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Numerical and experimental research on the heat transfer of seawater desalination with liquid film outside elliptical tube

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ABSTRACT

The falling film evaporation outside the elliptical tube was studied and compared with the circular tube for the design and improvement of seawater desalination system using the method of theoretical analysis, CFD numerical simulation and experiments. The experiment shows that the thickness of liquid film outside elliptical tube of E (ellipticity) = 1.5 obtained from the simulation agrees well with the experimental data and the maximum deviation is within 8%. This fully illustrates that the numerical model is correct and that analog calculation is feasible. The experimental results also manifested that heat transfer coefficient of the system with E = 1.5 elliptical tubes increases by 20–22% compared with circular tubes. This study testified that it is superiority and feasibility that elliptical tubes were applied to falling-film evaporation and seawater desalination of horizontal tubes. The exploratory researches will be conducted for promoting the design and application of falling film evaporation with elliptical tubes in the seawater desalination system.

1. Introduction

Horizontal tube falling-film evaporators are widely used in the low temperature multiple effect seawater desalination systems. The performance of heat and mass transfer of falling-film evaporator directly affects the cost of seawater desalination. For purpose of improving the thermal efficiency of falling film evaporation, several energy saving methods have been developed in the desalination technology, such as the coupling of multi-effect distillation (MED) and adsorption desalination (AD), absorption heat pump, heat transfer enhancement technology and so on [1–3]. Utilization of intensified heat exchange tube can be served as one kind of efficient way to reduce heat transfer material and manufacturing cost of devices in the distillation of desalination system [4]. The use of enhanced tubes with structured surfaces can increase heat transfer coefficient and improve the uniformity of the falling liquid film. A critical review of falling-film evaporation on horizontal tubes in 2005 indicated that liquid distribution outside evaporation tubes is one of the factors that affect the uniformity and dry out of the falling film [5]. Luo et al. presented a two-dimensional CFD model, and analyzed the flow and heat transfer characteristics of the falling water film on one circular tube, a drop-shaped tube and an oval-shaped tube. The results showed that the drop- and oval-shaped tubes have a lower dimensionless temperature and a thinner thermal boundary layer, which means a better heat transfer performance [6].

As a key component of the evaporator, heat transfer tubes with a circular cross-section are now in common use in the engineering practices. Numerous investigations have been carried out to clarify the influence of the sprinkling density on the liquid film flow behavior and the circular heat transfer. Muhammad et al. [7] measured the film boiling heat transfer coefficient for horizontal-tube evaporator experimentally. He indicated that the overall heat transfer coefficient can be decided by film thickness, velocity, liquid properties and the temperature differential across the film layer. Evaporative heat transfer of seawater is affected by the emergence of micro-bubbles within the thin film layer, particularly when the liquid saturation temperatures drop below 298 K. Mitrovic et al. [8] and Garcia et al. [9] pointed out that the transition of flow modes was dependent on the flow rate, fluid thermo-physical properties and tube structure. The use of enhanced (structured) surfaces can obviously improve the heat transfer coefficient.

Falling-film evaporator with elliptical tubes has been developed recently. It has been successfully applied to the industries of air conditioning, refrigeration and chemical industry, and the effect of power-saving is achieved. Many experts and scholars have implemented various researches on heat transfer of the elliptical tube [10–13]. In 2003, Hasan and Siren [14] carried out an experimental study on elliptical tube and circular tube. The study

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Nomenclature

d_i	tube inner diameter, m	L	length of heating zone, m
d_o	tube outer diameter, m	t	temperature, °C or K
F	heat transfer area, m^2	Δt	temperature difference, °C
G_1	flow rate of primary steam condensate, kg/s	γ	latent heat of vaporization of primary saturated steam, kJ/kg
G_2	flow rate of secondary steam condensate, kg/s	δ	the thickness of the fluid falling film, mm
G_g	the tangential component force of gravity	ν	coefficient of viscosity
I	enthalpy of secondary saturated steam, kJ/kg	ρ	the density of condensate, kg/m^3
i	enthalpy of saturated water at corresponding temperature, kJ/kg	φ	the circumferential angle along the wall of the tube
K	total heat transfer coefficient, kW/m^2·K	Γ	flow density, kg/(m·s)

indicated that the performance of heat transfer of the elliptical tube is 1.93–1.96 times of that of circular tube. Chen and Chen [15] studied boiling heat transfer of falling-film outside horizontal perforated elliptical tube. The results indicated that perforated of oval cross section could prominently improve heat transfer performance. In 2005, Khan et al. derived the closed-form expressions for the calculation of total drag and average heat transfer for flow across an elliptical cylinder under isothermal and isoflux thermal boundary conditions using an integral method of boundary-layer analysis [16]. Chu et al. performed the study of the heat transfer characteristics and fluid flow structure of heat exchangers with fin-and-oval-tubes, and it was found that the average N_u for the three-row fin-and-oval-tube heat exchanger with longitudinal vortex generators increased by 13.6–32.9% [17]. Javad and Mahnaz [18] analyzed the entropy generation in forced convection film condensation on a horizontal isothermal elliptical tube. A numerical approach has been used to investigate how parameters, including ellipticity of ellipse, Reynolds and Brinkman numbers, affect the irreversibility. The results showed that the effect of ellipticity on total entropy generation number is significant in case of E (ellipticity) > 0.7 and the increased value of ellipticity raises the amount of NS. AlaHasan [19] compared the single-tube heat transfer features of circular tube and elliptical tube under water film. Considering manufacturing costs, they constructed the circular tube and elliptical tube with the same perimeters, then controlled the variables one by one (length–diameter ratio of elliptical tube, air flow and spraying amount), and finally obtained the solution formula of overall coefficient of heat transfer based on theoretical formula.

Most of the previous researches concentrate on the fields of refrigeration and chemical industry, studying single-tube heat transfer, and the working medium is largely lithium bromide. Few researches have focused on seawater desalination's falling-film evaporation with elliptical tube. In this research, the falling film flowing outside the elliptical tube and heat transfer characteristics in the low-temperature multi-effect seawater desalination system is studied combining the method of theoretical analysis, numerical simulation and experiments. The liquid film forming mechanism and enhanced heat transfer characteristics are analyzed emphatically. The feasibility of the application of elliptical tube falling film evaporation in seawater desalination is investigated.

2. Mechanism analysis

In falling-film evaporation for seawater desalination, liquid is sprayed from distributor to the top of the tube, film-like liquid flows down along both sides of the tube, and then converges to be droplets at the bottom of the tube which drops to the tubes of next line, as is shown in Fig. 1.

If secondary steam's shear stress on liquid film is ignored, the driving force of liquid flow is considered to be the tangential component force of gravity along the wall of the tube G_g. A remarkable change of G_g will take place with the increase of the circumferential angle φ. Within the range $0 < \varphi < \pi/2$, G_g increases with φ grows, and liquid film's velocity gradually increases, resulting in the insufficient supply of upstream liquid and then liquid film thins; when $\varphi = \pi/2$, G_g equals to gravity G, and the driving force on liquid is the maximum, while the flow velocity becomes the maximum and liquid film thickness reaches the minimum; when $\pi/2 < \varphi < \pi$, G_g gradually decreases as φ increases, and liquid film's velocity decreases; The liquid will be gathered in the bottom of the tube due to the flow velocity in the bottom is slower than the top which leads to the increase of the thickness of the liquid film; until $\varphi = \pi$, $G_g = 0$, liquid separates from tube wall and drops downwards. As is indicated, in the area near $\varphi = \pi/2$, liquid film will reach maximum velocity and the thickness of the film will be minimum which will promote the fluid disturbance. Thus there is low thermal resistance and high heat transfer coefficient. If the proportion of the area with the big heat transfer coefficient increases, the heat transfer effect can be strengthened. Accordingly, the heat transfer tube with elliptical cross section is developed based on the previous theory. In the larger area of elliptical tube's perimeter (domain B) when form factor $E > 1$ (the ratio of major and minor axis), a great driving force on film exists, and the domain expands as form factor E increases. The results obtained from mathematical derivation are shown in Fig. 2 [20]. Under the same condition of Reynolds and temperature difference, area B of elliptical tube when $E = 2$ accounts for 75% of the semi-perimeter, while when $E = 0.5$ and $E = 1$ the value will be reduced to 14% and 54%; When $E > 2$, the heat transfer coefficient h_e will keep higher in a large flow area of the wall of the tube. While the heat transfer performance will be become worse relatively when $E < 2$ ($E = 0.5$ and 1.0).

3. Numerical simulation method

The model of liquid film flow of elliptical tube was established and calculated using the method of computational fluid dynamics so as to determine the tube structure and size with which flowing state of liquid film outside the tube is appropriate.

3.1. The establishment of physical model

The model of flow heat exchanging outside elliptical tube in horizontal tube falling-film evaporator is shown in Fig. 3. Liquid distribution hole is on the top of heat transfer tube and the top heat transfer tube is directly against the center of liquid distribution hole. The longitudinal section across the center of liquid distribution hole is used for cross-section study. Scheme language is employed in parametric design; parameterized modeling, mesh