STRUCTURAL PHASE CHANGES OF LIQUID WATER IN ALPINE SNOW

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ABSTRACT: The way free water is arranged in the complex texture of Alpine snow is measured by a series of different methods: Broadband electro-magnetic measurements ranging from radio-frequencies up to the microwave K-Band regime directly allow the detection of the geometrical structure of the water bodies; hydraulic measurements - measurements of water percolation through or water drainage off an Alpine snow cover - show a significant change of water movement characteristics which are caused by changes in the water geometrical configuration (structural phase changes) due to the natural variation in the free water saturation. Structural characteristics of water bodies included in snow are reflected by the dielectric depolarization factors, the special case of ring-shaped water inclusions is reflected by the magnetic permeability.
Field measurements have been carried out in the Alpine regions of the Stubai Alps, Austria, whereby metamorphism of these Alpine snow covers is characterized by several melt-freeze cycles. It results the existence of 4 main regimes of water saturation characterized by different structural properties of the free water bodies: the pendular zone with closed isolated water bodies, a funicular zone with confluent water bodies, a transitional zone where isolated water bodies begin to merge, and a sub-regime included in the pendular zone characterized by the existence of ring-shaped water bodies. Experimental results of a ten-year field study are presented.

KEYWORDS: Snow physics, electromagnetic properties, hydraulic properties

1. INTRODUCTION

Independent of the stage of metamorphism, liquid water in snow exists generally in different geometric arrangements depending on the amount of water present: the pendular regime with two different sub-zones, the funicular regime, a pendular-funicular transition zone and the regime of complete saturation (Colbeck, 1982; Denoth, 1982a). The pendular regime is characterized by isolated closed water bodies and ranges from the adsorbed-liquid limit to saturations at which some of the water bodies coalesce. Recently, the existence of closed ring-shaped water bodies within the pendular regime of Alpine snow which has experienced several freeze-thaw cycles has been proved (Denoth, 1999). The funicular regime at higher saturations shows continuous liquid paths throughout the pore space with an isolated and trapped gaseous phase. The actual arrangement and geometry of the individual components of wet snow - ice, water and air - influences both the electromagnetic and hydraulic response, and this offers a way to experimentally determine water geometry in the different saturation regimes. Experimental results of a ten-year field study are given. Field measurements have been carried out in the Alpine regions of the Stubai Alps in Austria, whereby only old or firn-type snow has been used with mean grain sizes exceeding 1 mm in diameter and which is characterized by several melt - freeze cycles.

2. METHODS AND MATERIALS

Electromagnetic and hydraulic measurements have been done with old or firn-type wet Alpine snow with mean grain sizes exceeding 1 mm. Grain shape and size has been derived from a photographical analysis of the individual snow samples (Denoth, 1982b); snow liquid water content, W, has been measured by a calibrated dielectric probe (Denoth, 1994), snow porosity, Φ, has been calculated from the measured density, and snow water saturation S has been calculated according to $S = W/\Phi$. Electromagnetic measurements have been done using a free-space technique, with the snow

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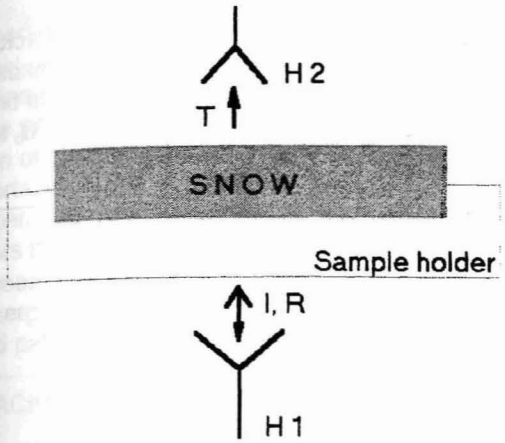

Fig.1 Free-space technique. H1, H2: horn antennas, I,R, T: incident, reflected and transmitted signal.

sample placed in between two high-gain microwave horn antennas. The principle of operation is shown in Fig.1. Reflected and transmitted signals are measured in the frequency range of 6 up to 16 GHz by a network analyzer, model HP8510A. Based on Fresnels formulae, snow dielectric permittivity, $\varepsilon = \varepsilon' - i.\varepsilon''$, and magnetic permeability, $\mu = \mu' - i.\mu''$, have been derived from the measured total reflection and transmission coefficients. Data analysis to deduce structural parameters of the liquid water component is based on the effective-medium model of Polder and van Santen (1946). In this model the geometry of the solid (ice) and the liquid (water) components are described by three-axial ellipsoidal bodies, and are characterized by the corresponding depolarization factors, G_1,G_2, and G_3, with $\Sigma G_i = 1$. Measured snow magnetic permeability is interpreted in terms of the induced diamagnetic effect of conducting water rings around contact zones of ice grains (Denoth, 1999), whereby the fraction of total water forming the rings has been used as fitting parameter. So, the geometrical shape of the water inclusions and the amount of water collected in the special shape of pendular rings can be derived from electromagnetic measurements.

It is obvious that changes in water geometry and arrangement affects the flow characteristics of water in snow. Consequentely, additional information as to the lower limit of the funicular zone or as to the range of bound or immobile water within the pendular zone can be obtained. So, in addition to the electromagnetic measurements, water movement through snow has been studied in the field by long-term drainage and percolation experiments. To be independent on the actual weather conditions, natural melting and/or precipitation rates have been simulated. Experimental setup and data evaluation is described by Wilhelm et al. (1992).

3. EXPERIMENTAL RESULTS

Electric and magnetic permeability of a total of 151 snow samples has been measured in the frequency range of 6 to 16 GHz, whereby water saturation S of the natural snow samples varied from 0% to 40%. Based on Polder and van Santens effective medium model the characteristic shape factors, G_i, have been calculated using least-square fitting routines. Fig.2 and Fig.3 show the dependence on water saturation of G1 and G2, respectively. Regions, where significant changes in the shape factors can be observed are marked by arrows.

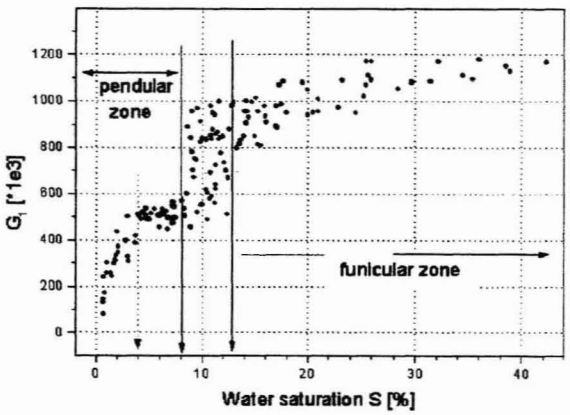

Fig.2. Dependence of shape factor G_1 on liquid water saturation.

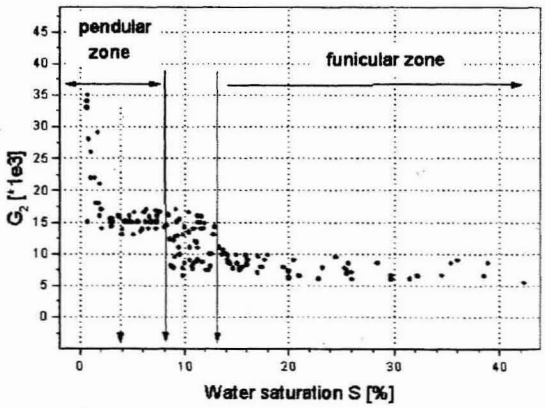

Fig.3. Dependence of shape factor G_2 on liquid water saturation.

Both shape factors, G_1 and G_2, vary significantely with water saturation: funicular and pendular saturation regimes are clearly separated by a transitional zone ranging from S ~8% to ~13% of the pore volume. Within the pendular regime at liquid saturations S lower than a critical saturation, S_c, [$S_c \approx 4\%$], a subzone is formed characterized by a strongly decreasing shape factor G_1: $G_1 \rightarrow 0$. In the subzone $0 < S < S_c$ capillary forces and surface tension may be dominant and control the geometric shape of the water inclusions, for $S > S_c$, gravity forces may play the dominant role.
The dependence of magnetic loss μ" on water saturation is shown in Fig.4 for a selected frequency of f = 14 GHz. Regions, where significant changes in the 'induced' diamagnetic losses can be observed are marked by arrows.

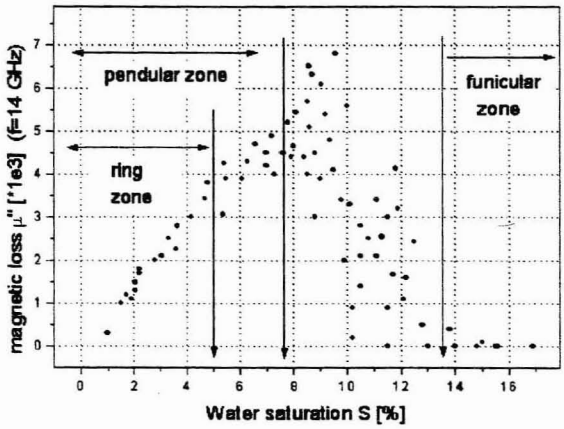

Fig.4. Dependence of magnetic loss on water saturation.

Compared to the low intrinsic magnetic permeability of bulk water, the relative high apparent magnetic losses are caused by electrically conducting ring - shaped water bodies. The range of existence, however, is limited to low water saturations, well within the pendular regime: for saturations less than approximately 5% more or less all the free water seems to be arranged in ring-like structures. For saturations exceeding $\approx 8\%$ magnetic losses decrease drastically, indicating a merging of water rings whereby closed spheroidal water bodies are formed. This transitional zone is followed by a zone characterized by μ" = 0, and this zone compares favorably with the funicular zone defined by the shap factors G_i.

Fig.5. shows a typical characteristic of water volume flux u* shown vs. time t* for two different initial water saturations, S<11%, and S=15%, respectively. To be independent on the actual initial hydraulic conditions of a specific experiment, the measured quantities flux u and time t have been related to intrinsic quantities u_o and t_o: $u^* = u/u_o$, $t^* = t/t_o$.

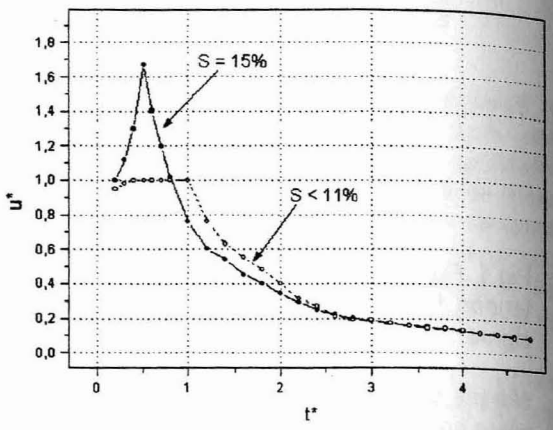

Fig.5. Variation of relative water flux u* with time for initial saturations of S=15% and S<11%.

A detailed analysis of long-term drainage and percolation experiments shows, that the 'gravity flow' theory (Colbeck, 1971) is suitable to model water flux through (homogeneous) snow only for initial saturations less than approximately 14% of the pore volume; for higher saturations considerable higher initial fluxes are observed. This may be explained by the formation of an additional flux in an spacially unstable channel system built up by merging water bodies in the pendular-funicular transition zone. Consequentely, an upper limit of $S \approx 14\%$ for water saturation of the transitional zone is also confirmed by hydraulic measurements. In addition to the measurement of water flux, water saturation has been recorded automatically, and it approaches asymptotically a limiting value S_i with $S_i = S(u^* \rightarrow 0)$: $S_i \approx 4\%$. It may be of interest, that S_i, the irreducible water saturation, compares excellent to the crititcal saturation, S_c, derived by electromagnetic measurements, and S_c and S_i may be identical. Consequentely, the saturation zone $0 < S \leq S_c \equiv S_i$ within the pendular regime is characterized by the domination of caplillary / surface forces over gravitational forces.

4. CONCLUSION

Measurements of the electromagnetic and hydraulic response of wet coarse-grained Alpine snow - which has experienced freeze-thaw-cycles - confirm the existence of ring -

shaped water bodies for saturations less than a critical saturation $S_c \approx 4\%$, where surface forces dominate over gravity forces. This regime is part of the pendular regime which extends to a saturation of $S \approx 8\%$, characterized by the increasing importance of gravity forces. The transition from the pendular regime to the funicular regime occurs in a relatively broad range of saturations between $\approx 8\%$ and $\approx 14\ \%$, and is characterized by merging water bodies building up continuous liquid paths.

5. ACKNOWLEDGEMENTS

The 'Wintersport Tirol AG' is thanked for supporting in part the field experiments made in the Stubai glacier area.

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EFFECT OF SNOW TEXTURE ON SNOWPACK SETTLEMENT RATES

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[EXTENDED ABSTRACT]

KEYWORDS: snow cover simulation, snow cover structure, snow texture, snow physical properties

1 INTRODUCTION

During the exceptional winter 98/99, 7 specially designed sensors were used to record continuously both snowpack settlement and snow temperature in situ at the SLF study site Weissfluhjoch/Davos, 2540 m a.s.l. The viscous behavior of quite different snow layers could thus be monitored under large and rapid natural loading.

It is well known that snow texture effects settlement of the snowpack. New snow, layers of either small rounded grains or larger faceted and cup-shaped crystals as well as wet snow all show different viscous behaviors. In snow-cover models, this effect is taken into account either assigning each type of snow a distinct viscosity law, or e.g. as function of temperature and density or by modeling snow viscosity completely in terms of microstructure parameters such as grain and bond size, bond neck length, coordination number and density. The latter approach was chosen in the Swiss snow-cover model SNOWPACK.

These in situ measurements as well as experiments done in the cold laboratory allowed to find a consistent set of parameters to improve model performance.

2 IN SITU MEASUREMENTS

One of the sensors used for this study is shown in Figure 1. It consist of a balsa wood frame across which a continuous tungsten wire is stretched to record temperature. Its side arms are clipped to two vertical wires serving as both guides and electric connectors to determine the sensor's depth. As snowfall buries the sensor in, the latter settles with the underlying snowpack (Weilenmann, 1999).

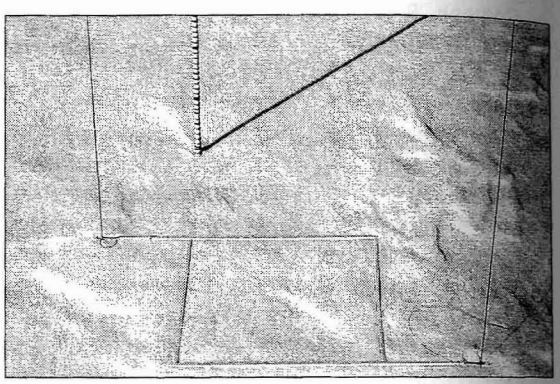

Figure 1 : Settlement and temperature sensor laid on top of the snowpack before a snowfall. The sensor is clipped onto the vertical guiding and depth measuring wires.

3 SNOW COVER MODELING

A full description of SNOWPACK is beyond the scope of this paper and the reader is referred to the publication by Lehning et al. (1999). Nevertheless it is worth mentioning that important properties and processes such as thermal conductivity and viscosity as well as bond and grain growth are based on micro-structural model formulations. Each of these has its own free parameter which has to be adjusted from experimental data. However, because e.g. conductivity and bond growth are related, a consistent set of parameters must be found.

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