion. The effective water vapor diffusion coefficients in snow are smaller than that in air.

学位論文審査の要旨

主　査　　教　授　　前　野　紀　一
副　査　　教　授　　秋田谷　英　次
副　査　　助教授　　成　瀬　廉　二
副　査　　助教授　　古　川　義　純
副　査　　教　授　　福　迫　尚一郎（大学院工学研究科）

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Experimental study on the heat and water vapor transport in snow

（雪の熱および水蒸気輸送に関する実験的研究）

雪の熱および水蒸気輸送過程は、地球の寒冷積雪域における質量およびエネルギーバランスにおいて重要な働きをするため、これまで多くの研究者によって研究が行われてきた。しかし、これまでに発表された雪の熱および水蒸気の輸送係数の結果は研究者によって大きく異なった。特に水蒸気拡散係数に関しては不一致が大きく、空気中の値よりも数倍大きいという結果も発表されており、多孔質物質の理論とも一致しなかった。本研究はこれらの未解決の問題に関する正しい理解を得ることを目的に行われた。

実験では雪内部の熱輸送、水蒸気拡散、CO_2拡散、および雪試料の構造と密度の測定が行われた。熱輸送と水蒸気拡散の実験では、雪試料の向かい合う２面を種々の温度に長期間（３-24日）保ち、内部の温度分布の時間変化が詳細に測定された。両面の温度差は４℃から12℃の範囲でかえられた。雪試料の熱流方向の断面積は18 cm x 18 cm、長さは10 - 40 cmで、熱流方向は、水平、垂直下向きおよび垂直上向きの三つである。雪内部の温度分布は、1 - 2 cm 間隔で設置された熱電対を用いて10分毎に測定された。雪試料は自然積雪、密度は199 - 518 kg/m^3 である。各実験終了後、雪試料は約1 cm厚に切断され密度測定と構造解析が行われた。雪内部のCO_2拡散係数は、円筒形の雪試料（長さ７cm、直径５cm）の両端にCO_2濃度差を与え濃度の時間変化をCO_2ガス電極で測定することによって求められた。CO_2拡散係数は拡散に対する温度勾配の影響を評価するために使われた。

雪試料に一定の温度差を与え定常状態に達した時の温度分布は、通常の均一物質におけるような線型ではなく、高温側に凸の二次曲線で表わされた。これから見積

もられた実効熱伝導度は広い範囲で変化し、その結果は密度の変化によっても氷の熱伝導度の温度依存によっても説明することが出来なかった。

次に、この問題を解明するため、より詳細な温度分布の測定と解析が行われた。その結果、雪内部の温度分布に顕著な波の形成が発見された。波は雪試料に温度勾配を与えた直後から形成され、その場所は各実験中変わらなかった。波長は3-8 cmで、雪試料全体に形成された（例えば、30 cm試料では5-6波）。同様な波は水平試料にも、垂直試料（熱流方向上向きおよび下向き）にも検出されるため、熱対流によるものではないと結論された。同様の波は密度分布にも認められた。更に構造解析の結果とも比較し、これらの波は、雪内部に生じた局所的な昇華蒸発領域と凝結領域、およびそれらの繰り返しによって形成されることが明らかになった。すなわち、雪試料の片面が加熱されると、熱輸送と同時に氷の昇華蒸発が起こり水蒸気拡散が進行する。水蒸気拡散は空隙の水蒸気過飽和度を増加させ、ある一定の距離で臨界値となり、凝結が始まる。その点で放出された潜熱は温度分布に波を形成する。また水蒸気の昇華蒸発と凝結は、密度分布にも波を形成する。更に、高温の凝結領域は、次の波形成の原因となる。

雪内部に形成される温度と密度の波状分布には明瞭な対応があるため、各々の波に関して、輸送された水蒸気フラックスと温度勾配を求めることが出来る。温度勾配から水蒸気勾配を見積もると、最終的に雪の水蒸気拡散係数が求められる。得られた値は $0.9\text{-}1.8\times10^{-5}$ m^2/sの範囲にあり、空気中の値（2.2×10^{-5} m^2/s, 0℃）より小さく、またこれまでの多くの測定値より数倍小さい。一般の多孔質物質における気体拡散と同様に温度勾配のない場合のCO_2拡散係数からは雪試料の屈曲度は1.73 と与えられた。温度勾配下での雪の水蒸気拡散係数を表現するために新たに「拡散増大因子（Diffusion enhancement factor）」という量が提案された。これは、氷と空気の熱伝導の差によって生じる雪内部の局所的温度勾配の影響を表わす。拡散増大因子の値は、実験に使われた雪の場合1.5-3.0と求められた。以上の結果から、過去の研究において異常に大きな雪の水蒸気拡散係数が報告された理由は、波状分布に関連する局所的温度および水蒸気濃度勾配の存在を考慮しなかったためと結論された。

審査員一同は、以上の成果が雪の熱輸送および水蒸気輸送の研究においてこれまで不明確であった点を明かにし、かつ雪氷学全般に寄与するところが大きいこと、また申請者が研究者として誠実かつ熱心であり、大学院課程における研鑽や取得単位等も併せ、申請者が博士（地球環境科学）の学位を受けるに十分な資格を有するものと判定した。