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Experimental study on heat and mass transfer of falling liquid films in converging-diverging tubes with water

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ABSTRACT

To improve the heat and mass transfer performances of falling films and develop a new type of falling film evaporator, the heat and mass transfer characteristics of falling film evaporation and sensible heating in four different sizes of converging–diverging (CD) tubes were experimentally explored in this study. By analyzing the relationship between the heat transfer coefficient and the falling film flow rate, it was found that the CD tube is suitable for falling film evaporation and sensible heating with a large Reynolds number. For different sizes of tubes, the key factor affecting the heat transfer performance in falling film evaporation and sensible heating is the rib height. At the same rib height and rib pitch, the longer the converging segment of the CD tube, the better the heat transfer performance. According to the comparative analysis on heat and mass transfer performances of falling film evaporation and sensible heating inside the four CD tubes, the CD tube 3# is the best. The evaporation heat transfer coefficient (when the Reynolds number of the liquid films is 2356), evaporation mass transfer rate (when the perimeter flow rate of the liquid films is 0.173 kg/(m·s)), and sensible heating heat transfer coefficient (when the Reynolds number of the liquid films is 1635) of CD tube 3# are 62%, 38% and 63% higher than that of the smooth tube, respectively. For the same CD tube, the evaporation heat transfer coefficient is greater than the sensible heating heat transfer coefficient, but both increases as the flow rate increases. The heat transfer correlations of falling film evaporation and sensible heating in the experimental range were obtained. It will provide a useful reference for future engineering design and industrial applications.

1. Introduction

The heat and mass transfer of the falling film flowing over a vertical heating surface is of great importance in many industrial operations, such as the temperature raise or evaporation of the liquid, or selective evaporation of specific components. Such operation, that is falling film evaporator, has been widely used in seawater desalination, pulp and paper, food processing, air-conditioning and many other industries [1]. With the rapid economic and social development, rising energy prices, and increasing environmental protection requirements, the industrial demand for energy-consuming equipment continues to rise. Therefore, the development of enhanced heat and mass transfer technology that can improve the heat and mass transfer performances of falling film evaporator and increase its evaporation efficiency is of great significance to the project investment, energy saving and consumption reduction.

Many studies have been conducted on the different influencing factors of the falling film heat transfer in a vertical smooth tube, e.g. flow regimes [2–6], liquid properties [7–9], liquid film surface tension [10], phase shear stress [11–13], and thermal entry length [14,15]. For literature involving different influencing factors, it is well known that the effect of the flow regime on heat transfer is most pronounced [7,16]. However, there are few studies on heat transfer enhancement of vertical smooth tubes. Existing enhancement methods include tube gas ventilation, tube insertion, and tube shape modification. Among these methods, the study of tube shape modification has received more attention. For example, Fagerholm et al. [17] used four enhanced heat transfer tubes (High flux, Gewa-T, Thermoexcel-E and-EC) to perform the falling film evaporation experiments, respectively, and found that the four enhanced heat transfer tubes can improve the heat transfer performance. Jiang [18] used corrugated tubes to divert the liquid film to

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Nomenclature

c_p	specific heat capacity of liquid films, J/(kg·K)
d_o	outer diameter of the heat transfer tube, m
d_i	inner diameter of the heat transfer tube, m
g	acceleration of gravity, m/s^2
h	falling film sensible heating or evaporation heat transfer coefficient inside the heat transfer tube, W/(m^2·K)
h^+	dimensionless falling film sensible heating or evaporation heat transfer coefficient inside the heat transfer tube
h_o	heating steam condensation heat transfer coefficient outside the heat transfer tube, W/(m^2·K)
K	overall sensible heating or evaporation heat transfer coefficient of falling films, W/(m^2·K)
L	effective heating length of heat transfer tube, m
m_l	mass of liquid films, kg
m_v	mass of liquid film evaporation, kg
q	heat flux density of falling film sensible heating or evaporation, W/m^2
r	vaporization latent heat of liquid films under saturation temperature, J/kg
r_o	heating steam condensation latent heat outside the heat transfer tube, J/kg
Re_o	Reynolds number of condensation liquid
Re	average Reynolds number of liquid films
T_o	outer wall temperature of heat transfer tube, K
ΔT_{LMTD}	logarithmic mean temperature difference, K
T_k	heating steam temperature outside the heat transfer tube, K
T	temperature of liquid films, K
t	experimental time, s
u_v	liquid film evaporation mass transfer rate, kg/(m^2·s)

Greek symbols

λ_o	thermal conductivity coefficient of condensation liquid, W/(m·K)
λ_s	thermal conductivity coefficient of heat transfer tube, W/(m·K)
λ	thermal conductivity coefficient of liquid films, W/(m·K)
Γ	liquid film perimeter flow rate inside the heat transfer tube, kg/(m·s)
μ	dynamic viscosity of liquid films, kg/(m·s)
μ_o	dynamic viscosity of condensation liquid, kg/(m·s)
v	kinematic viscosity of liquid films, m^2/s
π	constant
ρ_o	density of condensation liquid, kg/m^3

Subscripts

1	sensible heating
2	evaporative heating
i	inside of the tube
l	liquid
o	outside of the tube
v	vapor

flow downwards along alternant curves and to thin the turbulent boundary layer through flow rate. The results showed that the heat transfer performance of falling film evaporation was improved by about 10%. Gonda et al. [19] experimentally studied the falling film evaporation on a single vertical corrugated plate, and found that the heat transfer coefficient was at least 50% higher than that of the smooth plate. Fan et al. [20] studied the effect of the inner surface sintered porous tube on the heat transfer performance of falling film evaporation, and found that the heat transfer coefficient and total heat transfer coefficient were 103% and 78% higher than that of the smooth tube, respectively. However, due to the difficulties in manufacturing and maintenance, many enhanced heat transfer tubes have not been extensively applied in the industry.

The development and application of high efficiency enhanced heat transfer units have been the most active and vital research topic in the field of heat and mass transfer. Converging-diverging (CD) tube is a typical enhanced heat transfer tube, consisting of alternating divergence and convergence segments. In the case of higher heat transfer coefficient, smoother surface transition, and smaller flow resistance, the CD tube is widely applied in sulfuric acid, petrochemical and other industries [21,22]. The enhanced heat transfer in CD tubes has been extensively studied [23,24], the results consistently showed that CD tubes have better enhanced heat transfer performance. Our previous research has accumulated a lot of experimental data about the CD tube. For example, Zhang et al. [25,26] used CD tubes for natural convection heat transfer and natural convection boiling heat transfer experiments, and the results showed that the heat transfer coefficients were improved to some extent compared with the smooth tube. Chen et al. [27,28] studied the turbulence convection heat transfer in CD tubes through numerical simulations, and revealed the distribution laws of flow-direction field synergy that affecting the convective heat transfer intensity. Besides, based on the optimized CD tube proposed by Мигай [29], an improved structure of the CD tube was put forward by extending the length of converging segment and shortening the length of diverging segment, and they demonstrated its higher heat transfer coefficient than common CD tube. Huang et al. [30,31] studied the mechanism of enhanced heat transfer in CD tubes, and found that the key parameter affecting the heat transfer performance - roughness height should be located in the flow transition zone. Meanwhile, Duryodhan [32] carried out single-phase fluid flow and heat transfer in diverging and converging microchannels, and found that the heat transfer coefficient is 35% higher in converging microchannel compared with diverging microchannel. Currently, the research on CD tubes as high-efficiency enhanced heat transfer units mainly focuses on single-phase convection and boiling heat transfer inside or outside the tube, but rarely focuses on falling film evaporation or sensible heating. In this study, to improve the heat and mass transfer performances of falling films and develop a new type of falling film evaporator using water as a working fluid, the heat and mass transfer characteristics of falling film evaporation and sensible heating in four different sizes of CD tubes were experimentally explored and compared with the smooth tube. In the above literature, the falling film heat transfer has many influencing factors. However, this study mainly focuses on the effect of falling film flow rate on heat and mass transfer. The findings together with the analysis of the enhanced heat and mass transfer performances of falling film evaporation and sensible heating form the basis for applying CD tubes to falling film evaporators.

2. Experimental method

2.1. Experimental apparatus

The measurement of the heat and mass transfer performances of falling films was carried out in the experimental apparatus