Influence of liquid physical properties on liquid film flow characteristics of uneven wall

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Received 1 August 2014, www.tsi.lv

Abstract

Two-dimensional model of inclined uneven wall was established based on VOF method to numerically simulate the flow characteristics of liquid film. The impact of physical property on the flow field is studied. Water, acetone and ethyl alcohol were selected as the medium. The results indicate that liquid film thickness increases with liquid viscosity, while the phase difference between free surface and the uneven wall has no change. The continuous uniform film is easy to form while considering the surface tension. Furthermore, the phase difference and liquid film thickness both increase when taking the surface tension into account.

Keywords: uneven wall, liquid film, flow characteristics, physical properties, VOF method

1 Introduction

Liquid film flow is a common phenomenon in nature. It plays a pivotal role in the equipment of traditional industries and high-tech areas due to the advantages of high heat and mass transfer coefficient. The most important factors in the design of these devices are the thickness and the flow rate of the liquid film, which are the critical parameters affect the heat and mass transfer characteristics. Therefore, the investigation of the flow and heat transfer characteristics of liquid film has become an increasingly important research topic.

Over decades, plenty of theoretical and experimental research in the field of film has been done. Alexandre [1] studied the stability of liquid film flowing down an inclined wavy plane based on the finite element method. Ye [2] discussed the influence of interfacial shear stress and Reynolds number on the linear stability of liquid film surface wave on inclined wall based on boundary layer model. Hu [3] simulated a uniformly heated film flowing down an inclined plate by using Lagrangian finite element method, and the saturated periodic wave, quasiperiodic wave, multipeaked wave and solitary hump wave were received. Pak [4] analysed the influences of the electric field and the wavy structures by using the weighted-residual integral boundary-1ayer model. On the other side, some scholars have experimentally measured the liquid film surface wave velocity, wavelength, frequency and other parameters and studied the evolution of film and film-wave instability development by high-speed digital camera technology [5], high-frequency capacitance-type water film thickness [6], three-dimensional laser Doppler velocimetry (LDA) [7, 8].

As the development of computer technology and calculation methods, the adoption of numerical simulation method to investigate liquid film flow characteristics and heat and mass transfer performance has become a hot topic of intensive interests. Beata [9] established a two-phase counter current structured packing model to determine the effect of liquid and gas flow rates and physical properties of the flowing liquids on the interfacial area. Liu [10] computationally simulated the flow field of falling film down a vertical plate at high Reynolds number by using volume of fluid (VOF) method. Gu [11] also used the VOF method to investigate the gas-liquid two-phase liquid film flow and to study influence of the structure and liquid-phase flow rate. Sun [12] used the Fluent software for the purpose of consideration of corrugated plate film.

This thesis uses CFD software Fluent and based on the VOF method to simulate the liquid film flow on inclined uneven wall. The impact of physical properties on liquid film formation and development process is investigated to provide theoretical basis for the utility, optimization and development of liquid film.

2 Models and boundary conditions

2.1 PHYSICAL MODEL

The physical model in this paper is shown in Figure 1 and physical properties of each kind of liquid can be seen in Table 1.

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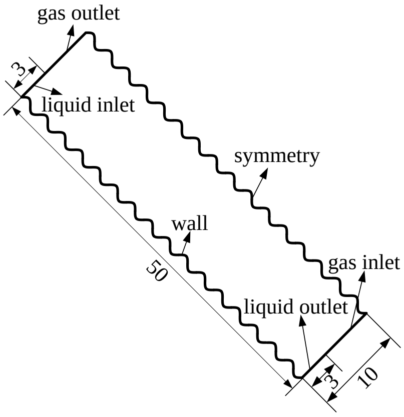


FIGURE 1 Physical model and boundary conditions

TABLE 1 Physical properties of liquid phase

fluid	ρ_L [kg/m^3]	μ_L [Pa·s]	σ [N·m^{-1}]	wavy wall θ_w [°]
water	998.2	0.001003	0.0722	57
acetone	791.0	0.00033	0.0229	40
ethyl-alcohol	790.0	0.00120	0.0214	40

2.2 GOVERNING EQUATIONS

Liquid film on uneven wall is the gas-liquid two-phase counter current process and VOF method is used to track the free surface.

(1) Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u}\right) = 0 . \tag{1}$$

(2) Momentum equation:

$$\begin{gathered}\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla \cdot \left(\rho \vec{u}\vec{u}\right) = \\ -\nabla p + \rho \vec{g} + \vec{F}_S + \nabla \cdot \left[\mu\left(\nabla \vec{u} + \nabla \vec{u}^T\right)\right]\end{gathered} . \tag{2}$$

(3) Volume fraction continuity equation:

$$\frac{\partial \alpha_q}{\partial t} + \vec{u} \cdot \nabla \cdot \left(\alpha_q\right) = 0 . \tag{3}$$

Here, ρ and μ respectively represents density and dynamic viscosity in each cell, $\vec{u}$ is velocity vector, $\vec{g}$ is gravitational acceleration, p is the pressure, t is time, $\vec{F}_S$ is the body force due to surface tension, and α_q is the volume fraction of the q^{th} phase. The volume fraction of each phase satisfies:

$$\sum_{q=1}^{n} \alpha_q = 1 . \tag{4}$$

Physical properties in governing equations of two-phase flow such as the density and viscosity can be described as:

$$\rho = \alpha_L \rho_L + \left(1 - \alpha_L\right) \rho_G , \tag{5}$$

$$\mu = \alpha_L \mu_L + \left(1 - \alpha_L\right) \mu_G . \tag{6}$$

In this paper, the surface tension model in simulation is the CSF (Continuum Surface Force) model, which the surface tension is attached to the VOF calculations as the source term $\vec{F}_S$, it can be expressed as:

$$F_{VOL} = \sigma_{ij} \frac{\rho \kappa_i \nabla \alpha_i}{\frac{1}{2}\left(\rho_i + \rho_j\right)} , \left(i \ j\right) = L, G , \tag{7}$$

where σ_{ij} is the surface tension coefficient, κ_i represents the interface curvature and it is the divergence of the unit normal vector on free surface:

$$\kappa = \nabla \cdot \hat{n} . \tag{8}$$

The force due to surface tension between the liquid and gas phase is called wall adhesion. We can incorporate it into the calculation of surface tension, and the normal vector at the wall is:

$$\hat{n} = \hat{n}_w \cos\theta_w + \hat{t}_w \sin\theta_w , \tag{9}$$

where the contact angle θ_w is the angle between the wall and the interface tangent, $\hat{n}_w$ and $\hat{t}_w$ is the unit normal vector and unit tangent vector at the phase interface.

2.3 BOUNDARY CONDITIONS

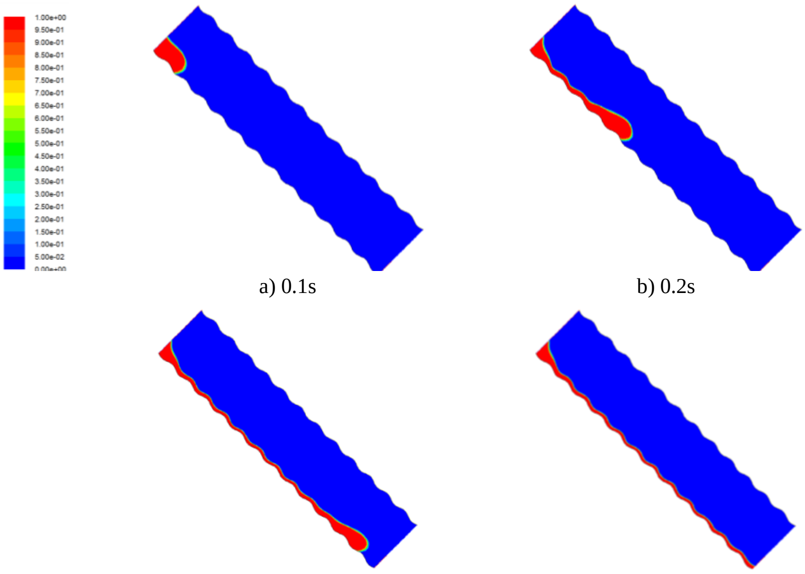
Assume that at the initial time the domain is full of stationary gas, that is, $t=0$, $\alpha_L=0$, $\alpha_G=1$. The wall is no slip and adiabatic, the gas and liquid inlets both are velocity inlet boundary conditions and the outlets are pressure outlet, the outlet pressure is atmospheric pressure, and the edge opposite to the wall is set to symmetric boundary.

3 Results and Analysis

We mainly study the influence of viscosity and surface tension on liquid film flow characteristics.

3.1 INFLUENCE OF VISCOSITY

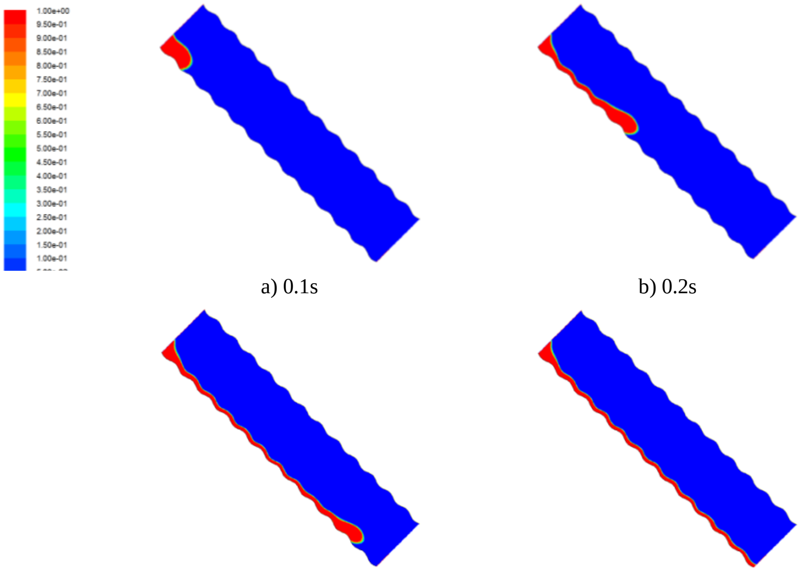
From Table 1 we know that there is less difference of the density and surface tension between acetone and ethyl alcohol, but the viscosity difference is large. Figure 2 and Figure 3 respectively shows the acetone and ethyl alcohol film formation process on inclined corrugated wall a at the inlet velocity of 0.05 m/s. The larger viscosity ethyl alcohol flows longer than acetone during the same time due to the viscosity retardation. Therefore, the larger fluid viscosity, the shorter distance of film flows.



a) 0.1s b) 0.2s

c) 0.28s d) 0.32s

FIGURE 2 Film of acetone flow on corrugated wall *a*

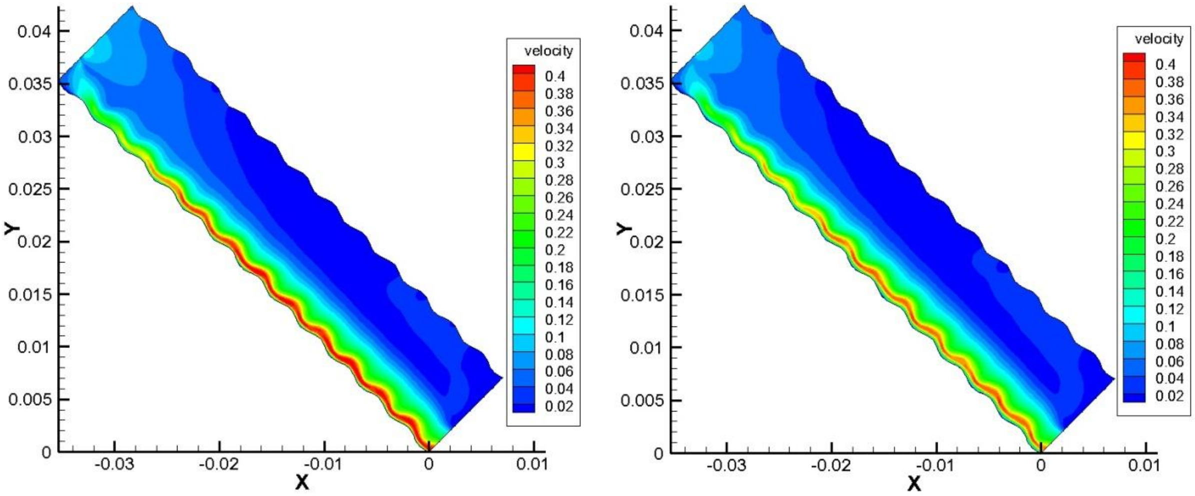


a) 0.1s b) 0.2s

c) 0.28s d) 0.32s

FIGURE 3 Film of ethyl alcohol flow on corrugated wall *a*

The stable velocity vector on corrugated wall a of the two kinds fluid are presented in Figure 4. We can see from the figure that the overall speed of the film decreases when the fluid viscosity increases. That is due to the fluid friction loss increases with viscosity, thus the overall film speed reduces. Figure 5 shows the free surface of acetone and ethyl alcohol film at the inlet velocity of 0.05m/s. It indicates that the phase of the free surface film hardly changes while the viscosity increases, but the film thickness increases. It is probably due to the larger viscosity fluid can stay longer on the wall surface. Therefore, the fluid film thickness increases with the viscosity, while the phase difference between the free surface and the wall does not change.



a) acetone film b) ethyl alcohol film

FIGURE 4 Velocity vector of acetone and ethyl alcohol film on corrugated wall *a*

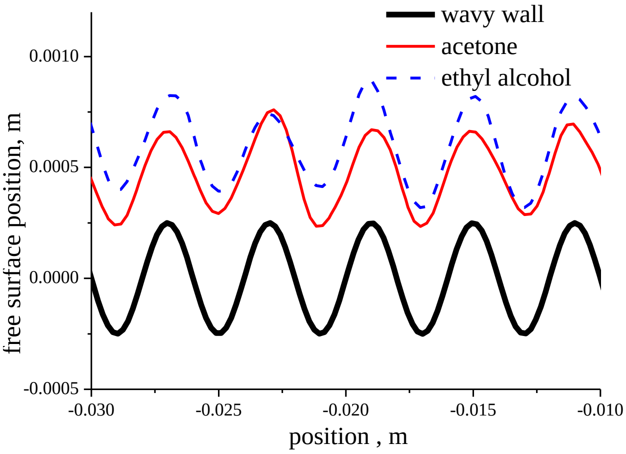
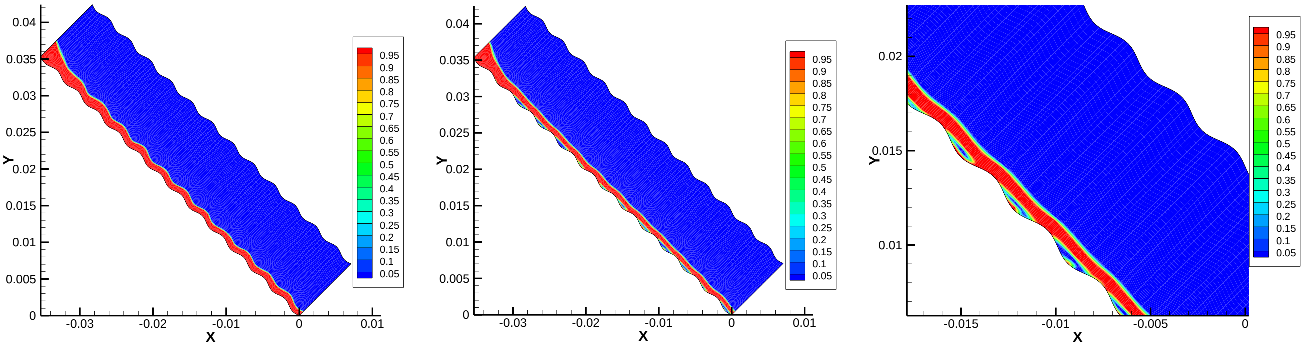


FIGURE 5 Influence of viscosity on free surface

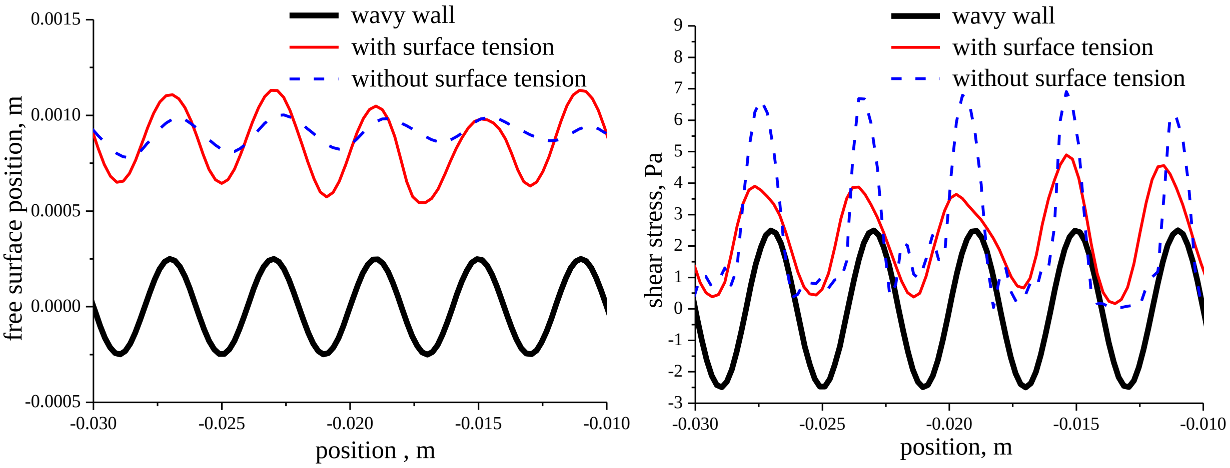
3.2 INFLUENCE OF SURFACE TENSION

Figure 6 shows the distribution of the liquid film on the wavy wall a with and without surface tension while the inlet-velocity is 0.1 m/s. It is clear that a uniform film could not form without considering the surface tension. The gas mixed between the wall and film would reduce the contact area, thereby the heat transfer efficiency reduces. While considering the surface tension, although there would be phase difference, the continuous and uniform film still forms.



a) with surface tension b) without surface tension c) detail of without surface tension liquid

FIGURE 6 Influence of surface tension on liquid film distribution



a) free surface b) wall shear stress

FIGURE 7 Influence of surface tension

Figure 7 respectively shows the free surface and the wall shear stress under the two different conditions. Obviously, the phase difference reduces and the liquid film almost immediately changes follow the wall while considering the surface tension. The liquid film thickness somewhat decreases while compared with the condition of considering surface tension. The change of the phase and film thickness would cause changes in wall shear stress, as Figure 7(b) shows. While considering the surface tension, the position of the maximum shear stress moves from the wave crest to the wave trough, and the amplitude of shear stress reduce compared with the condition of no-considering surface tension.

The above results indicate that the surface tension plays a very important role while handling the problem of a thin liquid film, and its variation would even change the structure of the whole flow field. Therefore, the surface tension must be considered.

4 Conclusions

This paper numerically simulates liquid film flow on uneven wall and investigates the impact of fluid properties on liquid film flow characteristics. The simulation results show that: The film thickness increases and overall film velocity reduces with the viscosity of fluid, but it does not affect the phase difference. It is not easy to form a uniform film without surface tension, and wall shear stress and the phase difference will change.

Acknowledgment

The project was supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (20110036110009).

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