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Heat transfer at ice-water interface under conditions of low flow velocities*

Nan LI（李楠）, You-cai TUO（脱友才）, Yun DENG（邓云）, Jia LI（李嘉）, Rui-feng LIANG（梁瑞峰）, Rui-dong AN（安瑞冬）
State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China, E-mail: linanscu@163.com

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Abstract: The heat transfer at the ice-water interface is closely related to the hydrodynamic and physical properties of the water body. It affects the ice cover thickness and the water temperature underlying the ice cover. This paper studies the heat transfer from the water to the ice cover. Based on the flume data, a linear relationship between the ice-water heat transfer coefficient and the flow velocity beneath the ice cover is established and the calculated dimensionless ice-water heat transfer coefficient is 1.1×10^{-3}. This empirical relationship can be applied to estimate the ice-water heat transfer of reservoirs, lakes and other freshwater bodies when the flow velocity under the ice cover is in the range of 0.024 m/s-0.110 m/s.

Key words: ice cover, heat exchange, ice-water heat transfer coefficient, low flow velocity, laboratory experiment

Introduction

The formation of ice cover is an important phenomenon in cold regions[1,2]. Ice in surface water bodies changes the hydraulic and thermal conditions of rivers, lakes and reservoirs[3,4]. The ice cover influences the operation of water resource projects, leads to reductions in power generation[5,6], causes ice disasters such as ice dam and ice flood[7,8], and hinders energy and mass exchanges between air and water, resulting in adverse effects on biological environment[9].

The thermal growth and decay of an ice cover is governed by heat-exchanges at the air-ice and ice-water interfaces. The ice-water heat transfer coefficient, which reflects the rate of heat exchange between the ice cover and the underlying water, is an important parameter for quantifying the heat flux at the ice-water interface, the thickness of ice cover, and the water temperature underneath the ice cover. During the past few decades, the heat-exchanges at the ice-water interface in rivers, lakes and oceans were extensively studied. The turbulent heat transfer from the flowing river water to the ice cover is shown to have a significant effect on the thickness of the ice cover, especially during the decay period when the water temperature is above the freezing point[3]. The thermal growth and melting of the lake ice is primarily a vertical one-dimensional heat transfer process[10-12]. It is possible to estimate the heat exchange flux between ice and water by a bulk formula[13]

$$q_{wi} = \rho_w c_w C_h u_w (T_w - T_0) \tag{1}$$

in which, ρ_w is the density of water, c_w is the specific heat of water, C_h is the dimensionless ice-water heat transfer coefficient, u_w is the current speed, T_w is the water temperature, and T_0 is the freezing point.

With considerations of the surface roughness, the ice thickness, the current and the temperature under ice, Hamblin and Carmack[14] estimated the dimensionless ice-water heat transfer coefficient C_h to be $(0.8\pm0.3)\times10^{-3}$ in lakes of Yukon River Basin, which is smaller than that was found in sea ice studies.

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Biography: Nan LI (1987-), Male, Ph. D. Candidate
Corresponding author: You-cai TUO,
E-mail: tuoyoucai@scu.edu.cn

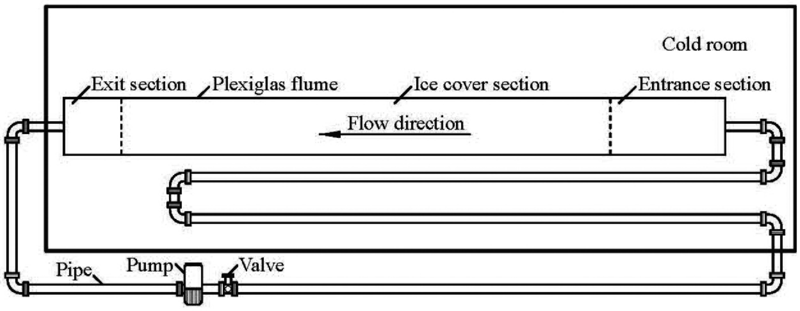

Fig.1 Schematic diagram of the experimental device

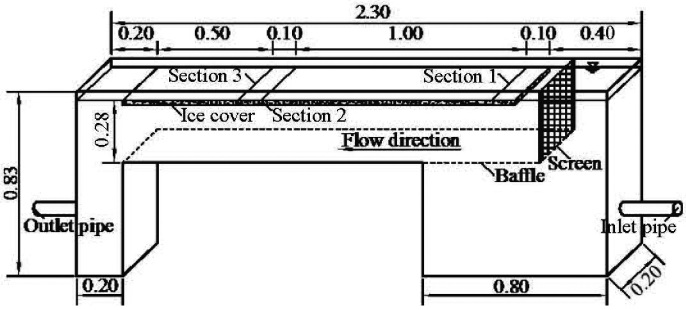

Fig.2 Detailed structures of the plexiglas flume (m)

Shirasawa et al.[15] obtained C_h of a value 0.39×10^{-3} from the HANKO and the BALTEX/BASIS experiments and used 2.0×10^{-3} as the value of C_h to calculate the ice-water heat flux in Saroma-ko Lagoon. Ji et al.[13] computed C_h to be $(0.16-0.50)\times10^{-3}$ through field observations in Bohai Sea in different periods, and found that the coefficient had a positive relation with the thickness of the ice cover and the roughness of the bottom surface of the ice cover.

However, the ice-water heat transfer coefficient is closely related to the hydrodynamic and physical properties of the water body. When the dimensionless ice-water heat transfer coefficients C_h mentioned above are applied to particular situations, it is found that they are not satisfactory for the water body under low flow conditions such as a reservoir.

The field observation method to study ice-water heat exchange involves many difficulties and various uncontrollable factors. No detailed laboratory study has been made to determine the ice-water heat transfer coefficient. In this study, a laboratory experiment is conducted to investigate the heat exchange from water to ice cover to establish an empirical formula for the ice-water heat transfer coefficient under low flow conditions.

1. Experimental setup

1.1 *Flume design*

The experiment is conducted in a small plexiglas flume of 4.0 m (length)×3.0 m (width)×2.0 m (height) in a cold room (Fig.1). The flume is wrapped with polyethylene plastic foam to prevent the heat exchange from sidewalls. A screen is installed in the entrance section, which makes the flow uniformly distributed. An ice cover is formed in the flume in each test. Figure 2 shows the detailed structures of the plexiglas flume.

1.2 *Instrumentation*

The measured data in the experiment include the flow velocity, the ice thickness variation, the ice temperature and the water temperature. Figure 3 is a photo of the experimental device and the measuring instruments.

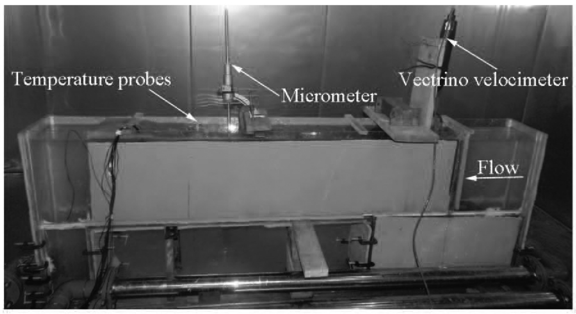

Fig.3 Photo of the experimental device and measuring instruments

The flow measuring section is 0.50 m from the entrance (Section 1, Fig.2). A Vectrino velocimeter