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Effective thermal conductivity of thermokarst lake ice in Beiluhe Basin, Qinghai-Tibet Plateau

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ABSTRACT

Effective thermal conductivity (ETC) of thermokarst lake ice (TLI) is a key factor in simulating the ice processes in permafrost regions of Qinghai-Tibet Plateau (QTP). Typical TLI blocks sampled from central QTP were prepared to measure their ETC in vertical and horizontal directions at various temperatures. The ETC values of TLI are ranging between 1.60 and 2.10 W/(mK). The ETC values in both directions are very close, and change obviously along the ice depth. The ETC of TLI increases monotonously with decreasing ice temperature between 0 and 25 °C. Both the theoretical modeling and experimental results demonstrate the effects of gas pore structures on ETC of TLI. The temperature-averaged ETC decreases gradually as the porosity increases. A simple linear combination of two structural models is proposed for predicting the ETC against the porosity by introducing an empirical coefficient. This coefficient is controlled by the gas pore size, content, shape and configuration.

1. Introduction

Lakes and rivers exist extensively in Qinghai-Tibet Plateau (QTP), and an increasing number of thermokarst lakes (refer to the collapsed depressions of talik resulted from thawing of ice-rich permafrost and melting of massive segregated ground ice lens overlain beneath) have formed and are forming probably as a result of recorded climate and permafrost warming and human activities (Lin et al., 2010; Niu et al., 2008). Due to high latitude and cold temperature, rivers and lakes are overlain by thick seasonal ice covers for over 7 months from November to May of the following year. Thermokarst lake ice on QTP has an unusual inner structure, such as gas inclusions and ice crystal pattern, compared with ice covers in plain lakes and rivers (Huang et al., 2012). So researches on QTP ice are likely to extend our understanding of natural ice.

Thermokarst lake ice (TLI) is supposed to be a seasonal component in finer local QTP climate and environmental system (Kääb and Haeberli, 2001; Lin et al., 2010), but has been always ignored by researchers due to their small areal fractions. To improve and refine the atmosphere-ice/water-permafrost models, and ice thickening and thinning simulations, accurate representations of both mechanical and thermodynamic properties, and physics of ice and permafrost are required fundamentally (Arp et al., 2011; Kääb and Haeberli, 2001; Lin et al., 2010; Wolfe and Thieme, 1963). Our focus in this study is the thermal conductivity, which controls the thermodynamic accretion rate, equilibrium thickness and conductive heat flux through the ice (Ashton, 2011; Pringle et al., 2007; Shen, 2010).

Based on salinity and forming environment and mechanism, natural TLI is considered as fresh ice. Previous findings have proved that mechanical and thermal properties of fresh ice, natural and artificial, have a rigorous effect of ice temperature, i.e. ice is a temperature-sensitive material (Fukusako, 1990; Gow and Ueda, 1989). Due to the low porosity of lake and river ice observed previously, the effects of the content and structure of gas pores were neglected. However, TLI over the QTP is characterized by high porosity and big gas pores with relatively regular shape (Huang et al., 2012), which probably makes it unique and beyond the validations of most of the existed numerical models predicting fresh ice ETC (Fukusako, 1990; Klinger, 1975). Therefore, TLI can be regarded as two-component (air-ice) and two-phase (gas-solid) heterogeneous compound, namely porous material. Multi-component porous media is always highlighted extensively and has been simulated theoretically and been investigated experimentally (Hamilton and Crosser, 1962; Molina et al., 2009) to estimate their effective thermal conductivity (ETC) (Dondero et al., 2011; Wang et al., 2008).

Firstly, this paper made a brief review of the structural models for ETC estimation of porous heterogeneous materials. Secondly, direct measurements of ETC of TLI specimens were conducted in laboratory. The gas pore structures were also measured using CT (computerized

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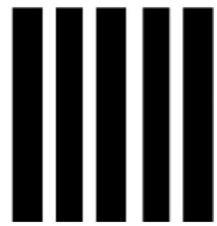
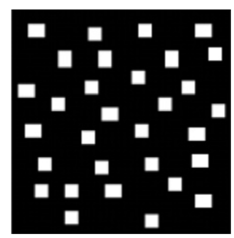
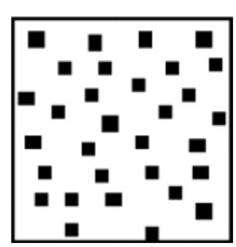
tomography) technology. Finally, this paper presented the results and discussed the effects of ice crystal, heat conduction direction, ice temperature and pore structure on the ETC. The intercomparisons of these results with the values calculated by various structural models were also discussed, and a new semi-empirical equation was formulated to estimate the ETC of TLI.

2. Estimation of ETC for porous heterogeneous materials

Natural fresh lake and river ice were used to be considered as pure ice with attention to thermal conductivity, due to their low porosity and small size pores. However, structural observations indicated that gas pores of large size are incorporated into the TLI covers on

Table 1
Five fundamental ETC structural models for two-component two-phase materials (assuming the heat flow is in the vertical direction). The solid phase is black, and gas phase is white in these figures.

Model	ETC equation	Structure schematic	Reference
Parallel model	$\lambda_e = \nu_1\lambda_1 + \nu_2\lambda_2$		
Maxwell–Eucken 1 (ME1) [λ_1 = continuous phase, λ_2 = dispersed phase]	$\lambda_e = \frac{\nu_1\lambda_1 + \nu_2\lambda_2\frac{3\lambda_1}{2\lambda_1+\lambda_2}}{\nu_1 + \nu_2\frac{3\lambda_1}{2\lambda_1+\lambda_2}}$		Maxwell, 1954; Eucken, 1940
Effective Media Theory (EMT)	$\nu_1\frac{\lambda_1-\lambda_e}{\nu_1+2\lambda_e} + \nu_2\frac{\lambda_2-\lambda_e}{\nu_2+2\lambda_e} = 0$		Landauer, 1952; Böttcher, 1952
Co-Continuous Model (CC)	$\nu_1\frac{(\lambda_1-\lambda_e)(2\lambda_1+\lambda_e)}{\lambda_1} + \nu_2\frac{(\lambda_2-\lambda_e)(2\lambda_2+\lambda_e)}{\lambda_2} = 0$		Wang et al., 2008
Maxwell–Eucken 2 (ME2) [λ_1 = dispersed phase, λ_2 = continuous phase]	$\lambda_e = \frac{\nu_2\lambda_2 + \nu_1\lambda_1\frac{3\lambda_2}{2\lambda_2+\lambda_1}}{\nu_2\lambda_2 + \nu_1\lambda_1\frac{3\lambda_2}{2\lambda_2+\lambda_1}}$		Maxwell, 1954; Eucken, 1940
Series model	$\lambda_e = \frac{1}{\nu_1/\lambda_1 + \nu_2/\lambda_2}$