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

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Outlines

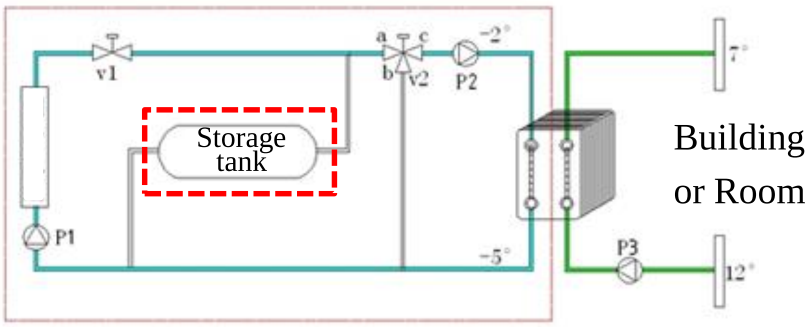
1. Background
2. Mathematical models
3. Solution cases and results
4. Conclusions

Background

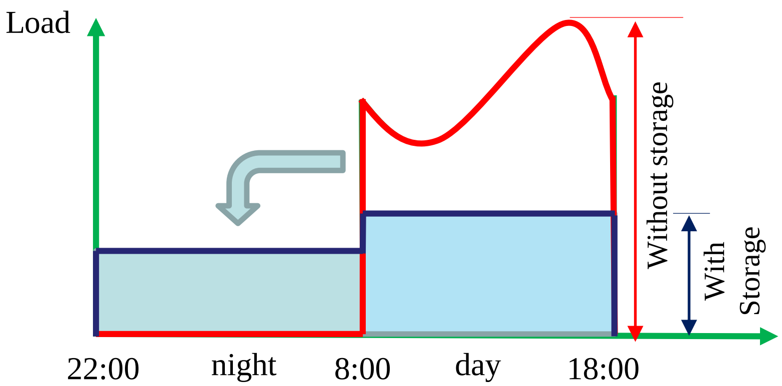
Conventional air conditioning systems used in buildings

V.S.

Air-conditioning systems incorporated with ice storage



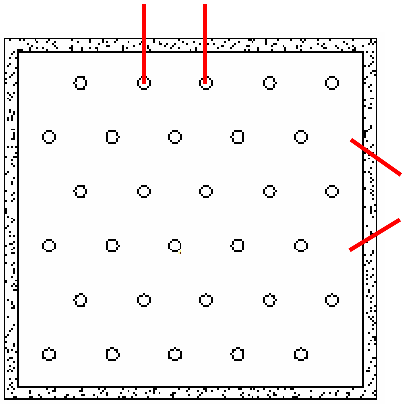
Schematic diagram of thermal storage system



Load of thermal storage system

Research status

Ice storage device



Cross section

The tube side is *one-dimensional* time dependent model

The tank side is *lumped capacity* time-dependent model

Background

Main drawbacks:

Existing models usually focused on a single pipe of the tank. Heat transfer among adjacent pipes and convection effect on ice melting were ignored or treated as empirical functions.

Conventional CFD methods need expensive computational cost for moving boundaries (melting or solidification problems).

Background

Lattice Boltzmann Method (LBM):

Introduced by McNamara and Zanetti in 1988.

LBM was originated from lattice gas automata (LGA) method, and can be used to derive the Navier-Stokes (NS) equations.

Advantages over conventional CFD:

- The convective operator is completely linear
- No iterate to solve mass and momentum equations
- Process the complicated boundary geometries easily
- Explicit scheme and local interactions
- ……

Outlines

Two-Fluid Lattice Boltzmann Method (TFLBM):

the particle distribution function

Collision operator

collision $$f_i(x, t+\Delta t) - f_i(x,t) = \Omega_i$$

streaming $$f_i(x + c_i \Delta t, t+\Delta t) = f_i(x, t+\Delta t)$$

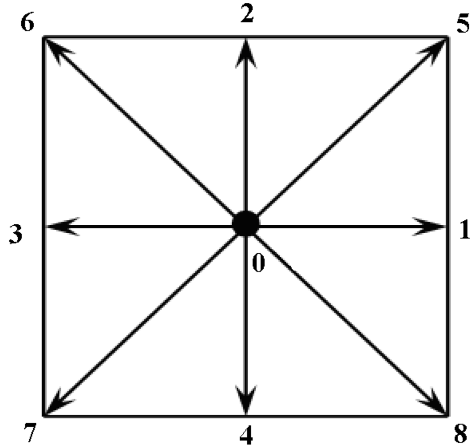
$$\rho_\sigma = \sum_{i=0}^{8} f_i^\sigma \qquad \rho_\varsigma = \sum_{i=0}^{8} f_i^\varsigma$$

$$u_\sigma = \frac{1}{\rho_\sigma}\sum_{i=0}^{8} f_i^\sigma c_i \qquad u_\varsigma = \frac{1}{\rho_\varsigma}\sum_{i=0}^{8} f_i^\varsigma c_i$$

$$\rho = \rho_\sigma + \rho_\varsigma$$

$$\rho u = \rho_\sigma u_\sigma + \rho_\varsigma u_\varsigma$$

D2Q9



A.A. Mohamad. Lattice Boltzmann method: fundamentals and engineering applications with computer codes [M]. Springer, 2011.

Mathematical models

Self-collision Body force

Collision operator: $\Omega_i^{\sigma} = \Omega_i^{\sigma\sigma} + \Omega_i^{\sigma\varsigma} - F_i^{\sigma}\Delta t$

Cross-collision

$$\Omega_i^{\sigma\sigma} = -\frac{1}{\tau_\sigma}\left[f_i^{\sigma} - f_i^{\sigma(0)} \right]$$

$$\Omega_i^{\sigma\varsigma} = -\frac{1}{\tau_D}\frac{\rho_\varsigma}{\rho}\frac{f_i^{\sigma(eq)}}{c_s^2}(c_i - u)\cdot(u_\sigma - u_\varsigma)$$

$$F_i^{\sigma} = -w_i\rho_\sigma\frac{c_i \cdot a_\sigma}{c_s^2}$$

$$f_i^{\sigma(0)} = f_i^{\sigma(eq)}\left[1 + \frac{1}{c_s^2}(c_i - u)\cdot(u_\sigma - u)\right]$$

$$f_i^{\sigma(eq)} = w_i\rho_\sigma\left[1 + \frac{(c_i \cdot u)}{c_s^2} + \frac{(c_i \cdot u)^2}{2c_s^4} - \frac{u^2}{2c_s^2}\right]$$

Mathematical models

Parameters Description

Self-collision τ_σ:

The kinetic viscosity of water or ice particle cluster

$$\tau_\sigma = 3\frac{\Delta t^2}{\Delta x^2}\nu_\sigma + \frac{1}{2}\Delta t$$

Cross-collision τ_{D}:

Interaction between water and ice particle cluster

$$\tau_D = f\left(Q, R, F, \cdots\right)$$

supplied heat Q, the rate of melting R, interaction force between ice particle and water F, and others…

Mathematical models

Features of the TFLBM

- The density, instead of temperature, is used to describe the phase change process.
- The kinetic viscosity of each phase and the melting characters are independent.
- The melting and migration process of ice cluster can be added to the TFLBM by the cross-collision.
- The detailed function relationship of cross-collision coefficient needs to be further studied.
- …

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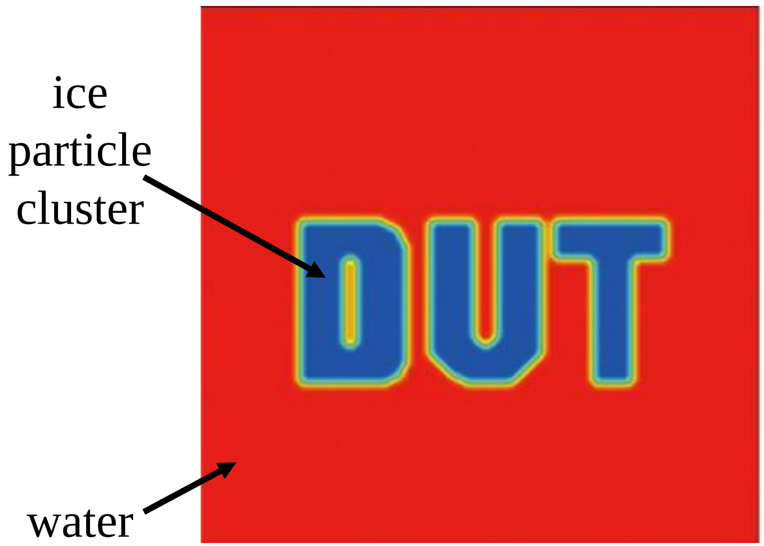
Test cases for the TFLBM



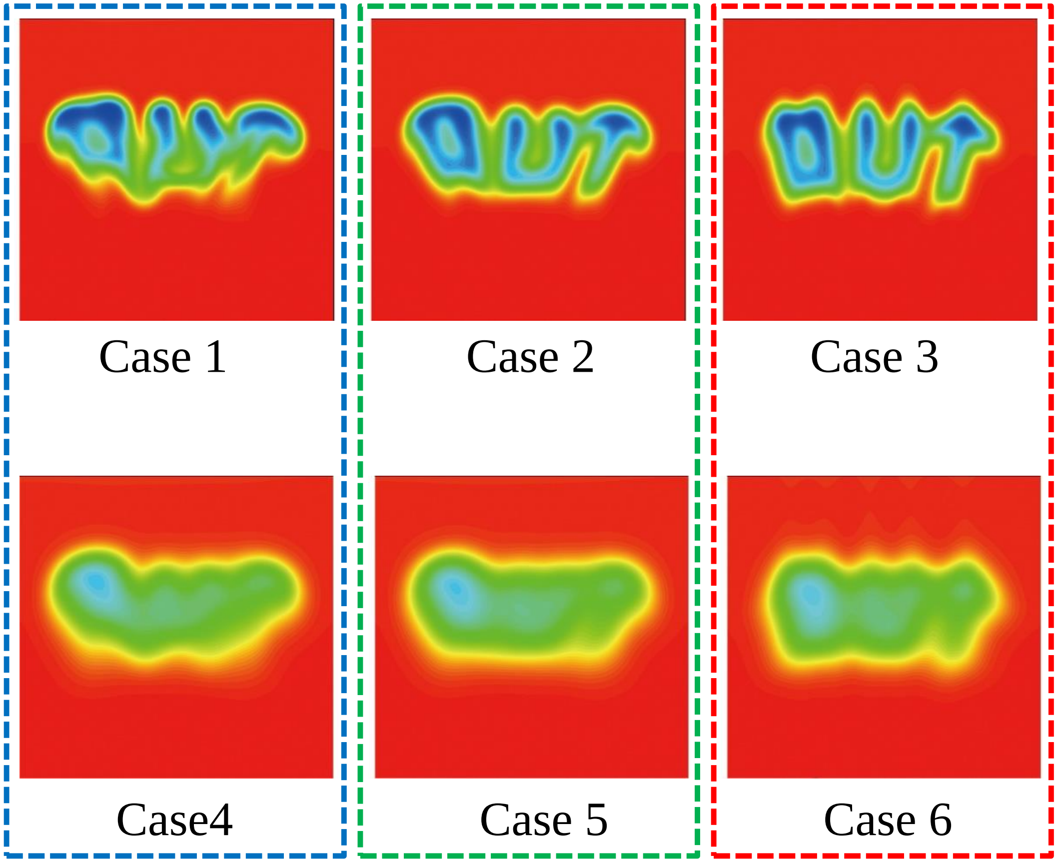
Initial state

<table>
<tr><th>Case</th><th>τ_{D}</th><th>τ_{water}</th><th>τ_{ice}</th></tr>
<tr><td>1</td><td rowspan="3">0.55</td><td rowspan="6">0.6</td><td>0.6</td></tr>
<tr><td>2</td><td>2.0</td></tr>
<tr><td>3</td><td>10.0</td></tr>
<tr><td>4</td><td rowspan="3">0.75</td><td>0.6</td></tr>
<tr><td>5</td><td>2.0</td></tr>
<tr><td>6</td><td>10.0</td></tr>
</table>

Parameters

Solution cases and results

Results of the 200th step



Case 1 Case 2 Case 3

Case4 Case 5 Case 6

Case	τ_D	τ_{water}	τ_{ice}
1			0.6
2	0.55		2.0
3		0.6	10.0
4			0.6
5	0.75		2.0
6			10.0

Parameters

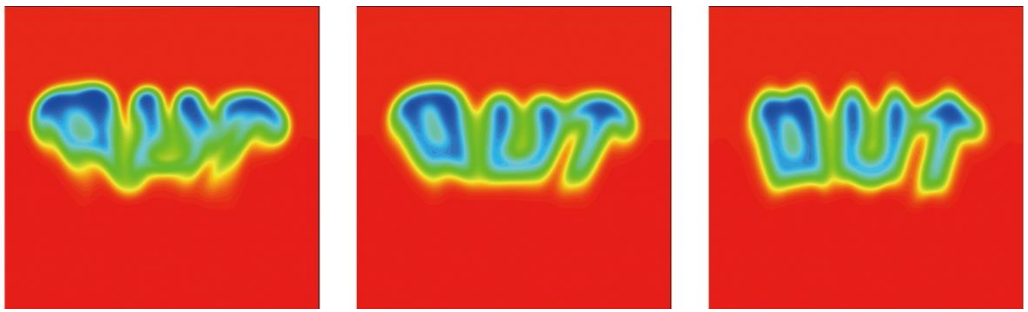
The same τ_{ice} and τ_{water}

Different τ_D

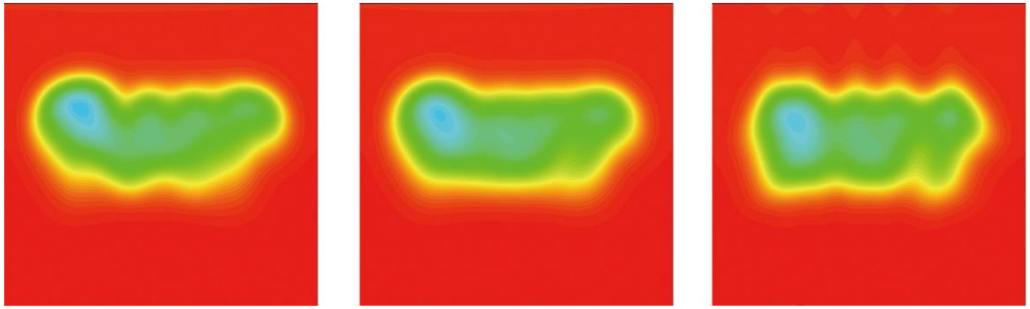
Large τ_D cause a big size of ice particle cluster, i.e., a fast melting of ice.

Solution cases and results

Results of the 200th step



Case 1 Case 2 Case 3



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Parameters

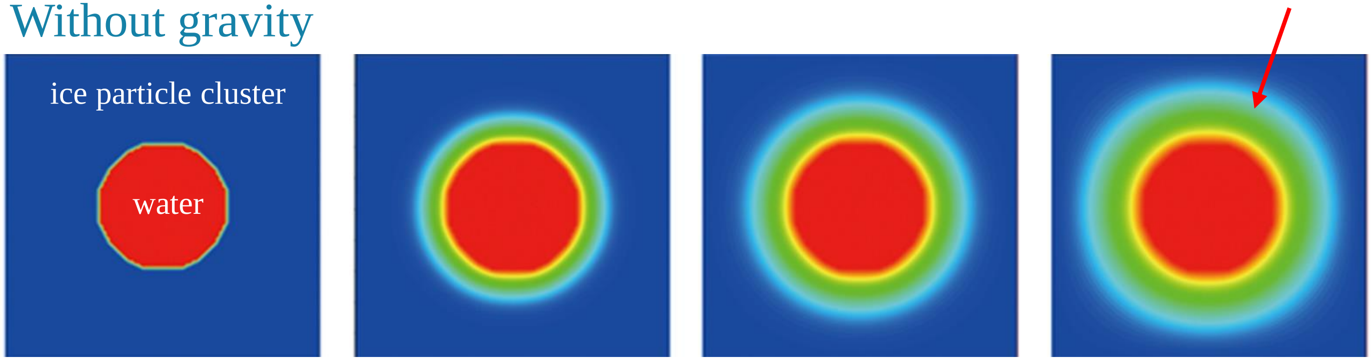
The same τ_D and τ_{water}

Different τ_{ice}

The shape of ice cluster is close to the initial shape of "DUT" with an increase of τ_{ice}.

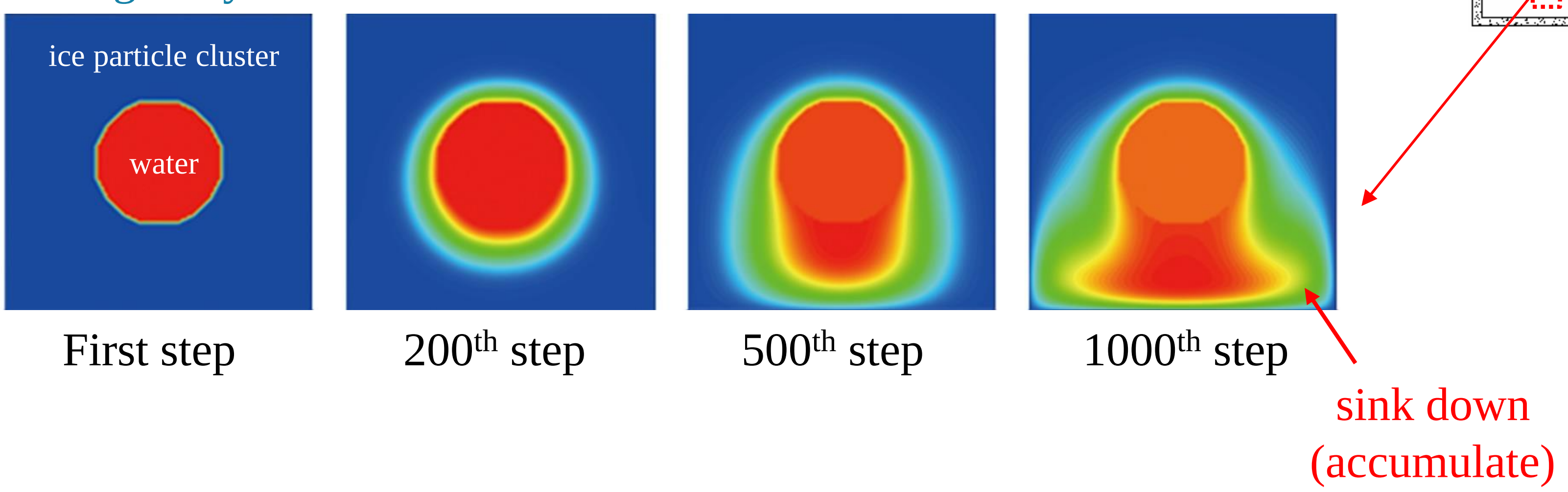
Results:

Without gravity



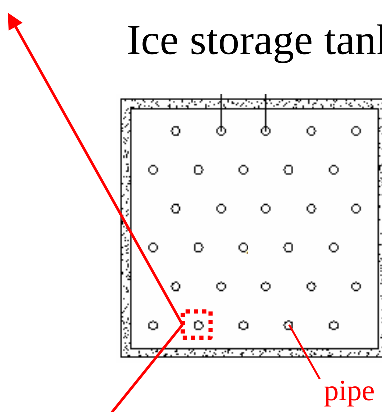
First step — 200th step — 500th step — 1000th step

With gravity



First step — 200th step — 500th step — 1000th step

Ice storage tank



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Conclusions

TFLBM for melting ice storage system was developed.

The melting process of the ice cluster is mainly governed by the relaxation time for cross-collision.

The deformation behavior and migratory ability of the ice cluster are mainly affected by its viscosity.

This work provides an insight on the design process which was followed to build an optimal cool storage device for cooling of both residential and commercial buildings.

Thanks for your attention!