Effect of Structural Optimization of Scrubbing Cooling Rings on Vertical Falling Film Flow Characteristics

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ABSTRACT: In order to study the influence of the structural optimization of the scrubbing cooling ring in the scrubbing cooling chamber on the flow characteristics of the vertical falling film, the flow characteristics of the turbulent falling film in the rising section of the development region at different internal platform heights of the scrubbing cooling ring and a high Reynolds number were studied by FLUENT software. First, the correctness of the model was verified by the maximum error of simulation and experimental results of no more than 9.836%. Then, the distribution of liquid film thickness (δ), velocity (V), and turbulence intensity (Iz) at 0° of the tube in the axial direction x = 0−500 mm were calculated and obtained when the platform height (H) was 0−30 mm and the liquid film Reynolds number (ReL) = 1.1541 × 10⁴−3.4623 × 10⁴. The results showed that δ in the entrance region increased sharply due to the “jet” effect with solid wall constraints formed by the structure of the water inlet pipe and the scrubbing cooling ring. On the contrary, the liquid film in the fully developed region showed a stable fluctuation trend due to the weakening of the “jet” effect. When H = 30 mm, the change of δ was relatively stable and the change of Iz was small, indicating that this platform height is conducive to the stable and uniform distribution of the liquid film. In addition, when ReL < 1.1541 × 10⁴, the liquid film was unstable due to the low flow rate and insufficient cohesion of the liquid film, but V increased slightly. In addition, with the increase of ReL, δ did not change significantly along the axial direction, that is, the Plateau−Rayleigh hindered the growth of δ. Finally, the empirical formula for δ applicable to ReL = 1.1541 × 10⁴−3.4623 × 10⁴ at the axial fixed position was fitted for the first time.

1. INTRODUCTION

China is rich in coal, poor in oil, and has less gas. The dominant position of coal in China’s energy structure will not change in the short term.¹,² Coal gasification technology is currently one of the most effective ways to achieve clean and efficient utilization of coal resources, including three kinds of fixed beds, fluidized beds, and entrained flow beds.³−⁶

A quench chamber is an important part of coal gasification, which is mainly composed of a spray bed and a bubbling bed. The spray bed is composed of scrubbing cooling rings and a descending pipe, with which mainly the cooling, washing, and humidification processes of coal gasification high-temperature syngas are completed. Bubbling beds are mainly used to achieve gas−solid separation. The scrubbing cooling chamber involves many complicated mechanism problems, such as multiphase flow, heat and mass transfer, and so on, and is also the core of the coal gasification process. Therefore, research on the mechanism of the scrubbing cooling chamber is the key to realizing the high-efficiency production of fuel gas by the coal gasification process.

In the scrubbing cooling chamber, the liquid film is uniformly distributed along the scrubbing cooling ring and flows downward along the scrubbing cooling tube. Such falling film flow has been widely used in various chemical engineering applications.
thermal energy engineering, mechanical engineering, and engineering thermo-physics and nuclear energy fields due to its excellent properties, such as the small flow rate, small temperature difference, simple structure, high heat- and mass-transfer coefficient, and low power consumption. Nowadays, the falling film evaporator, air conditioning refrigerator, horizontal falling film exchanger (HFFE), and condenser have been widely used in various heat exchange systems.

The falling liquid film can be divided into three regions as the distance increases during the flow process, including the entrance region, the development region, and the stable region. Generally, the entrance region is short and decreases with the increase of liquid Reynolds number. The liquid film flow state in the development region is constantly changing, and this region generally plays a pivotal role in heat and mass transfer. When the liquid film is in the stable region, the statistical parameters of the liquid film tend to be constant or change very little with the change of flow distance.

The thickness of the liquid film (δ) is an important hydrodynamic parameter, which is characterized both experimentally and numerically. The analytical solution was first established by Nusselt in 1916, and the expression of thickness of the liquid film was obtained by neglecting the inertial effect.

\[
\delta = \frac{3\mu \Gamma_{1/2}}{\rho_1 (\rho_1 - \rho_g) g \sin \theta}
\]

Later, Hao et al. found that there was a certain relationship between the tube diameter D, the tube spacing s, and the thickness of the liquid film, so the Nusselt formula was modified as follows

\[
\delta = C \sqrt{\frac{3\mu \Gamma_{1/2}}{\rho_1 (\rho_1 - \rho_g) g \sin \theta}} \left( \frac{s}{D} \right)^n
\]

In addition, Ji et al. conducted a numerical study on the liquid film under turbulent flow and found that the distribution of the liquid film is not symmetrical, so the minimum thickness position was set to θ = 120°.

\[
\delta = \frac{3\mu \Gamma_{1/2}}{\rho_1 (\rho_1 - \rho_g) g \sin(3\theta/4)}
\]

Zhao et al. also studied the effects of liquid load, surface tension, impact height, pipe diameter, and temperature on the thickness of the liquid film by numerical simulation. According to the calculation, the liquid film is divided into three regions: \(\theta = 2 - 15^\circ\), \(\theta = 15 - 165^\circ\), and \(\theta = 165 - 178^\circ\) and their correlations are given. In addition, most scholars favor the study of the liquid film in the stable region. Many researchers have studied the thickness distribution of the falling film in the stable region and obtained many accurate correlations.

Generally, when \(Re < 20 - 30\), the liquid film follows a laminar flow, then transforms into the fluctuating laminar flow at \(30 - 50 < Re < 250\), and finally becomes completely turbulent at \(Re > 250 - 500\). It should be pointed out that the critical Reynolds number for the transition of liquid film flow state is not constant, and it is controlled by various factors, such as the wall effect and so on.

The effective reduction of thickness of the liquid film is the main reason for enhancing the heat and mass transfer of liquid films. In practical applications, high \(Re\) is usually required to improve the heat-transfer coefficient of liquid films. However, due to the complexity of liquid films under turbulence, scholars have only obtained experimental correlations between the heat-transfer coefficient and the flow state. Coupled with the limitations of previous measurement methods and the randomness of the fluctuation characteristics of liquid films under turbulent conditions, few studies have been done on the fluctuation characteristics of liquid films in the turbulent state.

In the quench chamber of the opposed multi-burner (OMB) gasification technology, the syngas temperature is as high as 1300 °C, which frequently occurs in cold and hot contact with the cooling water and produces severe heat and mass transfer. The liquid film on the wall of the scrubbing cooling tube directly contacts with the high-temperature crude gas in industries, which can produce violent phase transformation, resulting in the uneven distribution of the liquid film thickness. The change of the liquid film thickness will lead to the change of the liquid film heat-transfer coefficient at the local position of the descending pipe, that is, the uneven distribution of thermal stress on the pipe wall will lead to the deformation of the pipe wall surface and the formation of a corrugated wall at the local position, which will affect the uniformity of liquid film thickness distribution and heat- and mass-transfer efficiency. During this process, the thickness of the liquid film is too large, the coefficient of heat and mass transfer is reduced, and the cooling efficiency is reduced. If the thickness of the liquid film is too thin, the wall of the descending pipe is prone to dry wall or even burn-through, which will ultimately endanger the safety production of the enterprise. Therefore, it is necessary to study the film formation and stability of the liquid film to ensure the stable and efficient operation of the gasification device and the scrubbing cooling chamber.

In summary, there are relatively few studies on the flow characteristics of the descending liquid film at high Reynolds number, and almost nothing on the optimization design of the structural parameters of the scrubbing cooling ring and the empirical formula for predicting the thickness of the liquid film at the fixed location of the rising section of the development region under turbulence has been reported. The stability and uniformity of liquid films are the key factors that directly affect the subsequent gas—liquid two-phase and gas—liquid—solid three-phase heat and mass transfer. Therefore, starting from how to make the liquid film distribution of the descending pipe more uniform and stable, FLUENT software is used in this paper to optimize the internal structural parameters of the scrubbing cooling ring and carry out three-dimensional numerical research, including four basic flow patterns of the platform height in the scrubbing cooling ring and quantitatively discuss the flow characteristics of the liquid film in turbulent conditions with different Reynolds numbers. This can lay a foundation for the follow up study of the heat and mass transfer between the high-temperature crude gas and the scrubbing cooling water in the pipe and ultimately provide a theoretical reference for the safe and stable operation of the OMB gasifier in the industry.

In this paper, an experimental device for turbulent falling film in a vertical descending pipe of a scrubbing cooling chamber was built. The instantaneous liquid film thickness was measured by ultrasonic Doppler velocimetry (UDV) and verified by FLUENT software. On this basis, the influence of the structural parameter optimization of the scrubbing cooling ring and the high Reynolds number on the turbulent falling
film flow characteristics was studied. The aim of this work is to lay a foundation for subsequent multiphase heat and mass transfer in the descending pipe of the scrubbing cooling chamber and provide a theoretical basis for the stable and efficient operation of the scrubbing cooling chamber. In addition, many scholars have shown that surface fluctuations still exist during liquid film flow in the absence of gas-phase-induced interfacial shear.\textsuperscript{20,30–33} Therefore, in order to eliminate the influence of gas factors, this study is only carried out under the conditions of liquid-phase flow.

### 2. RESULTS AND DISCUSSION

#### 2.1. Effect of Platform Height on Vertical Falling Film Flow Characteristics

Turbulent falling film flow is a complex three-dimensional flow in coal gasification quench chamber. The sudden expansion of the liquid film at the outlet leads to the instability of the liquid film, and the 1/4 length area at the upper end of the circular tube is the main area of heat exchange.\textsuperscript{34} Under such extreme conditions, the liquid film is very prone to boiling and evaporation, resulting in dry wall or even burn-through in the descending pipe wall, which affects normal production. The thickness distribution of liquid film directly affects the change of heat-transfer coefficient, and then affects the stable operation of scrubbing and cooling chamber. Therefore, it is essential to study the liquid film flow characteristics in the area where severe heat and mass transfer occurs in the descending pipe, so as to provide theoretical support for the subsequent research on heat and mass transfer between multiphase flow. In this section, we have studied the influence of the height of the internal platform in the scrubbing cooling ring on the flow characteristics of the liquid film by optimizing the structure parameters of the scrubbing cooling ring, and obtained some laws which provides a theoretical reference for practical application in industry. The specific model schematic diagram and simulation parameters are shown in Figure 1 and Table 1 respectively. In this paper, the velocity and turbulence intensity of the liquid film are extracted from computational fluid dynamics (CFD) according to the thickness of the liquid film, that is, the gas–liquid interface and the direction is Z axis. It is worth noting that this paper only studies single-phase flow, and does not involve multiphase flow and heat- and mass-transfer processes.

**2.1.1. Thickness of the Liquid Film**. In previous studies, the distribution of liquid film on the circumferential direction is uneven.\textsuperscript{25} Therefore, it is not accurate to choose the thickness of liquid film on different circumferential direction to observe the flow characteristics of liquid film. Therefore, this paper chooses the thickness of liquid film at different axial positions of 0° position for comparison. The liquid film is affected by gravity and wall shear stress in the course of falling. The vertical direction of gravity will increase the velocity of liquid film. The direction of wall shear stress is opposite to the direction of gravity and is vertical upward. It will produce a certain gradient in the liquid film, thus impeding the flow of liquid film. At the water inlet of the circular tube, the gravity of the liquid film is greater than the resistance caused by the shear stress on the wall, so the liquid film accelerates.

Wei et al.\textsuperscript{25} divided the average thickness of the liquid film into: entrance region I, development region (film thickness increase region II and film thickness reduction region III) and stable region IV. When $Re_l = 2.28 \times 10^3–3.43 \times 10^3$, the entrance region I range from 0 to 200 mm, development region in 200–950 mm (including liquid film increased region in 200–500 mm, liquid film to reduce the region of 500–950 mm); when $Re_l = 6.85 \times 10^3–8.00 \times 10^3$, the entrance region in the range is 0 to 50 mm, development region in 50–1200 mm (including liquid film increased region in 50–500 mm, liquid film to reduce the region of 500–1200 mm); when $Re_l = 1.31 \times 10^4–1.43 \times 10^4$, the entrance region I disappear, development region in 0–1200 mm (including liquid film increased region in 0–500 mm, liquid film to reduce the region of 500–1200 mm), and proposed that the critical $Re_l$ of the existence of region I is $7.5 \times 10^3$. It was worth noting that the length of descending pipe studied in this paper was different from that studied by Wei et al., so the results will be different.

The distribution of the thickness of liquid film at different platform heights and different axial positions is shown in Figure 2. The results show the overall that the thickness of liquid film increases gradually along the axial direction at 0° but the growth rate decreases gradually at the same platform height. The thickness of the liquid film decreases gradually with the increase of platform height at the same position. According to the distribution of liquid film thickness, we divide it into two regions: entrance region and fully developed region, corresponding to 0–0.1 and 0.1–0.5 m respectively. It can be seen from the figure that the increase slope of liquid film thickness in the entrance region is large and decreases with the

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**Table 1. Parameters of Working Conditions**

| material       | air inlet velocity ($m$ s$^{-1}$) | platform height ($H$/mm) | slot width/mm |
|----------------|----------------------------------|--------------------------|---------------|
| plexiglass     | 0                                | 0, 10, 20, 30            | 3.0           |
| temperature/K | $V_l$ ($m$ s$^{-1}$)             | $Re_l \times 10^9$       |               |
| 298.15         | 3.0                              | 3.4623                   |               |
increase of platform height. On the contrary, the thickness of the liquid film in the fully developed region is in a stable fluctuation stable. Surprisingly, the thickness of liquid film is far more than the slot width when the platform height is 0, 10 and 20 mm. The thickness of liquid film increases with axial distance due to the following reasons. First, the initial velocity of liquid film is large. The second is the liquid film forms a similar “jet” effect from the slot outlet (the sudden expansion of narrow space to semi-infinite space). Thirdly, a certain velocity component will be generated in the radial direction. In addition, the baffle plate on the side wall will make the liquid film converge towards the center of the downstream, resulting in the increase of the thickness of the liquid film. In contrast, when the platform height is 30 mm, the liquid film thickness in the entrance region is slightly larger than the slit width, which is relatively weak affected by the “jet” effect, while the liquid film thickness in the fully developed region tends to decrease. This indicates that this height of the platform is weakly affected by the outlet structure of the scrubbing cooling ring, which is conducive to the uniform distribution of the liquid film.

2.1.2. Velocity of Liquid Film. Distribution of the velocity of liquid film at different platform heights and different axial positions is shown in Figure 3. It can be seen from the whole that the velocity of liquid film increases with the increase of axial distance, but the slope gradually decreases. The velocity of the liquid film gradually decreases with the increase of the platform height at the same axial position.

There are three main factors that affect the axial distribution of liquid film axial velocity. One is gravity, which accelerates the liquid film. The second is the frictional resistance caused by

![Figure 2. Distribution of the thickness of liquid film at different platform heights and different axial positions.](https://doi.org/10.1021/acsomega.2c02492)

![Figure 3. Distribution of the velocity of liquid film at different platform heights and different axial positions.](https://doi.org/10.1021/acsomega.2c02492)
wall shear stress $\tau_w$ and eddy viscosity $\varepsilon_m$, which slows down the liquid film. The third is the rupture of the surface of the liquid film, which causes the mass loss of the liquid film and causes momentum loss, thereby reducing the axial velocity of the liquid film. However, since this paper studies the flow characteristics of the liquid film in the fully developed region under the condition of high turbulence, the fluctuation of the liquid film is very intense. In addition, the “jet” effect with solid wall constraint formed by the structure of water inlet pipe and scrubbing cooling ring leads to the decrease of liquid film velocity in this area insignificantly. The comprehensive result of the above reasons leads to a slight increase in the liquid film velocity in this region. Since this study does not involve the liquid film flow characteristics in the falling section of the development region and the stable section of stable region. It is speculated that the liquid film in the falling section of the developing region has a small acceleration effect due to the action of gravity, while the deceleration effect caused by friction resistance and the momentum loss caused by mass loss are significant, so the growth of $V$ decreases with the increase of $Z$. With the continuous increase of axial distance, the velocity of liquid film in the stable region tends to be stable, that is, the acceleration effect of gravity is balanced with the deceleration effect caused by friction resistance and momentum loss, and $V$ fluctuates near a stable value.

2.1.3. Turbulence Intensity at Different Platform Heights. Turbulence intensity ($I_Z$) is the physical quantity representing the intensity of turbulence development. Therefore, this quantity is introduced to describe the variation of turbulence intensity caused by the fluctuation of velocity. In this paper, the

Figure 4. The distribution of $I_Z$ of liquid film at different platform heights and different axial positions.

Figure 5. Distribution of the thickness of liquid film at different $Re$ and different axial positions.
velocity and turbulence intensity of the liquid film are extracted from CFD according to the thickness of the liquid film and the direction is Z axis.

Figure 4 shows the distribution of $I_2$ of liquid film at different platform heights and different axial positions. It can be seen that $I_2$ first decreases rapidly and then tends to a stable fluctuating state with the increase of axial distance. According to $I_2$ distribution, it will also be divided into two stages: entrance region and fully developed region, corresponding to $0−0.1$ and $0.1−0.5$ m respectively. It can be seen from the figure that the slope of the $I_2$ curve of the liquid film in the entrance region is the largest, which indicates that the liquid film fluctuates violently. The reason is that the liquid film here is affected by the outlet structure of the scrubbing cooling to form a "jet" effect, which corresponds to Figure 2. In addition, it can be judged from the $I_2$ variation ($\Delta I_2$) that when the platform height is $30$ mm, the $\Delta I_2$ of the liquid film is small, indicating that the height of this platform has a better effect on promoting the stability of liquid film flow.

2.2. Effect of $Re_l$ on Vertical Falling Film Flow Characteristics. It can be seen from the above simulation results that when the platform height $H = 30$ mm, the liquid film is relatively stable and well-distributed. Therefore, the influence of different Reynolds numbers ($1.1541 \times 10^4−3.4623 \times 10^4$) on the flow characteristics of vertical falling film would be studied by using this platform height.

2.2.1. Thickness of Liquid Film. In general, an increase in liquid film Reynolds number leads to an increase in flow and fluctuation, which directly leads to an increase in thickness of liquid film. However, due to the large curvature of the circular tube, the liquid film is unstable and uneven in the circumferential direction. The circumferential non-uniformity and instability of the liquid film at the inlet also increases when $Re_l$ increases. The liquid film at the position of $0^\circ$ flows to the thinner position (such as $8$ and $16^\circ$) on both sides due to insufficient cohesion. At the same time, it will increase the probability of liquid film surface rupture and droplet entrainment when $Re_l$ reaches a certain critical value. In addition, the fluctuation amplitude of the liquid film also increases with the increase of $Re_l$, which will eventually lead to the rupture of the liquid film surface and change the waveform of the liquid film.

Figure 5 shows distribution of the thickness of liquid film at different $Re_l$ and different axial positions. As can be seen from the figure, when $Re_l = 1.1541 \times 10^4$ and $1.7311 \times 10^4$, the liquid film thickness increases at $Z = 0−0.1$ m, while the liquid film thickness suddenly decreases at $Z = 0.1$ m. The reason is that the thickness of the liquid film increases due to the "jet" effect at the outlet of scrubbing cooling ring. However, due to its small flow rate and unstable liquid film, the influence of the outlet structure of the scrubbing cooling ring on the liquid film at $0.1$ m is weakened, so the thickness of the liquid film changes sharply. When $Re_l$ is increased, the liquid film thickness distribution is also divided into two regions: entrance region and fully developed region due to the joint action of $Re_l$ and outlet structure of scrubbing cooling ring. The results show that the liquid film thickness in the entrance region increases, while the liquid film thickness in the fully developed region decreases. It can be seen that the increase of $Re_l$ is beneficial to promoting the stability of liquid film. The increasing trend of thickness of liquid film at different positions with the increase of $Re_l$ is not obvious. The reason may be that the increase of $Re_l$ leads to the increase of flow, which increases the collision chance of high-frequency small-amplitude waves and gradually accumulates mass, which promotes the formation of large waves. In addition, the simulation area itself belongs to the rising section of development region. In this region, the liquid film is obviously affected by gravity and sidewall effect, and the probability of liquid film rupture is the largest. Therefore, the thickness of liquid film would not increase continuously. The reason for the rupture of the liquid film can be explained by the Plateau−Rayleigh stability: the frequency and velocity of the large wave increase with the increase of $Re_l$, which is conducive to the greater accumulation of mass in the large wave. When the large wave deviates too far from the equilibrium position, the fluctuation of the liquid film will be shown as a small linear water column, which will increase or decrease the radius of some parts of the water.
Meanwhile, the local Reynolds number will increase and cause strong disturbance due to the strong interaction between the large wave and the substrate. Therefore, the pressure in the smaller radius part of the water column is greater than that in other parts. Then, this pressure will cut the water column and form droplets and resulting in the rupture of the liquid film surface.36,37

2.2.2. Velocity of Liquid Film. Figure 6 shows distribution of the velocity of liquid film at different ReL and different axial positions. It can be seen from the figure that when ReL > 1.7311 × 10⁴, the velocity of liquid film increases with the increase of ReL at the same axial position. The velocity of liquid film increases gradually with the increase of axial distance at the same ReL, but the growth rate decreases gradually. This indicates that increasing ReL will increase the velocity of liquid film to a certain extent. There are four reasons. Firstly, the liquid film fluctuates more intensely in the development region. Secondly, the liquid film in this region is affected by gravity, wall shear force and eddy viscosity. Thirdly, the liquid film is affected by the structure of water inlet pipeline and scrubbing cooling ring. Fourthly, the “jet” effect and “sidewall” effect promote the acceleration, rupture, collision, merger and deceleration of the liquid film, so that the velocity of the liquid film would not increase continuously, but shows a trend of slow growth. However, when ReL < 1.7311 × 10⁴, the liquid film has the characteristics of small flow rate and instability, which leads to the fluctuation of the liquid film.

2.2.3. Turbulence Intensity at Different ReL. Figure 7 shows the distribution of Iz of liquid film at different ReL and different axial positions. Similarly, the Iz distribution is divided into two regions: the entrance region and the fully developed region. It can be seen from the figure that Iz decreases with the increase of axial distance in the entrance region due to the influence of the outlet structure of the scrubbing cooling ring. Iz has a turning point at Z = 0.1 m, indicating that the liquid film has been separated from the influence of the outlet structure of the scrubbing cooling ring, so it fluctuates greatly. When ReL < 1.7311 × 10⁴, the liquid film is unstable due to small flow rate,
so it fluctuates violently. When the \( R_e \) continues to increase, the stability of the liquid film is gradually strengthened, so that the \( I_z \) changes little. This indicates that increasing \( R_e \) can enhance the stability of the liquid film and reduce the fluctuation of the liquid film.

2.3. Empirical Formula Prediction. Karapantsios et al.\(^{38}\), Ye et al.\(^{21}\), and Brauer et al.\(^{39}\) have put forward an empirical formula for the liquid film thickness of vertical falling film, but it is only applicable to the stable section of the development region, and the formula as follows

\[
\delta = A^* R_e^{0.08143} (\nu^2/g)^{1/3}
\]

\[
\delta = 4.4765^* R_e^{0.01154} (\nu^2/g)^{1/3}
\]

\[
\delta = 3.1051^* R_e^{0.10154} (\nu^2/g)^{1/3}
\]

\[
\delta = 3.2991^* R_e^{0.01657} (\nu^2/g)^{1/3}
\]

\[
\delta = 2.9270^* R_e^{0.11759} (\nu^2/g)^{1/3}
\]

\[
\delta = 1.6598^* R_e^{0.16831} (\nu^2/g)^{1/3}
\]

\[
\delta = 1.0879^* R_e^{0.21897} (\nu^2/g)^{1/3}
\]

\[
\delta = 0.5543^* R_e^{0.27216} (\nu^2/g)^{1/3}
\]

\[
\delta = 0.6293^* R_e^{0.26854} (\nu^2/g)^{1/3}
\]

\[
\delta = 0.3779^* R_e^{0.33309} (\nu^2/g)^{1/3}
\]

so it fluctuates violently. When the \( R_e \) continues to increase, the stability of the liquid film is gradually strengthened, so that the \( I_z \) changes little. This indicates that increasing \( R_e \) can enhance the stability of the liquid film and reduce the fluctuation of the liquid film.

**Figure 9.** Schematic diagram of the experimental apparatus; 1-blower; 2-rotameter; 3-circulating water pump; 4-circulating water tank; 5-scrubbing cooling ring; 6-water inlet; 7-scrubbing cooling tube; 8-transducer; 9-water storage tank; 10-UDV; 11-computer.

At present, there are relatively few empirical formulas for turbulent falling film at high Reynolds number, and there is even a lack of formula for predicting the thickness of liquid film at the fixed position in the axial direction of the vertical falling film of the circular tube. Due to the rupture of the liquid film at about 0.1 m in the axial direction, this section selects the nonlinear fitting of the thickness of liquid film \( (\delta) \) at an interval of 0.01 m within the axial distance range of 0.01–0.1 m. The fitting diagram and formula are shown in Figure 8 and Table 2 respectively. It can be seen from the figure and table that the correlation coefficient \( R^2 \) of the fitting relationship is greater than 0.88, and the maximum standard error of the value of exponent and constant are no more than 0.27 and 0.07 respectively, which indicates that the fitting degree is high. It should be noted that the empirical formula in the following table takes the surface tension, viscosity and gravity into account, which is applicable to turbulent falling film under high \( R_e \) \((1.1541 \times 10^4–3.4623 \times 10^4)\).
3. CONCLUSIONS

The starting point of this paper is how to make the distribution of falling liquid film more uniform and stable. The influence of the optimization of the structural parameters of the scrubbing cooling ring in the quench chamber, the core component of coal gasification technology, and high Reynolds number on the flow characteristics of vertical falling film were studied by means of experiment and numerical simulation. It provides a theoretical basis for the follow-up development of multiphase flow heat and mass transfer. The following conclusions are drawn.

1. The thickness of liquid film in the entrance region increases sharply due to the “jet” effect formed by outlet structure of the scrubbing cooling ring, while the liquid film in the fully developed region fluctuates steadily. With the increase of platform height, the change of liquid film thickness and turbulence intensity is relatively stable, indicating that the increase of platform height is conducive to formation of stable and uniform liquid film.

2. When \( Re_L < 1.1541 \times 10^4 \), the liquid film is unstable due to the low flow rate and insufficient cohesion of the liquid film, but the velocity of liquid film increases slightly. In addition, with the increase of \( Re_L \), the thickness of liquid film did not change significantly along axial direction, that is, the Plateau–Rayleigh hinders the growth of liquid film thickness.

3. The empirical relationship of liquid film thickness at the fixed position of the rising section of the descending pipe development region of the scrubbing cooling chamber is proposed for the first time, and the fitting degree is high, which is applicable to turbulent falling film under high Reynolds number (\( 1.1541 \times 10^4 - 3.4623 \times 10^4 \)).

4. EXPERIMENTAL SYSTEM

4.1. Experimental Setup. The schematic diagram of the vertical falling film flow experimental platform in the scrubbing cooling chamber is shown in Figure 9. The main body of the experimental device is made of plexiglass, and the material used in the scrubbing cooling ring is made of stainless steel. The liquid phase used in the experiment is water, which is pumped out from the circulating water tank and transmitted to the scrubbing cooling ring through a rotameter. It is worth noting that the flow rate of the four inlets of the scrubbing cooling ring is the same. A baffle is arranged in the middle of the scrubbing cooling ring chamber, which can promote the uniform distribution of the working medium in the chamber and reduce the non-uniformity of film formation caused by the water inlet pipeline. After the water is distributed through the scrubbing cooling ring, it forms an annular liquid film through the slot and flows downward along the wall of the scrubbing cooling pipe. Finally, it is collected by the water storage tank and sent to the circulating water tank. The experimental environment was at room temperature, the working temperature of the medium was controlled at \( 25 \pm 2 \, ^\circ\text{C} \), and an infrared thermometer was used to monitor the water temperature in real time.

The structure diagram of the experimental system is shown in Figure 10. We define \( Z \) to be the axial direction, that is, positive direction. The inlet position of the scrubbing cooling pipe as \( Z = 0 \, \text{mm} \) and outlet position as \( Z = 500 \, \text{mm} \). Experiments were carried out to measure the liquid film thickness in the range of \( 0 - 500 \, \text{mm} \) at the \( 0^\circ \) position of the scrubbing cooling pipe (\( Z = 0 \, \text{mm} \)). The \( 0 - 100 \, \text{mm} \) interval is 10 mm, and the 100–500 mm interval is 25 mm. In addition, the experimental conditions and water flow directions are shown in Table 3 and Figure 11, respectively.

### Table 3. Experimental Conditions

| Temperature/K | Pressure/atm | Inlet Liquid Film Velocity/m s\(^{-1}\) | \( R_{f1} \) |
|---------------|--------------|----------------------------------------|-------------|
| 298.15        | 1.0          | 3.0                                    | \( 3.4623 \times 10^4 \) |

4.2. Error Analysis. 4.2.1. Ultrasonic Doppler Velocimetry. UDV was used to measure the thickness of turbulent falling film in the tube in real time. Its principle is that the transducer launches a certain frequency of ultrasonic waves to the experimental object, and the sound wave propagates through the medium in the fluid. When the ultrasonic wave passes through the wall—water and water—air interface, it will produce strong reflection waves. The time and intensity of the reflected wave are obtained by the sensor. Then, according to the time difference between the two received reflected waves and the propagation speed of the ultrasonic wave in the medium, the distance between the two interfaces can be calculated as the thickness of the liquid film. Li et al.,
Jayakumar et al.\textsuperscript{41} and Wei et al.\textsuperscript{22} used ultrasonic technology to measure the liquid film thickness under different flow conditions, thus proving the accuracy of ultrasonic probes in measuring liquid film thickness. The detailed measurement principles and usage of the UDV are described in the literature.\textsuperscript{41–43}

In this experiment, the transmitting frequency of the sensor was 4 MHz and the effective diameter of the sensor was 8 mm. The spatial resolution of the film thickness measurement was 0.12 mm and the time resolution was 10 ms. An ultrasonic measuring angle of 90° was used to minimize the error caused by the measurement angle and lower the degree of attenuation of ultrasonic waves.

4.2.2. Sound Velocity Error. The sound velocity of water in the experiments was obtained by consulting the website (https://webbook.nist.gov/cgi/fluid.cgi?Act%20ion=Load&ID=C7732185&Type=1&Bar&Digits=6&P=1&THigh=40&%20TLow=18&TInc=0.1&RefState=DEF&TUnit=C&PUnit=atm&DUnit=kg%20%2Fm3&HUnit=kJ%2Fmol&WUnit=m%2Fps&VisUnit=Pa*s&STUnit=N%20%2Fm#main) of the National Institute of Standards and Technology (NIST) for thermophysical properties of fluid systems and adjusted in time according to the change of water temperature. The error of sound velocity is defined as

\[ E = \frac{|V_N - V_M|}{V_M} \]  

(8)

where \( V_N \) is the sound velocity of water obtained by NIST and \( V_M \) is the sound velocity of water measured by UDV. The maximum error is 0.5%.

4.2.3. Accuracy of Film Thickness Measurement. To avoid systematic or operational errors, the thickness of liquid film of each location is repeated 50 times. The thickness of liquid film measurement accuracy was calculated and expressed as the relative standard deviation (RSD), as in eq 9.

\[ \text{RSD} = \frac{\sqrt{\sum \left( \delta_i - \delta \right)^2}}{\delta} \]  

(9)

where \( \delta_i \) is the mean value of liquid film thickness for per measurement and \( \delta \) is the mean value of liquid film thickness of the mean liquid film thickness. The RSD is calculated below 3.0%.

4.2.4. Wall Wettability. The effect of the viscosity of the liquid phase on wall wettability can be negligible.\textsuperscript{44} The Plexiglass wall was completely wet (about 1 h) before the experiment, and the temperature difference between water and the plexiglass wall was within 1 °C. Therefore, the influence of wall wettability on liquid film rupture and experimental measurements can be excluded.

The main errors of the experimental system were summarized as follows (Table 4):

The axial distribution of the measured value of the mean liquid film thickness is shown in Figure 12. It can be seen that the overall liquid film thickness first increases sharply and then fluctuates stably, that is, the slope decreases gradually. According to the distribution of liquid film thickness, it is divided into two regions: entrance region and fully developed region. Surprisingly, the thickness of the liquid film in the entrance region is even greater than the slot width. The reason is that the liquid film has undergone the evolution of “kinetic energy—hydrostatic energy—kinetic energy” at the entrance, interior, and outlet of the distributor, so the liquid phase forms a “jet” at the outlet of the distributor, that is, the liquid phase produces a velocity component in the “−X” direction, which increases the thickness of the liquid film.\textsuperscript{25} Therefore, the slow increase of liquid film thickness after \( Z = 0.1 \) m may be due to the rupture of the liquid film, and the effect of liquid film compensation later will increase the liquid film thickness to a certain extent.

5. SIMULATION VERIFICATION

5.1. Physical Model. Figure 13 shows the main view of the model diagram, which is part of the scrubbing cooling chamber of the OMB gasifier. It includes the scrubbing cooling ring and the descending circular tube. The structure diagram of the scrubbing cooling ring is shown in Figure 14. As can be seen from Figure 14, the scrubbing cooling ring has four water inlets placed opposite each other, and the intermediate structure is composed of four circular tubes nested, respectively. After the cooling water is distributed through the scrubbing cooling ring, an annular liquid film is formed on the inner wall of the scrubbing cooling pipe and flows down the wall under the action of gravity. It is worth noting that the middle part of the scrubbing cooling ring is the gas inlet. This simulation does not involve gas and \( V_g = 0 \) m/s. Table 5 illustrates in more detail about the range of operating conditions employed, for example, the liquid and gas flow velocity, range of geometry parameters of scrubbing cooling ring investigated, and so forth.

5.2. Numerical Model. 5.2.1. Problem Statement. In the scrubbing cooling chamber, the cooling water uniformly distributed by the scrubbing cooling ring flows downward along the descending pipe wall. This paper adopts the model of one to one reduction with the experimental device and carries out numerical calculation under the same \( R_e \). The single-phase liquid film flow is considered only in this paper without considering heat and mass transfer.

5.2.2. Numerical Assumptions. To simplify the CFD model, the following assumptions are made:

(1) The cooling water inlet flow rate is constant and does not change over time.

(2) The physical properties under normal temperature and pressure are adopted.

(3) The properties of the liquid phase do not vary with the temperature in the domain and are estimated at the inlet temperature.

(4) Assuming that the normal and tangential velocities at the wall are zero, there is no slip of the liquid film on the wall.

(5) To ensure wetting of tubes, wall adhesion contact angle is set to 90 value (\( \theta_w = 90^\circ \)).

5.2.3. Governing Equations. Due to the highly turbulent flow in the scrubbing cooling tube, the multiphase flow model

| Parameter        | measuring apparatus | errors |
|------------------|----------------------|--------|
| temperature      | RayTek Raynger ST60  | ±1 °C  |
| volume flow rate | rotar flowmeter LZB40| 2%     |
| slot distributor | Vernier caliper      | ±0.02 mm|
| sound velocity   | NIST                 | 0.5%   |
| Doppler angle    | UDV                  | 0.5°   |
| thickness of the falling film | UDV | 3%     |

Table 4. Main Errors of the Experimental System
is modeled by the VOF model in order to track the gas–liquid interface.\(^\text{15}\)

(1) Governing equations

### Continuity equation

To track the gas–liquid interface, volume fraction \(\alpha\) is introduced to solve the continuity equation.

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

(10)

where \(\rho_l\) is the density of the liquid phase and \(\alpha_l\) is the volume fraction of the liquid phase. Within each control body, the volume fractions sum to 1. The gas phase volume fraction can be calculated from the following equation.

\[
\alpha_l + \alpha_g = 1
\]

(11)

where \(\alpha_g\) is the gas phase volume fraction.

### Momentum conservation equation

Considering the influence of gas–liquid interfacial tension, the surface tension models are introduced.\(^\text{15,46,47}\) The equation is

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**Table 5. Operating Conditions and Geometry Parameters**

| parameter               | Value                          |
|-------------------------|--------------------------------|
| inlet liquid phase velocity | 1, 1.5, 2, 2.5, and 3 m s\(^{-1}\) |
| air inlet velocity       | 0 m s\(^{-1}\)                 |
| \(R_{\text{Wall}}(1,2,3,4)\) | 87, 73, 70, and 60 mm          |
| \(R_{\text{water-inlet}}\)  | 9.5 mm                        |
| slot width               | 3 mm                          |
| descending pipe height   | 0.5 m                         |

**Table 6. Solver Settings for the CFD Model**

| settings                  | selection                           |
|---------------------------|-------------------------------------|
| flow mode                 | turbulence \((R_l = 1.1541 \times 10^4 - 3.4623 \times 10^6)\) |
| multiphase model          | volume of fluid (VOF)               |
| transient formulation     | 1st order implicit                  |
| surface tracking scheme   | geo reconstruct                     |
| pressure velocity coupling| PISO algorithm                       |
| momentum discretization   | 2nd order upwind                    |
| surface tension modelling | continuum surface force (CSF) model |
| time step                 | flexible \((2.5 \times 10^{-4} \text{ s})\) |

---

Figure 12. Distribution of thickness of the liquid film at axial.

Figure 13. Model diagram (main view).

Figure 14. Scrubbing cooling ring model (top view).
Figure 15. Physical model and meshing (a) and the comparison of thickness of liquid film before and after mesh encryption (b).

Figure 16. Comparison of thickness of liquid film calculated by simulation and experiment.
\[
\frac{\partial \rho u}{\partial t} + \rho u \nabla u = -\nabla p + \nabla [\mu (\nabla u + \nabla u^T)] + F_s
\]  
(12)

where \(F_s\) is the surface tension, which is calculated by the following formula

\[
F_s = \frac{\sigma \rho_k \nabla \alpha_i}{\sqrt{2 \left( \rho_g + \rho_i \right)}}
\]  
(13)

The middle density and viscosity are calculated from the following formula

\[
\rho = \alpha \rho_g + \alpha \rho_i
\]  
(14)

\[
\mu = \alpha \mu_g + \alpha \mu_i
\]  
(15)

(2) Turbulence model: using the RNG \(k-\varepsilon\) turbulence model whose simulation results are closer to the experimental results, and the transport equations of the turbulent kinetic energy \(k\) and its dissipation rate \(\varepsilon\) of the model can be expressed as

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \alpha \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]  
(16)

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left( \alpha \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1s} \frac{\varepsilon}{k} (G_k + C_{3s} G_b) - C_{2s} \rho \varepsilon^2 \kappa - R_e
\]  
+ S_\varepsilon
\]  
(17)

Among them, the model constants are \(C_{1s} = 1.42\) and \(C_{2s} = 1.68\). \(G_s\) represents the generation of turbulent kinetic energy caused by average velocity; \(G_b\) is the turbulent kinetic energy generated by buoyancy; \(Y_M\) represents the contribution of wave expansion to the total dissipation rate in compressible turbulence; \(\alpha_1\) and \(\alpha_2\) are the reciprocal of \(k\) and \(\varepsilon\) effective Prandtl numbers respectively; and \(S_k\) and \(S_\varepsilon\) are user-defined source items.

5.2.4. Solver Setting. No slip boundary condition is adopted in the calculation process, and the standard wall function is used for the near wall surface. The inlet condition adopts speed inlet, the outlet condition adopts pressure outlet, and the operating condition are normal temperature and pressure. The finite volume method is implemented in ANSYS FLUENT software v.19.2, and the momentum equation and mass conservation control equation are discretized and applied to each element. PISO algorithm is used to solve the coupling of pressure and velocity. The volume fraction is solved by geometric reconstruction scheme. Momentum, turbulent kinetic energy and dissipation rate are calculated by using the second-order upwind scheme. The convergence criterion is that the flow field iterative residual is less than \(10^{-4}\), and the inlet and outlet flow difference is less than 0.1%. The solver settings of the CFD model are listed in Table 6.

5.2.5. Mesh Independence Check. To eliminate the influence of grid on the calculation results, the mesh independence test is carried out to find the optimal number of cells that save the calculational time without missing the accuracy. This article adopts the way of a quarter symmetry to structured grid model as shown Figure 15a. CFD results of six models with structured grid numbers of \(4.1 \times 10^5\), \(5.2 \times 10^5\), \(6.6 \times 10^5\), \(7.8 \times 10^5\), \(8.6 \times 10^5\) and \(9.5 \times 10^5\) were compared. Figure 15b shows the thickness of liquid film at the circumferential angle of \(0^\circ\) and axial distance \(x = 0.3\) m when \(R_0 = 3.4623 \times 10^4\). It can be seen from the figure that when the number of grids increases from \(8.6 \times 10^5\) to \(9.5 \times 10^5\), the thickness of liquid film has hardly changed, so the number of grids is selected as \(8.6 \times 10^5\) to reduce the amount of calculation. Considering the accuracy and calculation cost, the time step is discussed according to the method in the literature. When the time step increases, the courant increases, resulting in longer calculation time. When the time step decreases, more time steps are required to calculate the same time, which means that the actual calculation time increases. To sum up, we choose \(2.5 \times 10^{-4}\) s as the time step of this paper.

5.3. Model Verification. For the liquid film flowing along the vertical wall, the mass accumulation in the propagation of large waves is the direct cause of the rupture of the liquid film surface. Mudawar et al.49 pointed out that large waves can carry 40−70% of the total mass flow and play an important role in mass transmission in the film. Adomeit et al.50 and Song et al.51 reported that high-frequency small amplitude waves will accumulate mass during collision and absorption and promote the formation of large amplitude waves. Song et al.52 proposed that the rupture of liquid film is caused by the superposition of energy generated by nonlinear wave interaction, which is independent of gas phase. High \(R_0\) accelerates the frequency and velocity of large waves and promotes wave-to-wave collisions and mergers, eventually resulting in rupture of the liquid film, which is exacerbated by the “jet” action at the crest. Figure 16 shows the comparison between the simulation results and experimental data when \(R_0 = 3.4623 \times 10^4\). At the entrance of the tube, the gravity effect of the liquid film is greater than that caused by wall shear stress, so the liquid film velocity accelerates. Liquid flows from a slit to a semi-infinite space, similar to a jet. At this time, the liquid film has a horizontal velocity component. When the liquid Reynolds number is large, the liquid film is prone to rupture. Then, due to the action of the side wall baffle, the upstream liquid film converges downstream to supplement the liquid film thickness. However, due to the weakening of the baffle, the extension of the flow region of the liquid film to the side wall and the rupture of the surface wave, the thickness of the liquid film cannot increase continuously. This also explains the sharp increase in the thickness of the liquid film in the range of \(Z = 0\)−0.1 m and the subsequent steady fluctuation of the liquid film thickness. The results show that the liquid film error \(E\) is the largest at the entrance of descending pipe, which is 9.836%. With the increase of axial distance, the error value decreases slightly, and the \(E\) value decreases to 5.992% at \(Z = 0.5\) m. It shows that the simulation results are in good agreement with the experimental results, which verifies the correctness of the model.

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■ NOMENCLATURE
CFD computational fluid dynamics
VOF volume of fluid
CSF continuum surface model
d tube diameter (m)
F force (N)
HFFE horizontal falling film exchangers
K curvature
P pressure (Pa)
I turbulence intensity
V velocity in Z-direction (m/s)
Re$_f$ films Reynolds number
U inlet velocity
H platform height (mm)
$R^3$ fitting degree
$g$ the gravity acceleration (m/s$^2$)
$V_N$ sound velocity obtained by NIST (m/s)
$V_M$ sound velocity obtained by experiment (m/s)
E error (−)

■ GREEK LETTERS
$\alpha$ void fraction
$\rho$ density (kg/m$^3$)
$\mu$ dynamic viscosity (Pa s)
$\sigma$ surface tension (N/m)
$\theta$ angular position (°)
$\delta$ film thickness (mm)
$\Gamma$ mass flow rate per unit (kg m$^{-1}$ s$^{-1}$)

■ ABBREVIATIONS
UDV ultrasonic Doppler velocimetry
OMB opposed multi-burner gasifier

NIST National Institute of Standard and Technology
RSD relative standard deviation

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