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Numerical study of falling film flow on a horizontal rotating tube

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ABSTRACT

In this paper, a CFD simulation of falling film on a horizontal rotating tube is illustrated. The objective of this simulation is to explore the influence of various parameters on this kind flow. The simulation results show that in a certain range, the offset angle of the liquid column increases with the increase of the rotational speed, which agrees well with the experimental values. Compared to a stationary tube, the liquid film thickness at the left side of the liquid column is thinner but the right gets larger when the tube is rotating counterclockwise. And the liquid film velocity at the left side of the liquid column is equivalent to the linear superposition of the velocity at the standstill and the rotational velocity denoted by ω. Rotation has a great influence on the velocity distribution at the right side of liquid column. Increasing the rotational speed and the diameter, decreasing the inlet velocity and the inlet hole diameter will make the offset angle of the liquid film larger. The high temperature reduces the offset angle of the liquid column, and the gradient of the liquid column offset angle to temperature becomes smaller. When the temperature is above 65 °C, the effect of temperature on the offset angle of liquid column is negligible. When ω = 200 rpm, the offset angle increases first and then decreases with the increase of the inlet height, but when ω = 300 rpm, the offset angle increases with the increase of the inlet height.

1. Introduction

Falling film evaporator is a kind of efficient and energy-saving evaporator, which has been widely used in desalination [1], refrigeration system [2], food industry [3] and other process industries so on. Compared with other evaporators, falling film evaporator has several superiorities such as high heat transfer coefficient, less coolant, small temperature difference and good treatment of thermosensitive materials. It makes falling film evaporator have good economical efficiency, environmental benefits and broad application prospect.

The conception of flow pattern was first proposed by Honda [4] when he studied falling film cooling of low finned tube. Armbruster and Mitrovic [5] studied experimental flow characteristics of liquid film, and the experimental results indicated that the flow pattern of liquid film can be divided into 3 types: droplet flow, column flow, and sheet flow. On this basis, Hu and Jacobi [6,7] put forward the 5 type flow patterns: droplet flow, droplet-column flow, column flow, column-sheet flow, and sheet flow, and they proposed a new application criterion about the law of flow pattern transition which depends not only on Reynolds number *Re*, but also Galileo number *Ga*. Subsequently, Hu and Jacobi [8] confirmed that the tube spacing has an influence on the flow pattern of liquid film. Additional experimental observations for the flow characteristics and mode transitions of falling film were given by Mitrovic [9], Han [10], Wang and Jacobi [11]. They studied the influence factors of flow patterns, such as tube diameter, tube spacing, flow rate and fluid properties. Among them, Mitrovic found that columnar flow is the most stable among the 5 type flow in the experiment.

Much research on the flow pattern of liquid film has been done to obtain better heat transfer coefficient, because the high heat transfer coefficient, pursued by many scholars, is the most important characteristic of falling film evaporator.

Ribatski and Jacobi [12] summed up previous work and concluded that the main factors affecting the heat transfer coefficient of the falling film evaporation were: inlet flow rate, heat flux, inlet height, diameter, gas flow rate and saturation temperature so on. Therefore, the experimental and theoretical studies on the falling film heat transfer have been mainly carried out on these parameters. Moeykens and Pate [13] studied the influence of the factors such as the type of inlet hole, the flow rate and the diameter of the tube on the falling film evaporation. It is concluded that the smaller diameter of the heat exchange tube is more conducive to the falling film heat transfer, and the flow rate is the most important factor causing the dryout of the liquid film. Mu [14] and Shen [15] investigated the experiment of falling film evaporation on desalination. It is found that the factors such as saturation

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Nomenclature

D	diameter of rotating tube, mm
d	inlet hole diameter, mm
F	the surface tension force, N
Ga	Galileo number, $\rho\sigma^3/\mu^4 g$
g	gravitational acceleration, m/s^2
H	inlet height, mm
i,j	basis vector
k	curvature, m^{-1}
p	pressure, N/m^2
q	inlet flow rate, m^3/s
Re	Reynolds number, $4\Gamma/\mu$
T	temperature, °C
t	time, s
u	inlet velocity, m/s
x,y	Cartesian coordinates, m

Subscripts

g	gas
vol	volume
w	water

Greek symbols

α	phase fraction, %
θ	offset angle, °
μ	viscosity, Pa s
v	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension coefficient, N/m
ω	rotational speed, rpm

Abbreviations

CCD	Charge Coupled Device
CFD	Computational Fluid Dynamics
CSF	The Continuum Surface Force
PISO	The Pressure-Implicit with Splitting of Operators
VOF	Volume of Fluid

temperature of sea water and salinity of sea water have an effect on the heat transfer coefficient of falling film evaporation.

As an effective method to improve heat transfer, enhanced tubes are extensively utilized in falling film heat exchangers. Many experiments for falling film evaporation on enhanced tubes have been studied by many scholars. Ribatski and Jacobi [12] found that the enhanced structures of the outer surface greatly affect the convection heat transfer and film distribution. Besides, Fernández-Seara [2] pointed out that most enhanced tubes not only improve the heat transfer but also delay film breakdown compared to the plain tube.

With the development of process Manufacturing Technology, tube surface enhancement technology has developed from 2D structure to 3D structure. Liu [16] studied the evaporation heat transfer of water and R-11 falling films on the smooth, helically low finned and roll-worked single tubes. The experimental results revealed that roll-worked tube can greatly improve the heat transfer either for water or for R-11 at low and moderate heat fluxes, and helically low finned tube provides a better performance at higher heat flux. Zhao [17] investigated the four 3D-finned tubes in heat transfer performances for R134a and R123. It is indicated that for R134a, 3D-finned tubes with a wide cavity provide higher heat transfer coefficients, and for R123, the conclusion is the opposite of R134a.

Compared to enhanced surface technology, the rotary tube is a kind of enhanced tube that requires external energy supply. There have been some reports about the flow mechanics and heat and mass transfers from a horizontal rotating cylinder. Cheng [18] investigated the convective heat transfer on a radially rotating heated cylinder, and the results indicated that the heat transfer enhancement is greater than fixed cylinder at lower Reynolds number and higher rotational speeds, because of rotation which generates the cross-stream motion to additional mixing and enhances the heat transfer. Khanafer [19] studied mixed convection heat transfer in a lid-driven cavity with a rotating circular cylinder, and this study showed that compared with non-rotating cylinder, playing a rotating cylinder brings the maximum heat transfer. Because the moving boundary enhanced flow mixing on account of the shear stress generated by the moving surface. Ma [20,21] studied the convective mass transfer from a horizontal rotating large diameter cylinder with and without a slot air jet flow. The influences of rotational Reynolds number, jet-exit Reynolds number, and geometrical parameters of the nozzle on the flow mechanics and heat and mass transfer were studied experimentally. More impingement flow regions are achieved by rotating cylinder, which have higher heat transfer performance. Ma [22] investigated the air flow and characteristics of the heat transfer from a large diameter horizontal rotating isothermal cylinder, and the temperature distribution within the thermal boundary layer on the surface of rotating cylinder is measured by a micro-thermocouple made specially. The results showed that rotation can result in a offset of trailing vortex, and the worst heat transfer region doesn't appear in the trailing vortex region.

However, there has been less research on falling film on rotating tubes, and the problem of liquid column offset on rotating tube has not been paid much attention by scholars.

Paramane [23] reported the flow transitions for a wider range of Reynolds number and rotational speed and used heatlines to create a visualization of heat transfer. The stability of the liquid film flow on the outer surface rotating vertical tube has been studied by Chen [24]. It is found that increasing the rotational speed and increasing the diameter of the rotating tube in the evaporation of liquid film will result in the instability of the liquid flow. Mohamed [25] studied experimentally the flow behavior of liquid film on a horizontal rotating tube. The experimental results indicated that the rotational speed will effect the falling film mode transitions, the liquid film thickness and the dimensionless wavelength. To avoid instable falling film during rotation of the tube, the rotational speed should not exceed the maximum speed of rotation. The value of the film thickness has been slightly decreased by increasing the rotational speed.

The dry-out tube always occurs when the tube is incomplete wetting. As for rotating tube, dry spots are easily produced without controlling the offset of the liquid column. Mohamed's experiment [25] indicated that at high instability the falling film will lose contact with the tube. The reason is that the offset of the fluid column is too large because of excessive rotation. The experiment about upward vapor flows was carried out by Morison [26]. The results pointed that the vapor flow causes great offset of inlet liquid jets, which impedes the wetting of the next tube. A counter-current gas flow is capable of promoting the deflection of the liquid flow, affecting or even destroying the inter-tube flow mode [27].