

Numerical Simulation Study on Characteristics of Airtight Water Film with Flow Deflectors

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Abstract. In practical use, there is shrinkage in the width direction in existing overflow water film. This study introduces the "flow deflectors" to solve the problem of discontinuous water film. According to the principle of the experimental devices, the model was established by FLOW-3D software and the corresponding boundary conditions were set up, the minimum size of the grid was $0.25\text{mm} \times 0.25\text{mm} \times 0.25\text{mm}$. The film model was investigated under ten working conditions with three factors. Through the analysis of the distribution curves of velocities and thickness, impacts of unit width flux, tank width and the distance between the flow deflectors on the velocity and thickness of the liquid film were obtained. The results indicated that the water film was able to keep continuous and airtight with flow deflectors. The variation law of water film with unit width flux was obtained and a correlation formula was proposed according to Nusselt correlation. And, it was found that the tank width has little influence on the water film itself. The "dry zones" were also founded on the film when the distance between flow deflectors increased.

1. Introduction

In reality, in the event of a fire or an earthquake, toxic and harmful gases will spread in buildings, causing personal injury and property damage. In order to study a kind of energy-saving and high-efficiency obstruction device, this study aims to control the diffusion of poisonous and harmful gases by using a continuous closed liquid film with water as the medium. Some scholars have studied a new type of overflow tank [1, 2]. The formation of the water film has been discussed in theory and experiments, and the flow rate required to produce a continuous liquid film has been greatly reduced. However, the study of free continuous liquid film did not concern the shrinkage of the continuous liquid film along the width direction. The continuous liquid film is subject to contraction in the width direction due to the influence of gravity and surface tension during the falling process, failing to meet the requirements of continuity, and this will inevitably have a negative impact on the blockage of toxic and harmful gases. In order to improve the sealing effect of the liquid film, and to achieve the purpose of blocking toxic and harmful gases, the liquid film is continuously sealed by the introduction of "flow deflectors", and three factors have been studied for the quality of the liquid film through simulation calculations.

In this paper, the FLOW-3D software was used to simulate the continuous liquid film to verify that the "flow deflector" improves the quality of the continuous water film, and the correlation between the thickness of the liquid film and the Reynolds number was obtained.

2. Numerical Simulation

2.1. Assumptions



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The falling process of the continuous liquid film is an unsteady gas-liquid two-phase stratified flow process. In this study, VOF method was used to track the position of the free surface of the liquid film. The VOF method was applied to the calculation of two or more fluids that were not mixed with each other. The momentum equation and the volume fraction of each phase in the calculation domain were solved to simulate the multiphase flow. Because of the slow velocity of the liquid film, the density gap between air and water is large, for the purpose of simplifying the calculation model, this factor was neglected in this study[3]. In order to simplify the model, this study was based on the following assumptions:

- The fluid was a Newtonian fluid and flows in a steady state. The physical property parameters were constant.
- The liquid film was completely infiltrated with the flow deflectors, and the contact angle was 0° .
- The gas-liquid two-phase interface has no resistance;

Under these assumptions, the boundary conditions for describing the falling process of liquid film can be obtained.

2.2. Physical model and boundary conditions

There are two forms of the physical model in this paper: with and without flow deflectors. The flow deflectors are the vertical thin line group in front of the outlet of the tank, as is shown in Figure 1. The overflow water film experiment without flow deflectors is shown in Figure 2, and the overflow water film experiment with flow deflectors is shown in Figure 3. The thickness of the tank was 2mm, and the arc radius of the outlet of the tank was 22mm. The diameter of the flow deflectors was 1mm, and the distance between the flow deflectors was 1mm. The calculation domain height was 1042mm, and one side of the calculation domain was set as symmetry. The minimum size of the grid was 0.25mm x 0.25mm x 0.25mm. The liquid properties are shown in Table 1.

In order to form a liquid film along the flow deflectors, the flow rate of the liquid must be greater than a critical value. D.E. Hartley gives the formula for the minimum flow rate required to form a liquid film[4]. In this study, the minimum unit width flux was 291.15 kg/(m·h), namely 0.081 L/m·s. The unit width flux selected in this study satisfies the requirements.

Table 1. Physical parameters of water

Property	Water
Temperature ($^\circ\text{C}$)	20
Density(kg/m^3)	1000
Dynamic viscosity(Pa/s)	0.001
Contact angle($^\circ$)	0

The corresponding boundary conditions were shown in Figure 1: The inlet of the tank was volume flow rate inlet, the rate was 0.0128L/s~0.0384L/s; The air inlet and outlet were the pressure boundary, the pressure was 0 pa; The bottom of the calculation domain ($z=0$) was outflow; The left side of the calculation domain ($y=0$) was symmetric boundary; The solid wall was taken as a no-slip boundary condition and the wall surface was smooth. At the initial time, the tank was full of liquid phase, and the rest was gas phase.

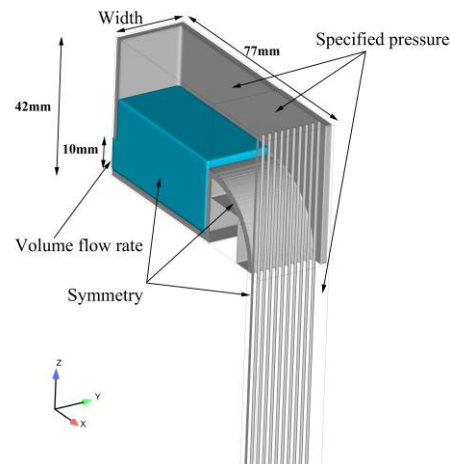


Figure 1. CFD physical model and its boundary conditions



Figure 2. Experiment of overflow water film without flow deflectors



Figure 3. Experiment of overflow water film with flow deflectors

The simulated working conditions in this paper are shown in Table 2.

Table 2. Working conditions of numerical simulation

Working conditions	Distance between the flow deflectors(mm)	Width of water tank(mm)	Height of computational domain(mm)	Unit width flux(L/m·s)
1	1mm	8	1042	0.64
2	1mm	8	1042	0.96
3	1mm	8	1042	1.28
4	1mm	8	1042	1.60
5	1mm	8	1042	1.92
6	1mm	8	542	0.64
7	1mm	16	542	0.64
8	1mm	24	542	0.64
9	1.5mm	24	542	0.64
10	2mm	24	542	0.64

3. Results

3.1. Determination of stabilization time

In this study, the change rate of the average velocity of the liquid film from the outlet of the water tank

to the bottom of the calculation domain and the change rate of the volume of the fluid in the calculation domain were used as the basis for determining the stabilization time. The average velocity and fluid volume of the liquid film under working condition 1 were shown in Figure 4. It can be seen from the simulated data that the maximum change rate of the average velocity of flow was 2.6% compared with the average velocity at $t=3s$, and the maximum change rate of the fluid volume was 1.7%, which can be considered that the calculation enters a stable phase from $t=3s$.

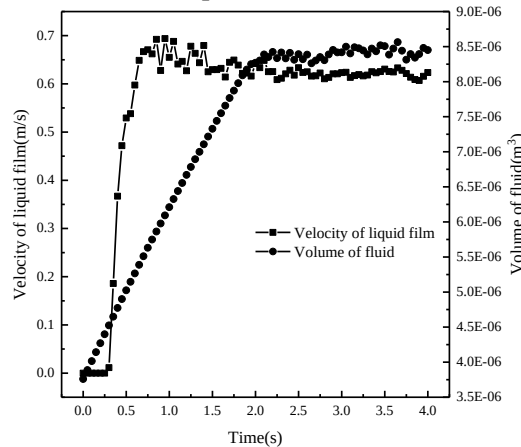


Figure 4. Variations of liquid film velocity and fluid volume with time under condition 1

The stabilization time of working condition 1~5 is shown in Figures 5 and Figure 6. From the variations of the fluid volume with time, it can be seen that with the increase of the unit width flux, the time required for the liquid film to enter stability becomes shorter. From the variations of liquid film velocity with time, we can see that the stabilization time was less affected by the unit width flux. To sum up, the flow enters stability from $t=3s$. The follow-up analysis takes the data of $t=3s$.

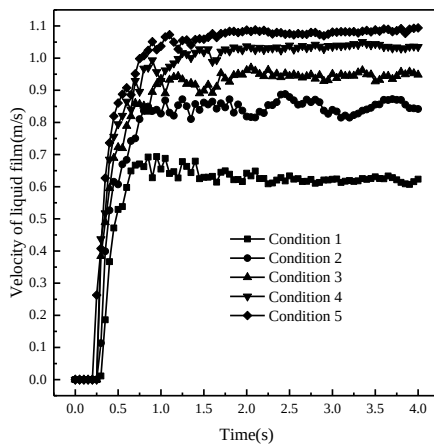


Figure 5. Variations of liquid film velocity with time under conditions 1~5

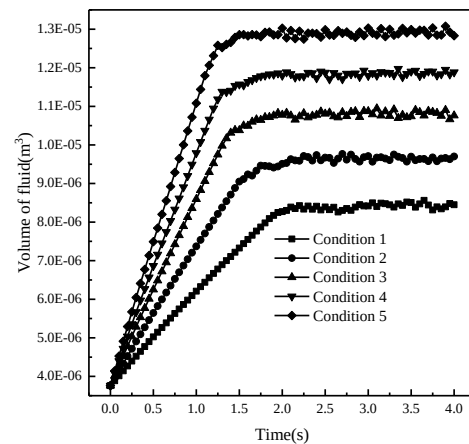


Figure 6. Variations of fluid volume with time under conditions 1~5

3.2. Effect of unit width flux on liquid film

The liquid film's average velocity of conditions 1~5 at $t=3s$ was analyzed. With the increase of the unit width flux, the liquid film's average velocity also increases. However, from the growth trend of the liquid film's average velocity in Figure 7, the growth rate of the liquid film's average velocity decreases with the increase of the unit width flux, which means that the liquid film's average velocity will no longer increase when the unit width flux increases to a certain extent.

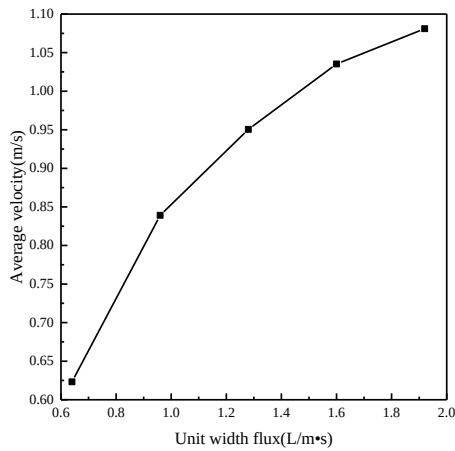


Figure 7. Variations of liquid film's average velocity with unit width flux

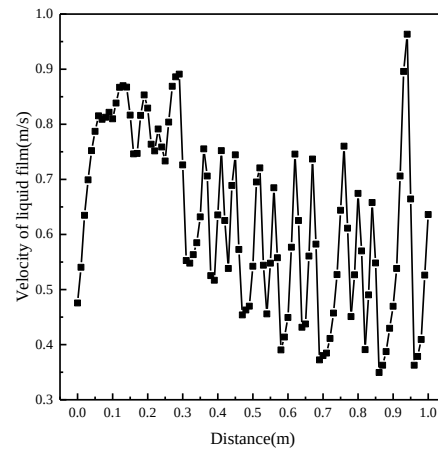


Figure 8. Distribution of liquid film velocity under condition 1

According to the distribution of liquid film velocity under condition 1, it can be concluded that the liquid film velocity began to increase from the outlet of the water tank. From the point of 0.29m away from the outlet, the liquid film velocity no longer increases and starts to fluctuate. With the increase of the flow distance, the velocity amplitude begins to increase gradually, and the variations is shown in Figure 8. The distribution of liquid film velocity was uniform under different unit width flux. From Figure 9, it is known that the distance to the fluctuation of the working condition 2~5 was 0.3m, 0.3m, 0.27m and 0.25m, which were all distributed around 0.3m. From this, it can be seen that the different unit width flux has little influence on the distance required for the liquid film to enter the fluctuation. In working condition 1, the liquid film's average velocity after entering the fluctuation was 37.26% lower than the velocity when entering the fluctuation, and it was 16.75%, 8.17%, 4.68%, 3.15% in working conditions 2~5 respectively. In summary, as the unit width flux increases, the gap between the liquid film's average velocity after the fluctuation and the liquid film's average velocity entering fluctuation was getting smaller and smaller.

In 1916, the correlation between Reynolds number and the thickness of liquid film was put forward under the assumption that the liquid film was laminar flow and no shear force at the gas-liquid interface. According to the correlation between Reynolds number and liquid film thickness proposed by Nusselt, the thickness of the liquid film under different Reynolds number corresponding to the working condition 1~5 was calculated, and the correlation between Reynolds number and the thickness of the liquid film in the range of 600~2000 was fitted. From Figure 10, we can see that the thickness of liquid film has a good linear relationship with Reynolds number, which was consistent with the basic form of Nusselt correlation.

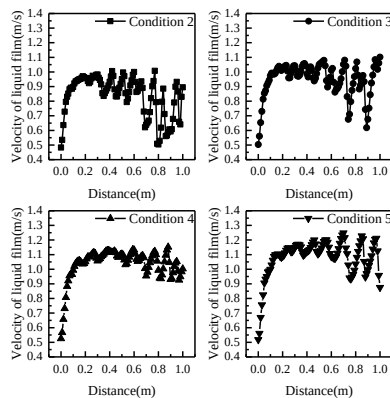


Figure 9. Distribution of liquid film velocity under conditions 2~5

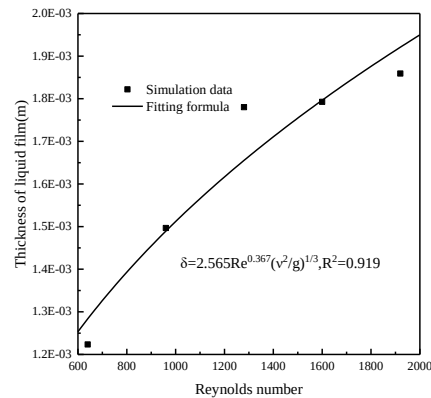


Figure 10. Fitting of liquid film thickness and Reynolds number

3.3. The influence of the width of the water tank on the liquid film

Working conditions 6~8 correspond to the case of 3 different tank widths under the same unit width flux. At $t=3s$, the average liquid film velocity of 6~8 was 0.697m/s, 0.699m/s and 0.704m/s, the maximum change rate was 1.00%; The average liquid film thickness was 1.622mm, 1.621mm and 1.698mm, the maximum change rate was 4.69%. According to the change rate of the characteristic value of the liquid film, we can see that when the width of the water tank changes, the characteristic value of the liquid film changes little under the same unit width flux. It can be seen that the change of water tank width has little effect on the characteristic value of liquid film, which can be ignored in numerical analysis.

3.4. The influence of the distance between the flow deflectors on the liquid film

From Figure 11 and Figure 12, it can be seen that with a constant unit width flux and a constant tank width, the liquid film's average velocity and the steady velocity of the liquid film gradually increase with the increase of the distance between the flow deflectors. The average liquid film thickness of conditions 8~10 was 1.698mm, 1.044mm and 0.859mm. The shear force on the flow deflectors was $2.498 \times 10^{-2}N$, $2.289 \times 10^{-2}N$ and $1.860 \times 10^{-2}N$. As the width of the water tank was constant, the increase of the distance between the flow deflectors will reduce the number of the flow deflectors in the computational domain, which leads to the smaller shear force, and the proportion of gravity increases gradually in the process of falling. Therefore, the liquid film's average velocity increased gradually, while the thickness of liquid film showed an opposite trend.

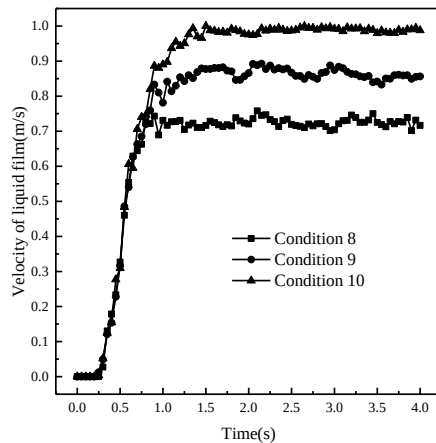


Figure 11. Variations of liquid film velocity with time under conditions 8~10

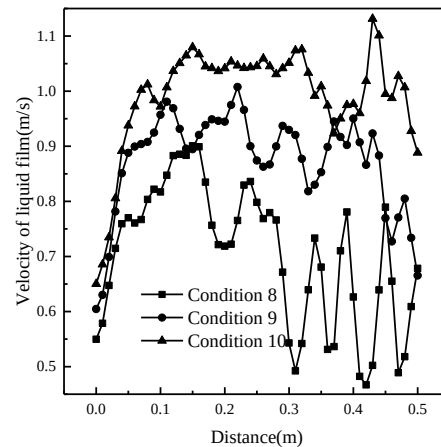


Figure 12. Distribution of liquid film velocity under conditions 8~10

The flow state of the liquid film of working conditions 1~8 can maintain continuity, but the liquid film in working conditions 9 and 10 shows a “dry zone” as shown in Figure 13, which destroys the continuity of the liquid film. In the process of increasing the distance between the flow deflectors, the velocity of the liquid film increases and the thickness decreases. During the fluctuation, some liquid film thicknesses were too thin, resulting in “dry zone” due to surface tension[5, 6]. In order to avoid the occurrence of local “dry zone” in practical applications, while increasing the distance between the flow deflectors, the unit width flux should be appropriately increased.

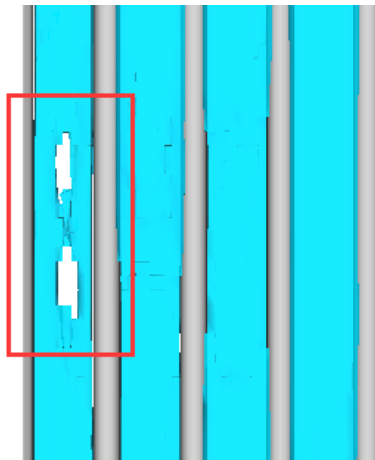


Figure 13. Schematic diagram of "dry zone" phenomenon

4. Conclusion

- With the increase of the unit width flux, the average velocity of the liquid film also increases, but when the unit width flux increases to a certain extent, the velocity of the liquid film will no longer increase significantly. The gap between the liquid film's average velocity after the fluctuation and the liquid film's average velocity entering fluctuation was getting smaller and smaller.
- According to the basic form of the Nusselt correlation formula, the average thickness of the liquid film at different Reynolds numbers was fit-calculated, and the correlation formula of the Reynolds number and the liquid film thickness that met the conditions of this paper was obtained.
- By changing the width of the water tank, it can be seen that when the width of the water tank changes, the change of the velocity and thickness of the liquid film was very small, which can be ignored in the numerical analysis.
- With the increase of the distance between the flow deflectors, the velocity of the liquid film increases, while the thickness of the liquid film decreases. At the same time, the continuity of the liquid film flow was affected, and some "dry zones" appear in the local area. It is suggested that in practical application, the unit width flux should be increased at the same time when the distance between the flow deflectors is increased.

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