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Simulation on falling film absorption based on lattice Boltzmann method at moderate Reynolds number

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ABSTRACT

The investigations on heat and mass transfer in the form of falling film flow were mainly focused on the simulation of heat and mass coupling adopting the continuity hypothesis of Navier-Stokes equations. Most of the previous works were done with laminar flow assumptions, or just deal with a very short smooth laminar section beyond the falling film entrance. In this paper, a study investigating the effects of wavy flow on stream absorption by falling liquid film is presented in the perspective of sorption refrigeration process. A multi-phase model lattice Boltzmann method is adopted to simulate the wavy falling liquid film flow, and the absorption process takes place in this flow field region. Absorption simulation was carried out using the laminar flow assumption with the semi-parabolic velocity distribution and the fluctuation results in the LBM simulation. When the overall simulation section is 1 m in length, with initial velocity 0.1 m/s for lithium bromide solution falling film flow, results show that the wave flow has apparent enhancement on heat and mass transfer. Local dimensionless numbers for mass (Sh) and heat (Nu) transfer with waves increase 4 times and 2 times, respectively, compared with the laminar flow.

1. Introduction

Falling film flow is a very common everyday phenomena, such as rain water flowing down along the windows. At the same time, because of its excellent heat and mass transfer characteristics, falling liquid film is widely used in energy, chemical and many other in many industrial applications. Especially in absorption refrigeration and heat pump systems, absorber is the most critical component, which determines the overall performance, the initial investment, and the operation and maintenance costs. Because of its small liquid flow and high mass transfer efficiency characteristics, vertical falling film absorption form is widely adopted.

Falling film flow is a hydrodynamic form which liquid forming a thin film on a solid surface under gravity. According to the different surface shapes, in practical application and research there are three categories in use: flat falling film, horizontal tube falling film and vertical tube falling film. Nusselt uses a fully developed laminar model to analyze the falling film flow and obtain the famous Nusselt parabolic velocity distribution. The absorber is one of the most critical components in the absorption chillers and heat pumps, and heat and mass transfer efficiency in it directly affects the performance of the system. The absorber and other components' coupling is capable to construct multi-stage or multi-effect absorption refrigeration systems with high efficiency like GAX family [1]. Falling film absorption is the most common form of absorber and generator in absorption chillers. It has the advantages of low flow rate and flow resistance resulting in less power consumption during transportation, high heat and mass transfer efficiency with simple construction resulting in economic benefits, being easy to be controlled and fabricated and so on. Falling film absorbers have two kinds of structure in application: horizontal tube and vertical tube. Compared with the horizontal tube bundles' falling film, vertical tube one has more adjustable features in the pressure and temperature, and therefore possible to construct more complex and efficient absorption refrigeration systems [2].

Falling film absorption is a simultaneous momentum, heat and mass transfer process. In the process of working fluid being absorbed by the solution, a large amount of latent heat is released. Models of coupled heat and mass transfer on falling film absorption were critically reviewed by Killion and Garimella [3], in which mostly based on the Navier-Stokes hypothesis. Falling film flow is inherently unstable, even without any external perturbation [4]. Chang et al.'s analysis [5] shows that there are two types of waveforms simultaneously in the fluctuation of vertical falling film: capillary wave and inertial wave (solitary-like structure). The falling liquid film has a laminar flow characteristic at a smaller Reynolds number and has a complex volatility when the Reynolds number

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Nomenclature

a, b	coefficient of of wall temperature in Eq. (15), (–)
C	concentration, (–)
c	lattice velocity, (lu/lt)
c_p	specific heat capacity, J/(kg-K)
e	lattice velocity base vector, lu/lt
F	force, N
f	density distribution function or frequency
g	gravity acceleration, m/s^2
h	specific enthalpy, W/(kg-K)
m	mass flow rate, kg/s
Re	Reynolds number, –
Q	absorption heat flux, kW/(m^2-s)
Sh	Sherwood number
t	time or lattice time, s or lt
T	temperature, °C
u,v	macrovelocity, m/s
x,y	longitudinal and transversal direction

Greek symbols

ρ	density
λ	heat transfer coefficient
ω	weight factor
ς	the ratio of longitudinal and transverse velocity

Subscripts and superscripts

a	Some kind of fluid
i	direction
0	initial condition
abs	absorption

increases [6]. This significantly increases the difficulty of modeling, while reducing the versatility of the falling film absorption model. Experiments conducted by Mudawar [7] showed that most of the liquid phase mass (40–70%) is carried by waves during the falling film absorption process, and in the practical applications, the quality carried by the rolling wave is higher. So wave has a significant effect on mass transfer. The earliest heat and mass transfer model established for falling-film absorption is generally considered to be Nakoryakov et al. [8,9]. In their study, the velocity of the entire flow field is constant. Heat and mass transfer models coupled with the concentration diffusion for the falling film absorption, almost all adopted laminar flow hypothesis. However these models can only predict process at the very low Re number, or falling film inlet section where waves have not yet formed significantly [10,11].

To simulate the falling film absorption process in the presence of wave, researchers must make assumptions that involve many simplified film fluid dynamics. Most researchers assume that waves are periodic. Experimental studies of wavy film flow show that wave is not stable and tends to develop into a seemingly disorganized three-dimensional model when Reynolds number exceeds 100. Nakoryakov and Grigor'Eva [12]'s laminar results can be applied to all regions but the crest of the wave. Yoshimura et al. [13]'s model, making a combination of perturbation frequencies and laminar flow hypothetical models, proposed a parameter related to the wave velocity, and their correlations are based on semi-experimental semi-theoretical forms. Islam et al. [14] studied the effect of solitary waves on falling-film absorption. The finite difference method was used to study the mass transfer of water vapor absorbed by lithium bromide solution on a fixed grid. In their simulation, recirculation was generated, which enhanced absorption significantly. In Patnaik and Perez-Blanco's work [15], the fluid dynamics were adapted from the work of Brauner [16]. Their absorption expression is divided into four equations based on the division of the rolling wavelength and film thickness: front, back, tail and substrate. At low Reynolds numbers, their results were in good agreement with the theory of penetration. However, a very large degree of scattering can be observed among experimental data for comparing with the theoretical results. The dimensionless mass transfer coefficient is about four times the mass transfer coefficient predicted by the laminar film model. Rastaturin et al.[17] studied the falling film absorption process with Re $\sim$ (40,75) and calculated the hydrodynamic parameters by solving the Kapitsa-Shkadov partial differential equation using a parabolic velocity distribution. The natural disturbances and forced disturbances are calculated respectively. It was found that the forced disturbance's type has the best frequency and the highest absorption intensity at the best frequency. As it is difficult to solve the influence of wavy flow on falling film absorption for theoretical and numerical simulation studies, researchers turned to using a combination of theory and experimentation [6,15,17]. Xu [18]gave a single hydrodynamic parameter β, which represented the gradient of the vertical fluctuating velocity at the interface, to determine the component's distribution and associated mass transfer. This operation significantly simplified the complexity of falling film flow, but at the same time loses the internal details of the flow field.

The lattice Boltzmann method (LBM) has been developed for three decades, and the numerical simulation technique is very useful for two-phase flow. LBM can easily describe, and automatically track the interface, and thus in the multi-phase flow, phase transition and interface dynamics and other microscopic interaction of the fluid systems LBM has been successfully applied, such as Rayleigh-Taylor instability [19] and Rayleigh-Bénard convection [20]. The color gradient model proposed by Gunstensen et al. [21], the Shan-Chen model [22] which is based on the introduction of phase separation for repulsive forces, and the free energy multicomponent LBM [22] are some famous multi-phase or multicomponent LBM. A compromise has to be accepted for accuracy, calculation speed, and numerical stability. For multi-phase or multi-component LBM falling flow, Hantsch [23] provided a detailed approach for falling liquid film flow by employing lattice Boltzmann methods. Lu et al. [24] simulated the flow pattern of the two-phase falling film with high density ratio (about density ratio of water to air) at low Reynolds number (1, 5, 10 and 20) which showed that the film is fully laminar.

In this paper, the lattice Boltzmann method is used to model and simulate the wave velocity distribution and energy distribution in the process of fluctuating falling film. With the lower frequency perturbation condition as the boundary condition of the lattice Boltzmann method, the velocity field distribution of the fluctuating form is obtained through simulation. Then, the falling film absorption process for lithium bromide solution and water vapor is solved, by the means of finite difference method combining the fluctuating velocity field. The concentrated parameter (average speed ratio) obtained in the LBM simulation process acts on the absorption process.

2. Models

2.1. Lattice Boltzmann model

In a lattice Boltzmann model, probability distribution function (PDF) describes the probability of a fluid's motion in all speed