Investigation on the Generation and Evolution Characteristics of Vortex as Liquid Film Flows on Uneven Walls

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Abstract. Based on Fluent numerical simulation software, a numerical model of vapor-liquid two-phase liquid film flow on inclined non-planar wall was established by VOF method. The three-dimensional liquid film flow of the corrugated wall was simulated and analyzed. The results show that the degree of volatility is a key factor affecting eddy current characteristics. Keeping the wavelength of the corrugated structure constant, when \( m = 0.0313, m = 0.0417 \), no vortex structure is generated. As the waveform increases, a diversion occurs and eddy currents are generated. \( m = 0.125, m = 0.1667 \), the eddy current size increases, and the shape becomes irregular. Taking the wall surface \( a \) of the corrugated structure as the research object, the larger the vortex in the corrugated structure, the larger the maximum velocity in the liquid film. Therefore, the existence of the amount of vorticity inside the wall structure can't be ignored for the effect of drag reduction.

1. Introduction
The thin film flow exists widely in nature and many important industrial fields. It is a simple low-speed open flow, and changes in the flow conditions such as the plate surface structure, liquid phase properties, and gas-liquid phase flow velocity have a great influence on the flow characteristics. Produce a very complex and rich dynamic behavior.

Matar studied the flow of liquid film beneath the elastically deformed wall and applied the theory of lubrication to obtain the evolution equations of wall deflection and liquid film thickness. It was found that reducing the effect of wall resistance or wall tension will lead to a decrease in stability. To improve the development of chaos in the weak nonlinear region, and then calculate the traveling wave spectrum by considering the detailed wall elastic deformation [1-3]. Eyov et al [4] consider the flow of compressible fluid on the elastic wall surface to obtain the physical properties of the surface wave. And compared with the situation of flowing through the rigid wall. Howell et al [5] applied the theory of lubrication to study the flow of liquid film through the elastic wall, and obtained the complete characteristics of the influence of the length and stiffness of the beam on the flow field of the liquid film and the deformation of the beam. In [6], the surface tension momentum source term and the gas-liquid shear stress momentum source term proposed by literature [7-8] were used to study the influence of important parameters such as plate surface structure on the flow characteristics of the liquid film.

In practical engineering applications, the wall surface on which the liquid film flows depends on the inclined non-flat wall surface. The flow characteristics of the liquid film and the vortex characteristics in
the wall surface structure will exhibit complexity and regularity, and the heat transfer and transfer of the liquid film will occur. Quality performance has a great impact [9-11]. Therefore, it is of great theoretical and engineering significance to thoroughly study the flow characteristics and heat and mass transfer characteristics of liquid film on non-flat walls.

2. Numerical Simulation

2.1. Physical model

The physical model of the simulated object in this paper is shown in Fig 1(a) and Fig 1(b) is the section taken along the flow direction. The length of the corrugated plate is 50 mm; the width is 6mm; the height of the calculation domain is 10mm, the height of the liquid phase inlet and the liquid phase outlet is set to 3mm, the height of the gas phase inlet and the gas phase outlet is 7mm; the angle between the wall surface and the horizontal direction is $\theta$, the ripple amplitude of the ripple wall is $h$ and the ripple period is $\lambda$. In this model, there are two inlets and two outlets. The liquid flows from the end of the wall to the bottom, and the flow direction of the gas is opposite to that of the liquid. Consider the influence of gravity on the liquid film. The gas inlet velocity is set to 0 m/s, and this article focuses on the influence of wall structure and fluid properties on the flow of the liquid film. Therefore, it is assumed that there is no gas outflow at the gas end outlet.

![Figure 1. Schematic diagram of the physical model mesh](image)

| Corrugated wall | Structural parameters |
|-----------------|-----------------------|
|                | $h$/mm | $\lambda$/mm |
| $a$             | 0.25    | 6            |
| $b$             | 0.5     | 6            |
| $c$             | 1       | 6            |
| $d$             | 0.25    | 8            |
| $e$             | 0.5     | 8            |
| $f$             | 1       | 8            |

2.2. Control equation

In the whole computational domain, the governing equations of the liquid film flow process include continuity equation, momentum equation and volume fraction continuity equation.

(1) Continuity and momentum equations:

$$\frac{\partial p}{\partial t} + \nabla \cdot \left( \rho u \right) = 0$$

$$\frac{\partial}{\partial t} \left( \rho u \right) + \nabla \cdot \left( \rho u u \right) = -\nabla p + \rho g + F + \nabla \left[ \mu \left( \nabla u + \nabla u^T \right) \right]$$

(2)
(2) Volume fraction continuity equation

The VOF method to track the equation of the phase interface distribution:

\[
\frac{\partial \alpha_q}{\partial t} + \mathbf{u} \cdot \nabla \cdot (\alpha_q) = 0
\]  

(3)

In the above equations, \( \mathbf{u} \) — Speed vector, \( g \) — Gravity acceleration, \( F \) — Source item, \( \alpha_q \) — Volume fraction of phase \( q \).

\[
\sum_{q=1}^{n} \alpha_q = 1
\]  

(4)

The physical properties of the fluid in the control equation are determined by the weighted average of all the interlinked systems, such as the mixing density and the mixed viscosity in the gas-liquid two-phase flow:

\[
\rho = \alpha_L \rho_L + (1 - \alpha_L) \rho_G
\]  

(5)

\[
\mu = \alpha_L \mu_L + (1 - \alpha_L) \mu_G
\]  

(6)

(3) The surface tension momentum source term:

\[
F = F_{VOL} = \sigma_{ij} \frac{\rho \kappa \nabla \alpha}{2(\rho + \rho_j)}, i(j) = L, G
\]  

(7)

\[
\kappa = \nabla \cdot \mathbf{n} = 1 \left[ \frac{n}{|n|} \left( \frac{n}{|n|} \nabla |n| - (\nabla \cdot n) \right) \right]
\]  

(8)

The wall normal vector:

\[
\mathbf{n} = \mathbf{n}_w \cos \theta_w + \mathbf{i}_w \sin \theta_w
\]  

(9)

In the above equations, \( \nu \) — Fluid kinematic viscosity, \( \mu \) — Fluid viscosity, \( \sigma_{ij} \) — Surface tension coefficient of each phase, \( \theta \) — Surface tension and wall angle, \( \kappa \) — Phase boundary curvature, \( w \) — Width of triangle structure, \( U_{\text{inlet}} \) — Fluid inlet velocity.

Subscript

\( G \) — Gas phase, \( L \) — Liquid phase, \( VOL \) — Surface tension term

2.3. Grid independence verification and CFD calculation verification

In order to show that the number of model grids has no effect on the simulation results, the model is now checked for grid independence: the number of grids is 120 000, 230 000, 360 000, 430000, and 560000. In five cases, when the Reynolds number is 850, The liquid film flow on wall \( f \) is simulated. The flow is fully developed. The relationship between the average thickness of the liquid film and the number of grids after reaching a stable state is shown in Fig 2.

As can be seen from the figure, the average thickness of the liquid film decreases with the increase in the number of meshes and remains unchanged. The average liquid film thickness is approximately the same when the number of grids is 430 000 and 560 000, indicating that the liquid film thickness is independent of the number of grids. At the same time considering the calculation time and the calculation accuracy, the model with a grid number of 430 000 is selected for simulation calculation. Other corrugated walls are also checked for mesh independence using this method.
In order to ensure the accuracy of the numerical simulation and the feasibility of the simulation scheme in this paper, the verification work was carried out. According to the experimental conditions and data of literature [12], the simulation of the liquid film flow on the surface of the semi-circular groove was performed. The free liquid surface amplitude, phase, and free fluid level fluctuations will characterize the free liquid surface to some extent. Comparing the morphology of the free liquid surface in the simulation results with the experimental results, it is found that the position and fluctuation degree of the free liquid surface in the two are not much different, and the degree of coincidence is very high, as shown in Fig 3. Therefore, the correctness and feasibility of the simulation scheme can be proved.

3. Simulation Results and Analysis
The wavelengths of the three kinds of corrugated structures shown in Fig 4, $\lambda$ are all 8mm, and the amplitude $h$ of the corrugations is 0.25mm, 0.5mm, and 1mm. The wavelengths of the three corrugated structures shown in Fig 5, $\lambda$ are all 6mm, and the corrugation amplitude $h$ is 0.25 mm, 0.5 mm, and 1mm in order. Define the ripple of the corrugated structure to be $m$.

Figure 2. Effect of the number of grids on the average thickness of liquid film

Figure 3. Comparison of free liquid surface morphology between experimental results and numerical simulation results

Figure 4. Wavelengths are 8 mm
Figure 5. Wavelengths are 6 mm

The above pictures show that the vortices in the corrugated structure increase with the amplitude, and the larger the amplitude, the more irregular the vortices. The amplitude of the corrugated structure is the key factor affecting the size and shape of the vortices. When the waviness is small, there is no vortex in the corrugated structure. With the increase of waviness, the phenomenon of flow separation begins to appear in the flow field. The higher the waveform, the larger the vortex in the trough. The larger the vortex, the lower the average velocity of the flow field. For the liquid film flow on the wall with larger waviness, the waviness plays a decisive role in the influence of the flow characteristics of the liquid film, and other factors have less influence. In addition, the corrugated structure of the corrugated wall has a certain effect on the fluctuation of the free surface.

Fig 6 shows the fluctuation of free surface and the velocity distribution perpendicular to the wall at different positions when the liquid velocity on the wall is 0.2 m/s. Three typical positions are selected to analyze the velocity perpendicular to the wall, and the flow in these three positions has reached a relatively stable state. The three locations are 1 where no vortex exists, 2 where liquid vortex exists, and 3 where more than one gas vortex exists and the free surface is relatively gentle, but the turbulence of the flow is intensified.

Figure 6. Speed in y direction at four different positions
Due to the existence of vortices in the corrugated structure, the direction of the viscous resistance in the corrugated structure is opposite to the direction of the total resistance. At positions 2, and 3, the velocity increases first and then decreases and then increases. Especially at position 3, due to the increased turbulence of the fluid, the number of vortices increases and the speed changes more frequently. The larger the vorticity in the corrugated structure, the greater the maximum velocity in the liquid film, so when the fluid flows on the non-flat wall surface, the presence of vortices in the wall structure can't ignore the impact of drag reduction.

4. Conclusion

By simulating the three-dimensional flow process of the liquid film on the inclined corrugated wall, the evolution of the vortex structure in the corrugated structure with time and the wave diagram of the free surface are studied in this paper. The simulation results show that:

The whirlpool in the corrugated structure increases with the amplitude increasing, and the larger the amplitude the whirlpool is, the more irregular the whirlpool. The ripple amplitude is the key factor affecting the whirlpool size and whirlpool shape in the corrugated structure;

With the evolution of time, the variation of vortex structure has obvious effect on the fluctuation of free surface. The larger the whirlpool in the corrugated structure, the greater the maximum of the velocity in the liquid film, so the vortex in the wall structure can't be ignored when the fluid flows on the surface of the wall.

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References

[1] Matar O K, Kumar S 2007 J. Eng. Math. 57 145.
[2] Matar O K, Craster R V, Kumar S 2007 Phys. Rev. E76 056301.
[3] Sisoev G M, Matar O K, Craster R V, Kumar S 2010 Chem. Eng. Sci. 65 950.
[4] Eyov E, Klar A, Kadri U, Stiassine M 2013 Wave Mo-tion. 50 929.
[5] Howell P D, Robinson J, Stone H A 2013 J Fluid Mech.732 190.
[6] LI Chao. CFD simulation of flow and mass transfer in structured packing[D]. Zhengzhou University, 2011.
[7] Gu F, Liu C J, Yuan X G, et al. CFD Study of Liquid Film Flow on Slanted Corrugated Sheets[J]. Journal of Chemical Industry and Engineering, 2005, 56(3): 462-467.
[8] Gu F, Liu C J, Yuan X G, et al. CFD simulation of liquid film flow on inclined plates [J]. Chemical engineering & technology, 2004, 27(10): 1099-1104.
[9] Hu Guohui, Hu Jun, Yin Xieyuan. Numerical simulation of falling liquid film on vibrating swashplate[J]. Computational Physics, 2006, 23(1): 57-60.
[10] Fan Xiaochao, Shi Ruijing. Flow and heat transfer stability of liquid film along a non-uniformly heated ramp[J]. Journal of Langfang Teachers College, 2010, 10(3): 35-39.
[11] Jin Zhihao, Wang Guanqing, Liu Jie, et al. Numerical simulation of fluid flow characteristics in corrugated plates[J]. Progress in Hydrodynamics, 2004, 19(1): 26-30.
[12] Zhao L, Cerro R. Experimental characterization of viscous films flows over complex surface[J].International Journal of Multiphase Flow, 1992, 18(14): 495-516.