Low-temperature Thermal diffusion in Rocks

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ABSTRACT: At low temperature, frost weathering due to the freezing/thawing process of pore water can fracture bedrock permafrost, which is of crucial importance in engineering. We focus on the low-temperature thermal diffusion that is primarily fundamental but poorly investigated. The experiment and simulation investigations are conducted on sandstones subject to low-temperature conditions. It shows that the heat capacity of sandstones is more sensitive to temperature at the condition of the low temperature than that at the condition of the high temperature. The thermal conductivity of dry sandstone decreases with temperature at the condition of high temperature. However, it reveals that the thermal conductivity increases with temperature at the condition of low temperature. Besides, the temperature evolution curve for the water-saturated sample remains quasi-constant with the time when the phase transition occurs, which is governed by the pore-size distribution.

Keywords: Heat transfer, Low temperature, Phase transition, Thermal conductivity.

1 INTRODUCTION

Geomaterials are commonly exposed to high temperature and pressure deep underground, and their physical properties have been extensively researched (Chakrabarti et al. 1996 and Wang et al. 2017). In certain regions such as polar areas, however, geomaterials are exposed to low temperatures and contain water, which can freeze. This phenomenon has implications for various aspects of our lives, particularly in understanding the mechanical behavior of porous mediums undergoing phase transitions, such as frost weathering. Freezing and thawing weathering is of great significance to geomorphology, Quaternary science, and engineering (Murton et al. 2006). It is a major cause of damage to transportation infrastructure in regions with seasonal frost, as well as damage to structures and interruptions in pipeline operations in soils susceptible to frost.

Apart from frost weathering, phase transition is the dominant feature during the exploitation of gas hydrates, which are a promising unconventional energy resource found abundantly in permafrost and oceans (Boswell 2009). When phase transition occurs, gas hydrates decompose into gas and water, which disturbs the temperature, pore pressure, and stress fields. Since hydrate decomposition is an endo-thermic process, the temperature field is significantly disrupted during gas hydrate exploitation, leading to a redistribution of the temperature field. The afore-mentioned processes involve heat and mass transfer, accompanied by induced mechanical responses at low temperatures (Coussy 2006).

As previously noted, there is a significant lack of research on thermal properties of geomaterials at low temperatures, which are characterized by the occurrence of freezing and thawing processes (Michalowski & Zhu 2006 and Liu et al. 2018). During phase transition process, heat is stored as specific heat and latent heat. While temperature varies when heat transfer is dominated by specific heat, it remains constant during mutual transformation of liquid water and solid ice. Therefore, heat transfer at low temperatures is not only governed by thermal properties of rock but also by the evolution of ice content, and rocks are a porous medium with a complex pore size distribution. This study addresses experimental and modeling investigations on the phase transition of heat transfer in sandstones.

2 GOVERNING EQUATION

Based on the Fourier's law, we can obtain the most general governing equation of heat transfer combining the heat diffusion equation

$$\rho c \frac{dT}{dt} = \nabla(k \nabla T) \tag{1}$$

where T is temperature, k is the thermal conductivity, W/(m·K), and ∇ is the gradient operator, t is time, s, ρ is the density of rock, kg/m^3, c is the specific heat, J/(kg·K). Heat is transferred in two forms during phase transition: specific heat, which involves a temperature change without a phase transition, and latent heat, which involves a phase change without a temperature change. As a result, the governing equation for heat transfer during phase transition is

$$\left(\rho c - L\rho_i \frac{d\theta_i}{dT}\right)\frac{dT}{dt} = \nabla(k \nabla T) \tag{2}$$

where L is latent heat of fusion per unit mass of water, J/kg, ρ_i is the density of ice, and θ_i is the volumetric fraction of ice. Assuming the phase-transition process is instantaneous, ρc-Lρidθi/dT is termed the equivalent volumetric heat capacity.

Different from freezing of Tm = 0°C at 0.1 MPa, the melting temperature of liquid is not fixed, but depends on the pore size, which is controlled by the Gibbs-Thomson equation (Coussy 2011). The presence of a critical pore radius at a specific temperature is indicated by the findings, which suggest that water will only solidify within pores that are larger than the critical radius. Furthermore, the relation between temperature and ice content can be utilized to determine the distribution of pore sizes, which serves as the fundamental principle behind thermoporometry (Sun & Scherer 2010).

3 EXPERIMENT AND SIMULATION

3.1 *Experiment*

To investigate heat transfer at low temperatures, sandstones saturated with water were subjected to heating tests ranging from -190°C to 20°C. The tested samples were comprised of 95.3% quartz and 4.7% clay minerals and were machined into cylindrical materials of the same size (50 mm in height and 25 mm in diameter). A 6 mm diameter and 20 mm deep hole was drilled in each sample for the placement of a PT100 temperature sensor. Prior to the tests, all samples were dried at 80°C in an oven for one week and subsequently saturated with water at 10 MPa for 24 hours in a water-filled container.

Prior to conducting the heating test, a MIP analysis was conducted to evaluate the pore-size distribution. The total porosity was determined to be 16.2%, with a maximum intrusion pressure of

413 MPa corresponding to a pore radius of 3.0 nm. To prevent the samples from fracturing due to freezing, they were first cooled in a refrigerator to -20°C for 1 hour and subsequently immersed in -190°C for 4 hours. The samples were then removed from the tank and allowed to reach ambient temperature, 20°C, while the temperature evolution was measured using a temperature sensor. Figure 3 illustrates the relation between temperature and time.

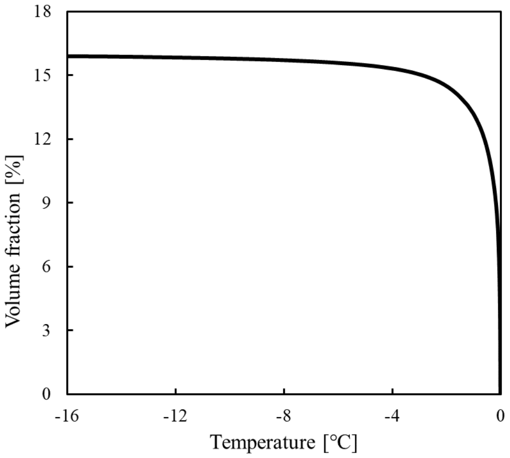

Figure 1. The evolution of the volume fraction of ice with temperature.

3.2 *Simulation*

Regarding the simulation of the dry sample, the curve exhibits an initial concave-up shape as depicted in Figure 2. In the absence of phase transition, the temperature evolution in the dry sample is solely dependent on the thermal conductivity of rock. The thermal conductivity of the rock is temperature-dependent and can be represented as $k = m + nT$, where m and n are material constants. Based on the average experimental data, the calibration process yielded m = 0.4105 W/(m·K), n = 0.0014 W/(m^2·K). The simulated temperature-evolution curve exhibits a close resemblance to the experimental results.

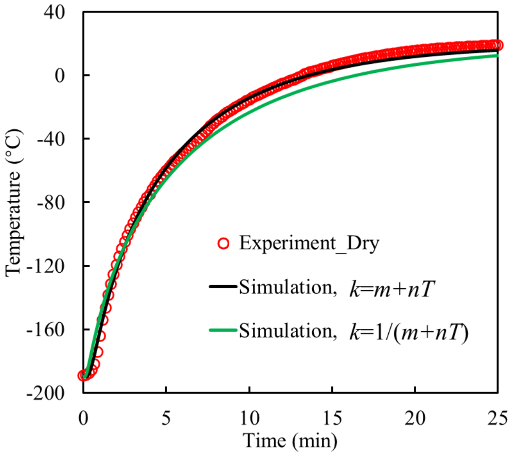

Figure 2. Simulation of the heating tests in dry samples.

It is important to highlight that the calibration process requires the expression $k = m + nT$, where conductivity increases with temperature. This expression differs significantly from the commonly used expression found in the literature, $k = 1/(m + nT)$, which implies a decrease in conductivity with temperature (Wen et al. 2015). It is worth noting that the expression $k = 1/(m + nT)$ is a phenomenological model established by fitting a wide range of rocks in the high-temperature range. However, it appears to be less suitable for sandstones at low temperatures. Both pure quartz and air, the two primary components of the dry sample, possess thermal conductivity that increases with temperature. Therefore, it is suggested that the thermal conductivity of dry sandstone increases with temperature.

Figure 3 illustrates that the temperature evolution of the water-saturated sample exhibits a temperature plateau, the rate of temperature evolution is less than 0.01°C/s around 0°C. The heating test in the water-saturated sample is simulated using the equivalent heat-capacity method. The simulation curve closely reproduces the experimental data in Figure 3, demonstrating the validity of the established model.

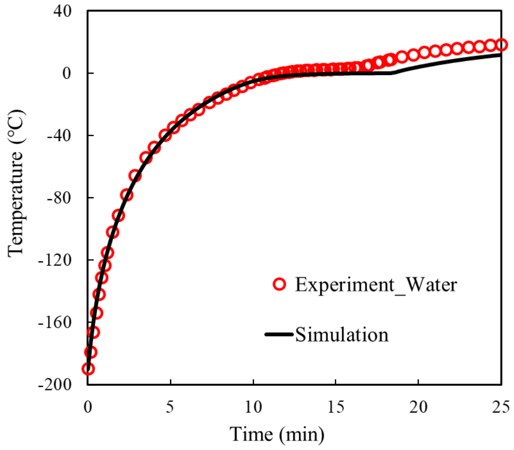

Figure 3. Simulation of the heating tests in water-saturated samples.

The temperature plateau observed in the water-saturated sample is due to the sharp change in the equivalent heat capacity in that temperature range, resulting in a sudden increase in the latent heat term associated with the rapid accumulation of ice content (Figure 1). However, it should be noted that the simulated temperature plateau does not perfectly match the experimental data, as the length of the simulated temperature plateau is longer than that observed in the experiment. This discrepancy may be due to a mis-estimation of the pore-size distribution by MIP, which is caused by the pore-connection effect. Rocks contain a network of pores of different sizes (Diamond 2000 and Kaufmann et al. 2009), and when a pore is connected with smaller entrances, mercury can enter only if the entrances are intruded at higher pressure. In such cases, a larger pore might be mistaken for a smaller one, leading to an underestimation of the pore-size distribution. This is supported by the fact that no pore larger than 10 μm was detected from the MIP data for the tested material. Additionally, the MIP test requires the sample to be dried, which can alter the smaller pores due to induced capillary pressure (Espinosa & Franke 2006). Furthermore, the intrusion pressure used in MIP can reach 413 MPa, causing significant pore deformation.

4 RESULT AND CONCLUSION

In summary, we investigated heat transfer in water-saturated geomaterials at low temperatures using experimental and theoretical approaches.

We developed a governing equation for heat transfer with phase transition and used MIP data to establish the relation between ice content and melting point of pore liquid.

We found that the temperature sensitivity of the heat capacity of sandstone skeleton was more pronounced at low temperatures than at high temperatures. Unlike the commonly documented decreasing tendency of thermal conductivity with increasing temperature in the high-temperature regime, our results revealed that thermal conductivity increased with temperature in the low-temperature regime.

Additionally, our results show that the established model is able to simulate the heat transfer process of water-saturated sandstone with phase transition around 0°C, and that the temperature evolution curve featured a plateau regime influenced by phase transition. The position and length of this plateau were found to be governed by the pore size distribution, enabling us to assess the variation of the temperature field in the heat transfer process with phase transition using only the pore size distribution of geomaterials.

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