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# A lattice Boltzmann model for solidification of water droplet on cold flat plate

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ABSTRACT

Since the solidification of water droplet is the initial and essential process in the whole process of frosting, a model is developed by the lattice Boltzmann method (LBM) that applies the velocity and temperature distribution functions to investigate the solidification process of water droplet on cold flat plate. The thermal transport and liquid–solid phase transition in the present model are both based on the pseudo-potential model combined with the enthalpy formation. By this LB model, the solidification process is simulated in form of temperature and solid phase variations in water droplet on cold flat plate, and the shape of solid phase in freezing can also be predicted. In addition, we apply the present LB model to preliminarily study the frost formation process. Numerical results agree well with our experimental data.



# Un moèle lattice Boltzmann pour la solidification de gouttelette d'eau sur plate plane froide

*Mots clés :* Méthode lattice Boltzmann ; LBM ; Solidification ; Gouttelette d'eau ; Plaque plane froide

## 1. Introduction

The frost formation has important effects on many fields, such as refrigeration industry, air-conditioning, aviation, etc. The process of frost formation combined with transient heat and mass transfer is extremely complex, which will happen only if the temperature of cold flat plate is less than 0 °C and the ambient dew point temperature. The presence of frost will deteriorate refrigeration capacity due to lower heat transfer coefficient and higher pressure drop, and defrosting will lead to higher energy consumption and operation cost. Hayashi et al. (1977) photographed the whole process of frost formation, which was divided largely into three stages: crystal growth period, frost layer growth period and frost layer full growth period. Over the last several decades, research has focused on frost layer growth and frost layer full growth period by physical–mathematical and experimental methods (Lee et al., 1997; Matsumoto et al., 2014; Yang et al., 2006; Yun et al., 2002). As the inception of crystal growth period, the solidification of water

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## Nomenclature

| | |
|---|---|
| $c_p$ | heat capacity (J K$^{-1}$) |
| $c_s$ | isothermal sound velocity (m s$^{-1}$) |
| $\mathbf{e}_i$ | discrete velocity |
| $F$ | total force (N) |
| $F_g$ | gravity force (N) |
| $F_t$ | fluid–solid interaction force (N) |
| $F_\sigma$ | fluid–fluid interaction force (N) |
| $f_i$ | velocity distribution function |
| $f_s$ | volume fraction of solid phase |
| $G$ | fluid–fluid interaction coefficient |
| $G_t$ | fluid–solid interaction coefficient |
| $G(\mathbf{x},\mathbf{x}')$ | Green's function |
| $H$ | total enthalpy (J) |
| $H_e$ | enthalpy value at the end of freezing (J) |
| $H_s$ | enthalpy value at the start of freezing (J) |
| $k$ | Boltzmann constant (J K$^{-1}$) |
| $R$ | universal gas constant (J mol$^{-1}$ K$^{-1}$) |
| $RH$ | relative humidity |
| $r$ | droplet radius (mm) |
| $s(\mathbf{x}+\mathbf{e}_i)$ | indicator function of solid phase |
| $T$ | temperature (°C) |
| $T_i$ | temperature distribution function |
| $t$ | time (s) |
| $\mathbf{u}$ | velocity (m s$^{-1}$) |
| $V$ | volume of water droplet (μl) |
| $\upsilon$ | velocity of air (m s$^{-1}$) |
| $\mathbf{x}$ | position |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$ s$^{-1}$) |
| $\delta h$ | latent heat of phase transition (J kg$^{-1}$) |
| $\delta x$ | lattice spacing |
| $\delta t$ | time step |
| $\theta$ | contact angle (rad) |
| $\upsilon$ | kinematic viscosity (m$^2$ s$^{-1}$) |
| $\rho$ | density of fluid phase (kg m$^{-3}$) |
| $\sigma$ | interfacial energy (kJ m$^{-2}$) |
| $\tau$, $\tau_c$ | dimensionless relaxation time |
| $\Phi_t$ | source term |
| $\varphi(\mathbf{x})$ | function of local densities |
| $\omega_i$ | weight coefficient |

*Subscripts and superscripts*

| | |
|---|---|
| a | air |
| w | cold flat plate |
| $i$ | direction in a lattice |
| eq | equilibrium |

droplet has an essential role in the whole process of frosting and attracted more and more attention recently. The study of solidification has been conducted in many fields, such as metal processing (Mortensen and Jin, 1992), solidification of castings (Cantor and O'Reilly, 2002) and energy storage system (Esen, 2000; Esen and Ayhan, 1996; Esen et al., 1998), but few aiming at water droplet solidification in frost formation. Hoke et al. (2000) used a high speed camera to observe the freezing process of droplets on a variety of plates and found that the structure and form of the ice immediately after freezing are plate dependent. Tabakova and Feuillebois (2004) constructed a numerical model by the finite-difference fully implicit scheme which can be used to simulate the solidification and subsequent cooling of a supercooled liquid droplet. Wu et al. (2007) investigated the freezing of supercooled condensate droplets in the frost formation, and the freezing onset time and diameter of condensate droplets were characterized. Bahadur et al. (2011) developed a physics-based model to predict ice formation on cooled superhydrophobic plates resulting from the impact of supercooled water droplets, and this modeling approach analyzed the multiple phenomena influencing ice formation on superhydrophobic plates. Despite several studies have been conducted on solidification of water droplet on cold plate, both the temperature distribution and phase transition process in droplet are still not entirely clear from experimental and analytical results. Thus, an elaborate numerical simulation considering thermal transport is required to predict the phase transition process and temperature field of such freezing water droplet.

The lattice Boltzmann method (LBM) has become a particularly successful scheme to simulate fluid flow and complex physical phenomena (Aidun and Clausen, 2010; Chen and Doolen, 1998; Shan and Chen, 1993; Sheikholeslami et al., 2014; Yu et al., 2003). LBM can also effectively simulate the heat and mass transfer in porous media and phase transition. Jiaung et al. (2001) acted as pioneer in applying the enthalpy equation in LB model to simulate liquid–solid phase transition, and numerical results obtained from the improved LB model agreed well with previous analytical or numerical results in the literatures. Guo et al. (2002) first proposed a LB model considering porosity in the equilibrium distribution function, which was improved by Guo and Zhao (2005) to solve convection heat transfer problems and simulate temperature field in porous media. Semma et al. (2008) adopted LBM for solving melting and solidification problems, which was first validated for natural convection with or without coupling of phase transition. Eshraghi and Felicelli (2012) developed a LB model to solve the heat conduction problem with phase transition, and good accuracy was demonstrated compared to finite element method. LBM has the advantages of simple implementation, capability for simulating highly complex geometries and boundaries, computational efficiency and inherent parallel-processing structure in comparison with traditional numerical methods (Eshraghi and Felicelli, 2012). In addition, owing to its statistical roots, LBM might be a more elaborate method to cover the kinetic aspects of the liquid/solid phase transition, especially the interaction of flow and growth kinetics (Miller, 2001). In present paper, our purpose is to simulate the solidification process of water droplet combined with both phase transition and complex boundaries. However, different LB models have different limitations in scopes and conditions of application (Guo and Zheng, 2009; He et al., 2009). The phase transition model and pseudo-potential model are applied in present paper. The phase transition model based on the enthalpy is unable to solve the influence of the phase