HYSTERESIS IN THE WATER RETENTION CURVE OF SNOW MEASURED USING AN MRI SYSTEM

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ABSTRACT: Recently, a compact magnetic resonance (MR) imager was developed for use in a cold-room. A new method for determining the distribution of water in snow is based on the contrast between the MR images of snow and water. This method was used to measure the water retention curves (WRC) of snow. A WRC can be classified as either a “primary wetting curve” (PWC) or a “primary drying curve” (PDC). In this study, both types of WRC were measured directly in the same snow sample at 0°C in a cold-room. The snow sample was placed in a sample case, and 0°C water was added to the case until the lowest few centimeters of the sample were submerged. When the water movement in the sample reached a steady state, the distribution of volumetric water content was measured, and the result was considered to represent a PWC. After measurement of the PWC, the same sample was fully submerged in the 0°C water in the sample case. After 30 min, water was drained from the sample case. The sample was then maintained at 0°C until it reached a steady state. The distribution of volumetric water content was then measured, and the result was considered to represent a PDC. Although the PWC and PDC were obtained for the same snow sample, the shapes of these two curves are strikingly different. This suggests the existence of hysteresis in the WRC of snow, which will be helpful in understanding the processes by which water moves in snow.

1. INTRODUCTION

Recently, we developed a compact magnetic resonance imaging (MRI) system to be used in a −5°C cold-room laboratory to measure the detailed distribution of snow and ice in snow cover.

Although this MRI system can be used to obtain a three-dimensional dataset of snow and ice with a spatial resolution of $(100\ \mu m)^3$, the image range of the system is too small (about 30 mm diameter spherical volume) to measure the three-dimensional distribution of water in snow.

In this study, we introduced a 0.21 T magnet to obtain a larger static magnetic field. Using the MRI system, we attempted to measure the detailed distribution of water in snow.

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2. THE COMPACT MRI SYSTEM

The compact MRI system in this study consisted of a permanent 0.21 T magnet, a gradient coil set, an RF coil, and an MRI console. The MRI console was installed in the laboratory under normal temperature conditions, and the permanent magnet, gradient coil set, and RF coil were installed in a 0°C low-temperature room. The specifications of the permanent magnet were as follows: magnetic field = 0.21 T; gap = 25 cm; homogeneity = 25 ppm over a 0.15 m diameter spherical volume; and weight = 1350 kg (Fig. 1).

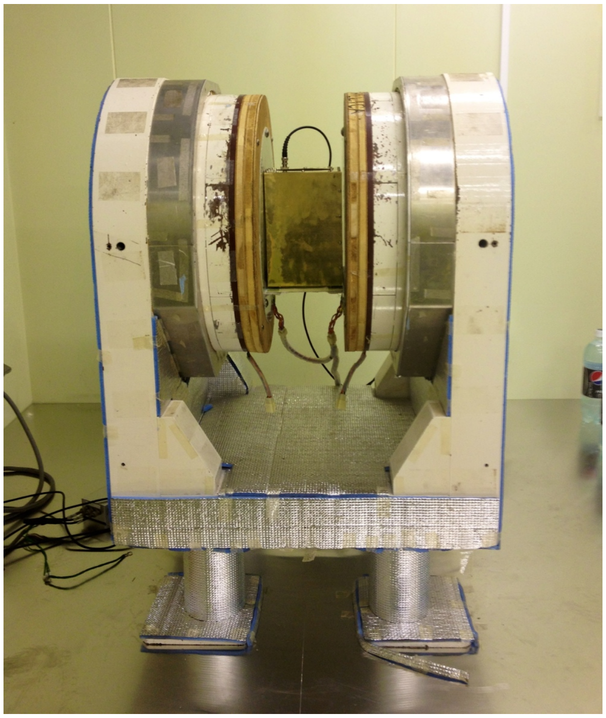

Fig. 1. Permanent magnet (0.12 T)

The RF coil was a 16-turn solenoid wound on an acrylic pipe (0.11 m inner diameter) using a 2.0 mm diameter polyethylene-coated Cu wire and placed at the center of the RF shield box. The solenoid coil was tuned to the NMR resonance frequency (9.03 MHz) and matched to 50 Ω using three variable capacitors. The RF box was fixed in the gap space of the magnet, and the RF coil and the gradient coils were connected to the MRI console. The MRI console consisted of an industrial PC, an MRI transceiver, a transmitter, and a three-channel gradient driver.

3. METHOD

3.1. *Snow samples*

In this study, we used refrozen melt forms that were kept in a cold-room at −10°C for one year. The grain size of each snow sample was controlled by using several sieves having different mesh sizes. We used two different grain sizes: in the first sample, the grain size was from 1.0 to 1.4 mm diameter (representative diameter is 1.0 mm); in the second sample, the grain size was from 2.8 to 3.4 mm diameter (representative diameter is 3.1 mm). The samples were put into an acrylic pipe (8 cm diameter), which was taped so that the densities of the samples were controlled to be 500 kg/m^3. The samples were then extracted from the acrylic pipe, and the columnar snow samples without the acrylic pipe were used in the measurements.

3.2. *Measurement of the water retention curve of snow*

A water retention curve (WRC) can be classified as either a “primary wetting curve” (PWC) or a “primary drying curve” (PDC). In this study, both types of WRCs were measured directly in the same snow samples. A columnar snow sample was put into an acrylic case with a diameter that was sufficiently larger than that of the snow sample. Then, 0°C water was added to the acrylic case until the lowest few centimeters of the sample were submerged. When the water movement in the sample reached a steady state (30 min), the distribution of the volumetric water content was measured using MRI (the method was shown later). We considered this result to be representative of a PWC. After measurement of the PWC, the same sample was fully submerged in the 0°C water in the acrylic case. After 60 min, water was drained from the sample case, and the sample was then maintained at 0°C until it reached a steady state. The distribution of volumetric water content was also measured using MRI, and the result was considered to represent a PDC.

3.3. *Measurement of the distribution of water content in snow using MRI*

To measure the distribution of water content in snow, we used the trabecular bone volume fraction measurement, which is one of the standard methods used in the field of medicine to measure the ratio of bone volume in the body using an MRI system. First, MR image data were measured with a larger pixel size than the snow particles. Then, the luminosity value of the obtained MR image of snow was compared with the luminosity value of a standard substance. The calculated value became the water content in the snow pack, which is given by the following formula:

$$\text{Volumetric water content} = \rho_c/\rho_p * \rho_{e2}/\rho_{e1},$$

where ρ_c is the average luminosity value of the snow pack area, ρ_{e1} is the average luminosity value of the water area, and ρ_p and ρ_{e2} are the average luminosity values in the same range as ρ_c and ρ_{e1} of a standard substance (Fig. 2).

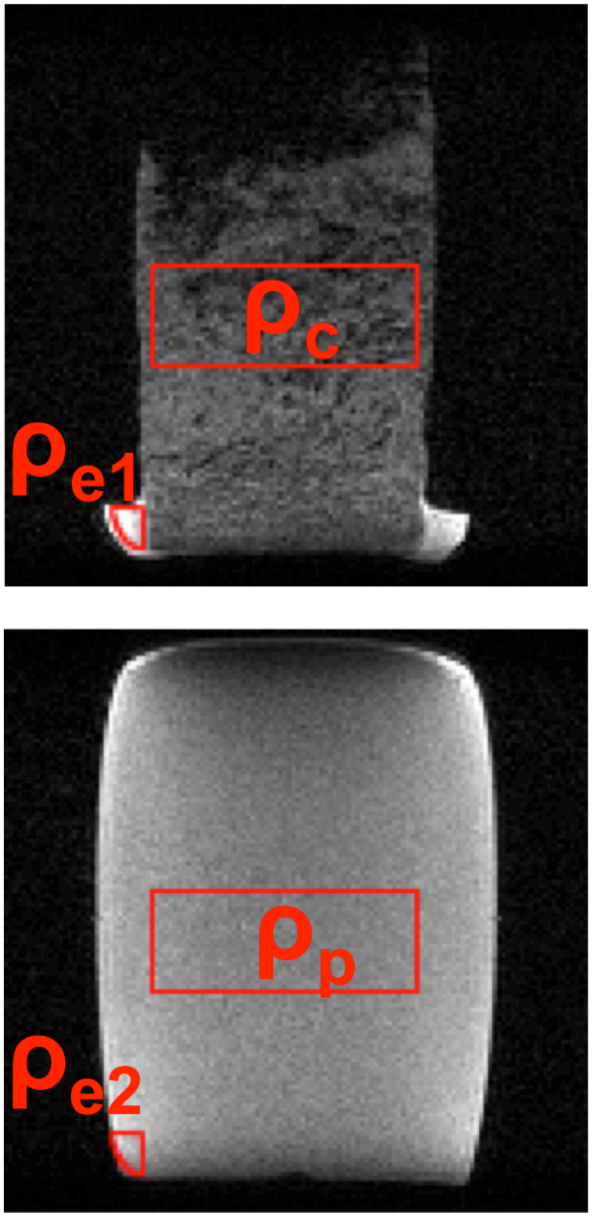

Fig.2. Refrozen melt forms and standard substance MR image

4. RESULTS AND DISCUSSION

Figure 3 illustrates the measured distribution of volumetric water content at the two different grain size samples, with a resolution of every 1 cm in height from the water table level. Although the PWC and PDC were obtained for each snow sample, the shapes of these two types of WRCs are strikingly different: Air entry suction of the PWC is smaller than that of the PDC. Moreover, the ratio of change of the volumetric water content against suction, which is defined as the height from the water table level, also seems to be different between the PWC and the PDC. These results suggest the presence of hysteresis in the WRC of snow. The dependence of the strength of hysteresis of the WRC, taking into account the difference in the PWC and the PDC, becomes larger with a decrease in grain size. This result implies that the strength of hysteresis of the WRC of snow can be formulated using the grain size. Furthermore, it will be helpful in understanding the formation process of the passing of water, which results in preferential penetration.

5. CONCLUSIONS

We have developed a compact MRI system used in a cold-room laboratory to measure the detailed distribution of water content in snow. Using this system, we measure two types of water retention curve (WRC) of the snow samples: a “primary wetting curve” (PWC) and a “primary drying curve” (PDC). We were able to use our system to measure both types of WRCs in the same sample. Therefore, we believe that our system will be a useful tool to measure the detailed conditions of water in snow non-destructively. Our results indicate the existence of hysteresis in the WRC of snow, which will be helpful in understanding the processes by which water moves in snow. Moreover, the strength of hysteresis of the WRC of snow depends on the grain size: hysteresis becomes larger as the grain size decreases. The results of this study, although preliminary, provide good information on the mechanism behind the developmental process of water passing, which results in preferential penetration.

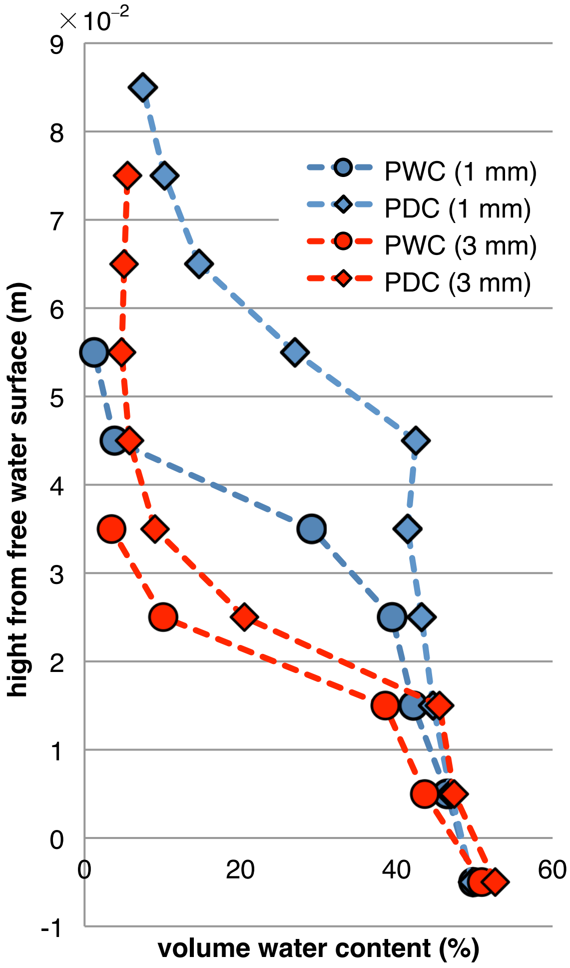

Fig. 3. Water retention curves of refrozen melt forms

5. REFERENCE

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