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Simulation of the Melting Process of Ice Slurry for Energy Storage Using a Two-Fluid Lattice Boltzmann Method

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Abstract

Ice slurry can be used as the thermal storage media in latent cool storage systems for both residential and commercial buildings. This paper presents the investigation of the phase change characteristics of the ice slurry using a two-fluid Lattice Boltzmann Method (TFLBM). The melting and migration processes of the ice slurry are simulated by improving the equilibrium distribution function and matching the relevant parameters such as the kinetic viscosity of ice particle cluster and cross-collision coefficient. The sensitivity analysis of the ice slurry viscosity and cross-collision coefficient are achieved through six numerical experiments, and the ice melting in the internal-melt ice-on-coil thermal storage device is then calculated. The results could be potentially used to guide the design of the ice slurry for cooling both residential and commercial buildings.

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Keywords: Ice storage; Phase change; TFLBM; Numerical simulation

1. Introduction

Over the last two decades, the energy and environment issues have attracted intensive attention. The air-conditioning systems account for a large proportion of total energy consumption worldwide. In order to alleviate this

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issue, air-conditioning systems incorporated with cold storage are being considered as a promising solution [1]. Solid-liquid phase change materials (PCMs) can absorb and release a large amount of thermal energy within a small temperature range [2] and are one of the alternative storage media for cold storage systems. As the most commonly used PCMs, ice slurry, which is composed of water and ice particles, has been extensively studied. So far, the thermal storage technology using ice, called ice storage, is generally divided into two types [3]: dynamic storage and static storage. Chaichana [4] developed a computer model to compare energy use in conventional air cooling systems and ice thermal storage systems. Under Thailand electricity tariff rates, the results showed that the ice thermal storage can save energy up to 55%. Koller [5] constructed and experimentally investigated an ice storage unit, which was implemented in the cooling system of an institute building. Long-term measurements of the system showed good in-service behaviours of the ice store. Ruan [6] analyzed the building combined cooling, heating and power (BCHP) plants with an ice storage system, and determined the optimal capacities and operating schedules. However, the ice storage system also brings some difficulties during the preparation, preservation and transportation processes. In practice, the melting and migration always happen because of partially adiabatic tank/tube and density difference between ice particles and water. Thus, optimal design of thermal storage systems for ice slurry requires a thorough understanding of interfacial transport phenomena within the slurry. Because the experimental measurement of interphase interaction in ice slurry is challenging, numerical models with different levels of complexity have been developed and used to analyze such systems [2, 7].

Two traditional methods based on Navier-Stokes equations [8] and molecular dynamics equations [9], are often used in CFD studies. Both methods are differentiated as macroscopic and microscopic schemes, respectively. Eulerian-Eulerian approach or Mixture approach has a high efficiency without an accurate description of the phase interface, while direct numerical simulation (DNS) or molecular dynamics simulation (MDS) requires a significant amount of computational resources [2]. As a powerful alternative to the above two methods, Lattice Boltzmann Method (LBM) bridges the gap between them, which is referred as a mesoscopic scheme. Although LBM is limited by low Mach number (i.e. the velocity is far less than the speed of sound), it is not a key problem in this study as most practical binary mixtures have a slow melting process in real applications [10].

In this paper, the migration and phase transition between water and ice particle cluster are presented. Based on the existing two-fluid Lattice Boltzmann Method (TFLBM) [11], in which cross- and self-collisions are treated independently, TFLBM for a melting ice storage system is developed by improving the equilibrium distribution function and matching the relevant parameters. Sections 2 and 3 describe the TFLBM model and its key parameters, respectively. A sensitivity analysis of collisions terms and numerical simulations of the melting and migration processes are then discussed in the internal-melt ice-on-coil thermal storage device in Section 4. Section 5 provides some conclusions and further development in this direction.

2. The Two-Fluid Lattice Boltzmann Model

The lattice Boltzmann equation was initially derived from the lattice gas automata (LGA) theory. It is also considered as a specially discretized form of the Boltzmann equation in time, space and particular velocity spaces [12]. The popular LBMs divide the physical region into regular special lattices, and the grid point of the lattice is called lattice site. Microscopic particles are put into each site, where they can only move from one site to its neighboring sites within one computational step (Δt). This movement is often referred to as propagation or streaming.

$$\begin{aligned} &\text{collision} \quad f_i(x,t+\Delta t) - f_i(x,t) = \mathbf{\Omega}_i \\ &\text{streaming} \quad f_i(x+c_i\Delta t, t+\Delta t) = f_i(x,t+\Delta t) \end{aligned} \tag{1}$$

where the subscript i means the predefined propagation directions, $\mathbf{\Omega}_i$ is a collision operator, f_i represents the probabilities of the distributions in the specified directions i. For the sake of simplicity without loss of generality, the D2Q9 discrete velocity model with two dimensions and nine predefined propagation directions was used in this study.