International Journal of Heat and Mass Transfer 87 (2015) 576–582

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Free surface entropic lattice Boltzmann simulations of film condensation on vertical hydrophilic plates

Morten A. Hygum [a,*], Iliya V. Karlin [b], Vladimir N. Popok [a]

[a] Department of Physics and Nanotechnology, Aalborg University, 9220 Aalborg, Denmark
[b] Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 31 March 2015
Accepted 11 April 2015
Available online 2 May 2015

Keywords:
Film condensation
Entropic lattice Boltzmann
Free surface lattice Boltzmann

ABSTRACT

A model for vapor condensation on vertical hydrophilic surfaces is developed using the entropic lattice Boltzmann method extended with a free surface formulation of the evaporation–condensation problem. The model is validated with the steady liquid film formation on a flat vertical wall. It is shown that the model is in a good agreement with the classical Nusselt equations for the laminar flow regime. Comparisons of the present model with other empirical models also demonstrate good agreement beyond the laminar regime. This allows the film condensation modeling at high film Reynolds numbers without fitting, tuning or empirical parameters.

1. Introduction

Condensation processes play a crucial role in various engineering and scientific aspects affecting energy conversion, safety and reliability issues as well as design aspects of devices and constructions. Condensation can be divided into two main types: dropwise and film condensation [1,2]. Dropwise condensation occurs on hydrophobic surfaces. Alternatively, condensate can wet the surface and form a film. This case is typical for hydrophilic surfaces. Since the thermal resistance is low at dropwise condensation the heat transfer is significantly higher than for the film condensation. Moreover, in order to consider droplet formation, a number of parameters need to be taken into account and modeling becomes rather involved. Therefore, a majority of the models are developed for the film condensation.

The first model for film condensation was introduced almost a century ago by Nusselt [3]. Nevertheless, Nusselt's model remains very popular and it is often used because in this case the closed-form analytical solution is available. Nusselt's model assumes (i) a linear temperature distribution across the film condensate, (ii) constant film properties, (iii) the shear stress at the surface and inertia effects are negligible, (iv) laminar flow in the forming film, and (v) pure still vapor from which the condensation occurs. In Fig. 1 an illustration of the system considered by Nusselt is shown. Nusselt obtained analytical expressions for the velocity profile in the film, the film thickness, mass flow and the heat transfer coefficient along a hydrophilic wall.

Nusselt's model has been found to have a good accuracy but only for low flow velocities [2]. One of the reasons for low accuracy at high flow velocities is the neglect of inertia and interface shear effects. The role of these effects has been intensely studied in the literature and it has been found that at low Prandtl numbers the interface shear must be taken into account while at high Prandtl numbers the effect of shear is small and can be neglected [4,5]. Both effects (inertia and interface shear) lower the mass flow rate. Also, subcooling effects are discarded in Nusselt's model which may alter the condensation flux at the liquid–gas interface. In [2] it is shown how the above effects can be taken into account.

Nusselt's model also assumes a laminar film without ripples or waves at the interface. This assumption has been studied and found to be valid for film Reynolds numbers $Re_f \lesssim 33$ [6]. To classify different condensation flows the film Reynolds number is defined as

$$Re_f = \frac{4\dot{m}(z=L)}{\mu_l}, \tag{1}$$

where $\dot{m}$ is the mass flow in the bottom of the film at the length L and μ_l is the dynamic viscosity of the film. For $Re_f \gtrsim 33$ the condensate film turns wavy-laminar and for $1000 \lesssim Re_f \lesssim 1800$ the flow in the film becomes turbulent [2]. These surface wave and turbulence effects have been suggested to alter the film thickness that leads to a significant change in the heat transfer coefficient. Therefore, it is normal practice to use empirical correlations for these regimes [1,2].

On the other hand, the lattice Boltzmann (LB) method has over the last two decades become a successful numerical approach to

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.04.032
0017-9310/

efficiently simulate various complex flows [7–14]. Different LB methods for multiphase flows have been suggested [15] and recently a LB model to predict film and dropwise condensation was developed [16,17] using the so-called Shan-Chen multiphase method. It was, however, reported that the model becomes numerically unstable if the Prandtl number deviates from one. Furthermore, a general issue using the Shan-Chen method is that the interface between the vapor and the liquid is diffuse [15].

To address tracking of interfaces between the gas and liquid phases as well as further strengthen the model, a free surface LB (FSLB) methods have been developed [18–20]. However, to ensure numerical stability, adaptive time steps [19] or adaptive grids [21] need to be implemented in the model which causes a significant complication.

In this paper we suggest a free surface entropic LB (FSELB) model and demonstrate how the model can be used to predict film condensation. Unlike the previous LB models, the entropic LB scheme in the free-surface framework demonstrates excellent stability and accuracy without considering adaptive grid or time steps. Furthermore, the model is not limited to laminar flows and, thus, it is applicable to laminar, wavy-laminar and turbulent film flows. We consider the construction in detail in two dimensions (2D); extension to 3D is straightforward.

It is worth mentioning that a lattice Boltzmann condensation model with no limitation on model parameters has not been developed so far. Moreover, the presented model is the first FSELB model. Finally, adding mass transfer to the liquid–vapor interface in FSLB methods is an extension which to our best knowledge have not been reported before. Thus, FSELB allows for modeling of more complex processes, e.g. evaporation and condensation.

The outline of the paper is as follows: in Section 2.1 the entropic lattice Boltzmann (ELB) model will be described and in Section 2.2 the modeling of the temperature field is presented. In Section 2.3 the FSLB method developed in [19] is reviewed and in order to validate the FSELB model the key concepts and equations of Nusselt's model are presented in Section 2.4. Finally, in Section 2.5 the setup of our model will be described showing how it is developed from the FSLB framework. The results are presented and discussed in Section 3 while Section 4 concludes the paper.

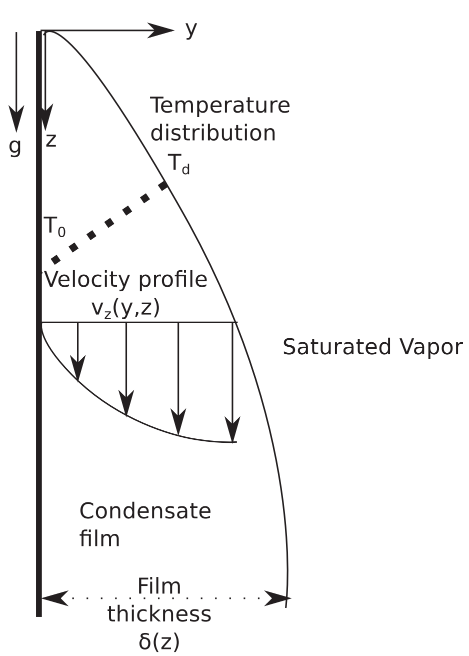

Fig. 1. Film condensation on a vertical surface according to Nusselt's model. T_o is the wall temperature and T_d is the temperature at the interface between the gas and liquid phase.

2. Model descriptions

The 2D FSELB model, presented here, is constructed using the ELB approach for modeling of the flow in the film. The liquid–gas interface is treated as a boundary according to the FSLB framework and the temperature field is treated as a passive scalar described below in Section 2.2.

2.1. Entropic lattice Boltzmann

The LB method concerns a discrete kinetic equation which solves for populations $f_i(\vec{x},t)$ corresponding to discrete velocities $\vec{c}_i, i = 1,..,n_d$. The velocities fit into a regular spatial lattice with the nodes $\vec{x}$. The ELB method is a generalization of the LB method and involves restoring the second law of thermodynamics. This additional step renders excellent non-linearly numerical stability and drastically reduces the computational demand at high Reynold numbers [11,22].

The ELB equation with the lattice Bhatnagar–Gross–Krook (LBGK) collision operator including a body force is given as [11]

$$f_i(\vec{x}+\vec{c}_i dt, t+dt) = f_i(\vec{x},t) + \alpha\beta(f_i^{eq}(\rho,\vec{u}) - f_i(\vec{x},t)) + f_i^{eq}(\rho,\vec{u}+\Delta\vec{u}) - f_i^{eq}(\rho,\vec{u}), \tag{2}$$

where β is related to the kinematic viscosity ν as follows:

$$\nu = c_s^2\left(\frac{1}{2\beta} - \frac{1}{2}\right)dt. \tag{3}$$

Here, c_s is the speed of sound in the model, dt is the time step, ρ is the density, $\vec{u}$ is flow velocity, and α is the non-trivial root of the entropy estimate which will be described below. The density and momentum are obtained from the populations as:

$$\rho = \sum_{i=1}^{n_d} f_i \tag{4}$$

and

$$\rho\vec{u} = \sum_{i=1}^{n_d} \vec{c}_i f_i. \tag{5}$$

The body force is incorporated using the exact difference method which provides the expression for the velocity increment $\Delta\vec{u}$ as [23]

$$\Delta\vec{u} = \frac{\vec{F}}{\rho}dt, \tag{6}$$

where the force $\vec{F} = \vec{g}\rho$ with $\vec{g}$ to be the gravitational acceleration. The actual fluid velocity $\vec{U}$ is obtained by averaging the fluid momentum before and after the collision:

$$\rho\vec{U} = \rho\vec{u} + \frac{dt\vec{F}}{2}. \tag{7}$$

The equilibrium function f_i^{eq} is the minimizer of the discrete entropy function H under local conservation laws of mass and momentum. The entropy function is given as

$$H = \sum_{i=1}^{n_d} f_i \ln\frac{f_i}{W_i}, \tag{8}$$

with W_i to be the lattice specific weights. Expanding the minimization problem to the order u^2 gives rise to

$$f_i^{eq}(\rho,\vec{u}) = \rho W_i\left(1 + \frac{\vec{c}_i\cdot\vec{u}}{c_s^2} + \frac{(\vec{c}_i\cdot\vec{u})^2}{2c_s^4} - \frac{\vec{u}\cdot\vec{u}}{2c_s^2}\right). \tag{9}$$

The entropy balance is maintained at each node for each time step through the parameter α. It is obtained as the non-trivial root of the following equation: