VIBRATION MODEL OF FALLING FILM FLOW BASED ON LATTICE BOLTZMANN METHOD

Huayu Zhang[1], Hongtao Gao[1*], Yuying Yan[2]

[1]Institute of Refrigeration & Cryogenics Engineering, Dalian Maritime University, 116026, Dalian, China
[2]Fluids & Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

1. INTRODUCE

Falling film flow process is a key process in absorption refrigeration, which is mostly used in fixed places, and it is still immature in mobile equipment such as ships and automobiles. About 50% of the energy of a ship's engine becomes waste heat, which can be used to drive absorption refrigeration. However, the sloshing and vibration of the hull during sailing will cause unstable vibration of the liquid film, thereby affecting the heat transfer to the wall. Therefore, the vibration problem is a problem that has to be faced when the absorption refrigeration system is applied to ships or automobiles.

The lattice Boltzmann method (LBM) is based on the mesoscopic method, which interprets the macroscopic behaviour of microscopic particles and realizes the simulation effect of the flow field. Not only that, LBM can spontaneously form a liquid film surface without tracking the surface, which has advantages in simulating falling film flow.

The existing literature shows some studies on the falling film flow by the LBM. A. Hantsch and U. Gross [1] use the LBM to simulate the flow effect of different Reynolds numbers and the falling film flow under the pulsating inlet velocity. Shi etc. [2] further simulate the random variation of the inlet velocity.

In this paper, a stable falling film flow LBM model will be established, and the actual physical dimensions will be obtained. The feasibility of the model is verified by the obtained pressure, density and velocity results. Then a falling film flow in a vibrating state is established, and the flow effect of the liquid film depends entirely on the simple harmonic vibration outside the hypothetical device. Vibration-induced vorticity changes are analysed.

2. BASIC MODEL

2.1. Lattice Boltzmann model

In the lattice Boltzmann model, the D2Q9 model is used to simulate a two-dimensional flow field, in which the particles on the lattice node are distributed in 9 velocity directions in the form of probability. The particle distribution function f is represented by the speed discrete form of the Boltzmann equation:

$$f_i(\boldsymbol{x}+\boldsymbol{c}_i\delta t, t+\delta t) = f_i(\boldsymbol{x}, t) - \frac{1}{\tau}[f_i(\boldsymbol{x}, t) - f_i^{eq}(\rho, \boldsymbol{u})] \tag{1}$$

Shan and Chen [3] proposed a pseudopotential scheme to simulate a multi-component multi-phase flow model. They embodied the interaction of fluids through non-local forces in the flow field. The potential function as follows:

$$V_{\sigma\bar{\sigma}} = G_{\sigma\bar{\sigma}}\psi_\sigma\psi_{\bar{\sigma}} \tag{2}$$

*Corresponding Author: gaohongtao@dlmu.edu.cn

To implement the evaluation of the potential function in the LBM model, the Green function G is only valid for adjacent grid points, and the potential function is discretized as follows:

$$\boldsymbol{F}_\sigma(\boldsymbol{x}) = -\psi_\sigma(\boldsymbol{x}) \sum_{\bar{\sigma}} G^{\sigma\bar{\sigma}} \sum_i \omega_i \psi_{\bar{\sigma}}(\boldsymbol{x} + \boldsymbol{c}_i)\boldsymbol{c}_i \tag{3}$$

Fluid density and momentum are statistical results of distribution functions that satisfy the following equations:

$$\rho_\sigma = \sum_i f_i \tag{4}$$

$$\rho \boldsymbol{u} = \sum_\sigma \rho_\sigma \boldsymbol{u}_\sigma + \delta_t \sum_\sigma \boldsymbol{F}_\sigma /2 \tag{5}$$

The fluid evolution relies on equilibrium distribution f^{eq}, which is related to density and equilibrium velocity. To implement the force applied into the model, Shan and Doolen proposed a fluid equilibrium velocity as follows:

$$\boldsymbol{u}_\sigma^{eq} = \sum_\sigma \frac{\rho_\sigma \boldsymbol{u}_\sigma}{\tau_\sigma} \Big/ \sum_\sigma \frac{\rho_\sigma}{\tau_\sigma} + \tau_\sigma \delta_t \frac{\boldsymbol{F}_\sigma}{\rho_\sigma} \tag{6}$$

The discretized form of f^{eq} is:

$$f_i^{eq} = \omega_i \rho \left[1+3\cdot\boldsymbol{c}_i\boldsymbol{u}^{eq}+\frac{9}{2}\cdot|\boldsymbol{c}_i\boldsymbol{u}^{eq}|^2-\frac{3}{2}|\boldsymbol{u}^{eq}|^2\right] \tag{7}$$

2.2. Falling film model

When the device represented by the model performs simple harmonic motion, the motion of the device outside the flow field can be presented as $A\sin(2\pi f t)$. Taking the second derivative of the equation of motion with respect to time, the vibration of the fluid is obtained as follows:

$$\boldsymbol{F}_{vib} = -\rho(2\pi f)^2 A\sin(2\pi f t) \tag{8}$$

The forces on the fluid in the simple harmonic vibration model include component repulsion, gravity, and vibration:

$$\boldsymbol{F} = \boldsymbol{F}_{pseudo} + \boldsymbol{F}_{gravity} + \boldsymbol{F}_{vib} \tag{9}$$

2.3. Macro equation

Compared with traditional CFD, LBM method can describe the exact behavior of fluids at different scales. Through the Chapman-Enskog multi-scale analysis, equation (1) can be restored to the mass and momentum equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{10}$$

$$\frac{\partial(\rho \boldsymbol{u})}{\partial t} + \nabla \cdot \rho \boldsymbol{u}\boldsymbol{u} = -\nabla p + \nabla \cdot [\rho\nu(\nabla \boldsymbol{u})+(\nabla \boldsymbol{u})^T] \tag{11}$$

When the fluid density does not change much, the equation can be regarded as the standard incompressible fluid governing equation. The pressure p is related to the fluid density and Green's function G:

$$p_\sigma = \left(c_s^2 \Sigma_\sigma \rho_\sigma + \Sigma_{\sigma,\bar{\sigma}} G_{\sigma\bar{\sigma}} \psi_\sigma \psi_{\bar{\sigma}}\right) \rho_\sigma / \sum_\sigma \rho_\sigma \tag{12}$$

The fluid viscosity is a function of dimensionless relaxation time:

$$\nu = c_s^2 (\tau - 1/2) \delta_t \tag{13}$$

3. MODEL BUILDING

The basic design of the falling film flow model is shown in the Fig.1, using the D2Q9 plane model.

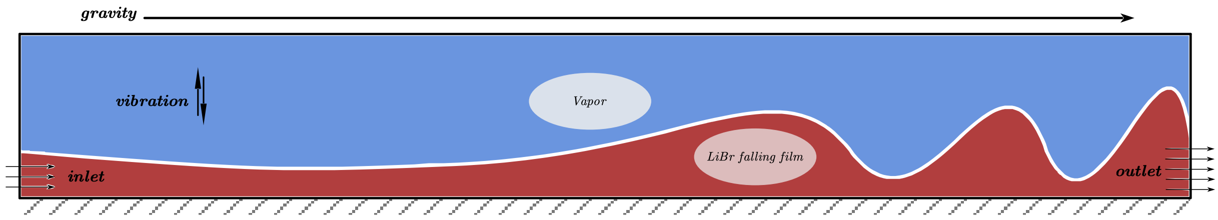

Figure 1: Falling film flow diagram.

An absorber using lithium bromide-water as working medium pair is selected as the reference working environment. And the fluid parameters refer to the actual working lithium bromide solution, shown in the Tab.1.

Table 1: Parameters of the experimental program.

Parameters	Values
Liquid film density/kg·m^{-3}	1699.7
Working pressure/Pa	1000
Viscosity/m^2·s^{-1}	3.15×10^{-6}
Reynolds number (Re)	5

The Reynolds number (Re) takes the film thickness as the characteristic length and the average inlet velocity as the characteristic velocity:

$$\mathrm{Re} = {}^{\bar{u}_x \delta}/_{\nu} \tag{14}$$

Where the average speed $\bar{u}_x$ is obtained by integrating the Nusselt velocity:

$$u_x = g \cdot (\delta \cdot y - y^2/2)/\nu \tag{15}$$

$$\bar{u}_x = \int_0^\delta \frac{u_x}{\delta} dy = \frac{(3g-1)\delta^2}{6\nu} \tag{16}$$

Finally, the liquid film thickness δ and the average inlet velocity $\bar{u}_x$ can be obtained from Re:

$$\delta = \sqrt[3]{3\mathrm{Re} \cdot \nu^2 / g} \tag{17}$$

$$\bar{u}_x = \mathrm{Re} \cdot \nu / \delta \tag{18}$$

In the model, the liquid film flow length is set to $100\times\delta$, and the vibration direction is normal to the film flow direction. The bottom of the model is set as the rebound boundary, the right side is the free outlet boundary, the left side below the liquid film thickness is the velocity inlet boundary, and the rest are the pressure inlet boundary.

4. RESULTS ANALYSIS

4.1. General falling film flow

Fig.2 shows the flow state when the falling film flow instant is located at 0.6 times the characteristic time t0. A characteristic time t0 represents the time it takes for a fluid unit to enter from the inlet to leave the outlet. Fig.2(a) shows how the falling film flow is well represented in the LBM model, which is well confirmed by the waves on the surface of the liquid film. Fig.2(b) shows the variation of the pressure gradient, the pressure obtained in the model matches the actual pressure set. Fig.2(c) shows the longitudinal velocity obtained from the LBM model compared with the theoretical Nusselt velocity, it can be seen that it is almost consistent. The fluctuation of the liquid film causes the actual velocity of the liquid surface to deviate from the theoretical velocity.

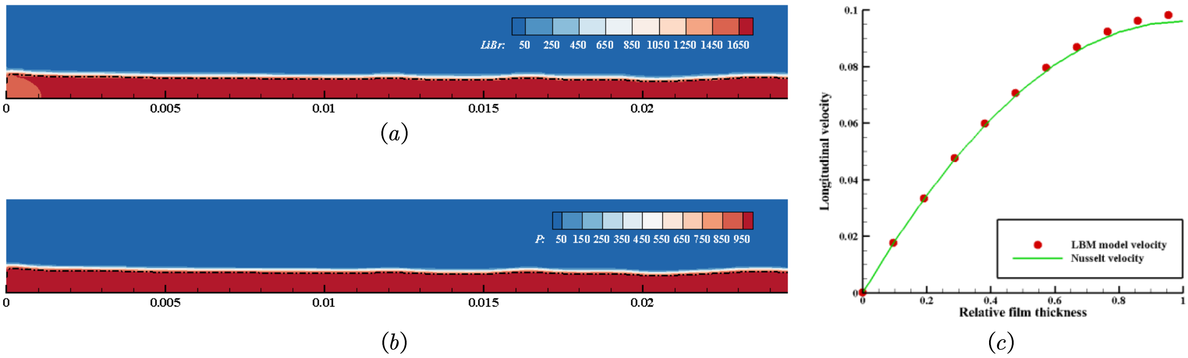

Figure 2: Flow state diagram at flow time $0.6\times t_0$. (a) LiBr density distribution; (b) Pressure distribution; (c) Comparison of longitudinal velocity in LBM model with Nusselt's theoretical longitudinal velocity.

4.2. 50Hz vibration model

Fig.3 shows the vibration effect when the frequency is 50 Hz and the amplitude is 4 times the liquid film thickness. Obviously, compared with the ordinary falling film flow, the liquid film shows periodic fluctuations. Fig.3(b) and Fig.3(c) show the change of flow field vorticity when the wave rises and falls. It can be seen that the rise of wave front vorticity causes the liquid film to fluctuate, while the rise of wave back vorticity causes the liquid surface wave to fall.

Fig.4(a) shows the flow effect when the frequency is 50 Hz and the amplitude is 5 times the thickness of the liquid film. When the flow is at $0.6\times t_0$, the fluid leaves the wall by the vibration effect, which is also the beginning of the liquid film rupture. Fig.4(b)(c)(d) shows the evolution of vorticity as a droplet leaving the wall flows over time. From the change of vorticity, it can be seen that the droplet is moved by gravity and rotates clockwise after escaping.

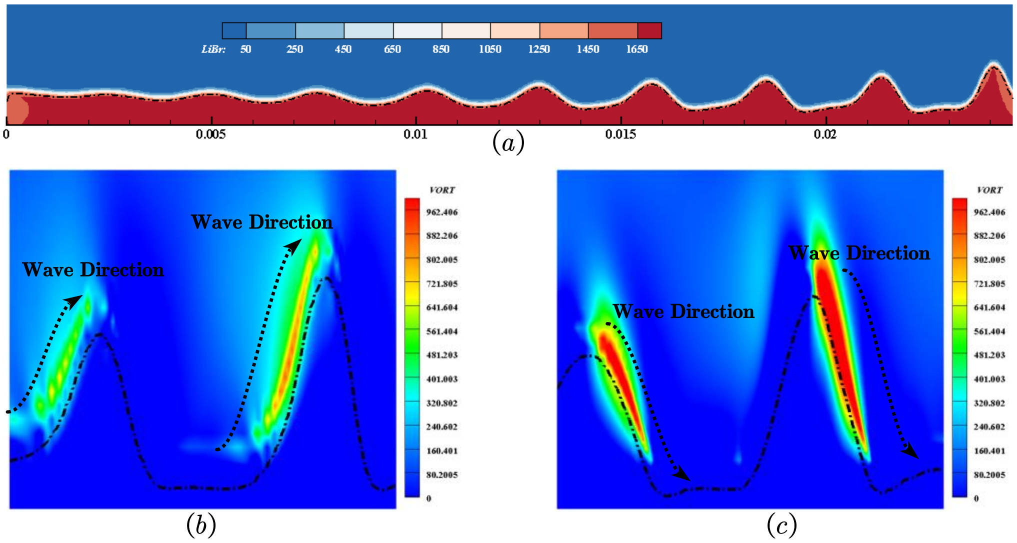

Figure 3: Flow state when the amplitude is $4\times\delta$. (a) The liquid film distribution at the flow time of $0.74\times t_0$; (b) The vorticity distribution when the liquid film wave rises; (c) The vorticity distribution when the liquid film wave descends.

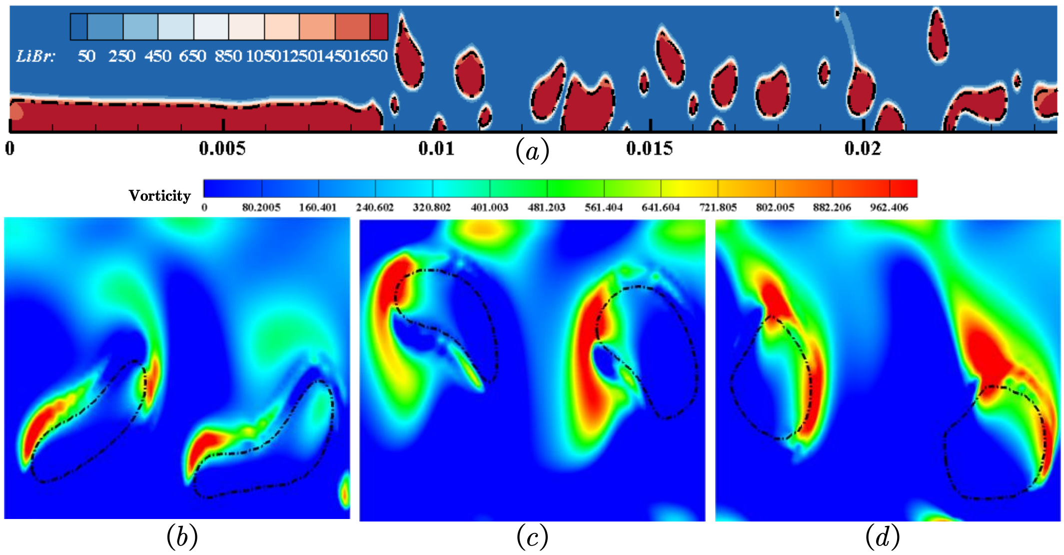

Figure 4: Flow state when the amplitude is $5\times\delta$. (a) The liquid film distribution at the flow time of $0.6\times t_0$; (b)(c)(d) The time-varying distribution of the vorticity around the droplet detached from the wall.

4.3. Vibration model with an amplitude of 1×δ

Fig.5 shows the falling film flow state at an amplitude of $1\times\delta$ and a vibration frequency of 100 Hz and 200 Hz, respectively. Compared with low-frequency vibration, when the liquid film flows along the wall, the waves generated by the vibration are denser, and the distance between the peak and the valley does not decrease due to the decrease in amplitude, but increases. This means an increase in the contact area with the refrigerant vapour, which is very beneficial in the actual falling film absorption process. The vorticity change due to vibration is not significantly different compared to low frequency vibration.

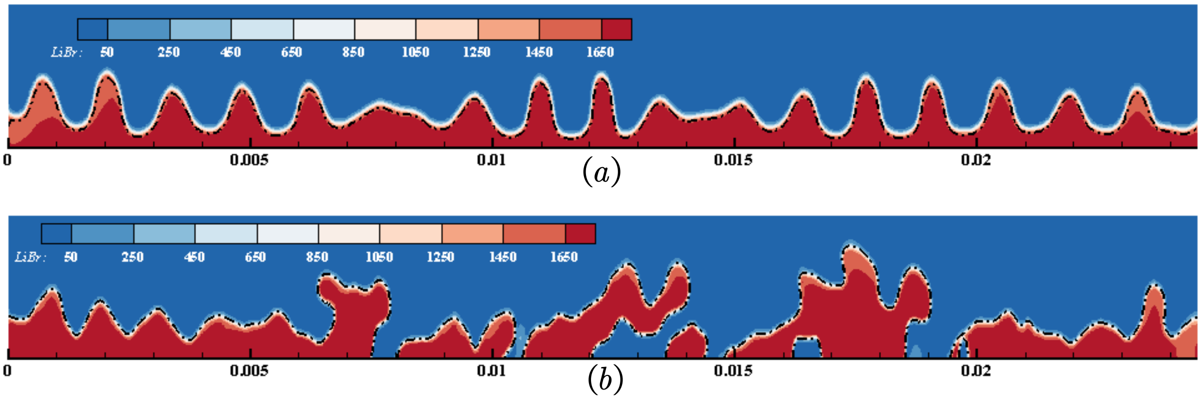

Figure 5: Flow state when the amplitude is $1\times\delta$. (a) Frequency is 100Hz (b) Frequency is 200Hz

5. CONCLUSIONS

In this paper, a falling-film flow model based on the LBM equation is established, and the pressure, density and velocity distributions that conform to the theoretical values are obtained. The falling film flow with vibration force was realized by the force model of LBM, the vorticity change caused by the liquid film fluctuation during the vibration process was obtained, the flow distribution of the liquid film detaching from the wall was simulated, and stable results were obtained. Falling-film flow under high-frequency low-amplitude flow conditions produces denser surface waves than low-frequency high-amplitude flow, and the distance between peaks and troughs does not decrease due to the decrease in amplitude. No matter what scale the vibration is, it will increase the contact area with the environment to varying degrees. In applications such as absorbers that require a large contact area, appropriate vibration will have a beneficial effect.

ACKNOWLEDGEMENTS

This work was financially supported by Research funds of the Maritime Safety Administration of the People's Republic of China(2012_27), and the Fundamental Research Funds for the Central Universities (3132019305).

REFERENCES

[1] A. Hantsch, U. Gross, Numerical simulation of falling liquid film flow on a vertical plane by two-phase lattice Boltzmann method, *J. Eng.* **2013** (2013).

[2] Y. Shi, G. Chen, Q. Wang, Q. Chen, Simulation on falling film absorption based on lattice Boltzmann method at moderate Reynolds number, *Int. J. Heat Mass Transf.* **128** (2019) 991-998.

[3] X. Shan, H. Chen, Lattice Boltzmann model for simulating flows with multiple phases and components, *Phys. Rev. E* **47** (1993) 1815.