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Falling water film evaporation on newly-designed enhanced tube bundles

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ABSTRACT

Experimental studies are presented on falling film evaporation of water on 6-row horizontal enhanced tube bundles in a vacuum condition. Turbo-CAB (19 fpi and 26 fpi), Korodense, and smooth tubes were tested in a range of film Reynolds number from about 10 to 110 and in the condition of only convective evaporation, without nucleate boiling. The flow modes and heat flux will affect the transition Reynolds numbers. Tubes with enhanced inner surface provide better heat transfer performance. Hotter heating water may lead to better heat transfer performance mainly due to higher heat fluxes. Correlations were also derived to predict the heat transfer coefficients and the enhancement ratio.

1. Introduction

Falling film evaporators have always been used in desalination, refrigeration, and air-conditioning industries. Compared with the conventional flooded tube bundles, falling film evaporator have the advantages of high heat transfer coefficients and low refrigerant charge; thus, the cost and the space required for the facilities can be reduced [1]. Also, a falling film evaporator can be applied in absorption chillers and organic Rankine cycles, as the falling film evaporates in the at small temperature difference between the working fluid and the tube wall. However, this type of evaporator is not widely used now because of the unrefined design and operation strategies for practical applications [1].

So the advantages of falling film evaporators drive the researchers to do experimental studies to guide the design and operation strategy for falling film evaporators. But, because of the fact that nucleate boiling and convective evaporation may both occur in falling film evaporation, different trends were observed in the experimental results on the effects of the falling film Reynolds numbers. For smooth tubes in convection dominated conditions, Liu et al. [2] and Fujita et al. [3] found that, as the Reynolds number of the falling film increases, the heat transfer coefficient first, decreases and then increases after reaching minimum value. However, Yang and Shen [4] and Parken et al. [5] found that the heat transfer coefficient increases with the film Reynolds numbers. Awad and Negeed [6] did analytical and experimental studies on falling water film evaporation on horizontal tube bundles; they found that the Nusselt number decreased with increasing Reynolds number. With falling film evaporation on enhanced tubes, the Reynolds number may not affect the convective heat transfer coefficients for both water and water/salt mixtures [2], if nucleate boiling occurs in the liquid film.

Additionally, in horizontal tube bundles, partial dryout of the lower tubes is a crucial problem in practical applications. The lower tubes may suffer from dryout, because the film flow rates decrease due to evaporation while flowing downwards. Thus, careful selection of operation conditions are needed for falling film evaporation on tube bundles. The heat transfer coefficients on the dry spots are low, as the dry areas transfer little heat by natural convection of the vapor only. Thus, Thome et al. [7,8] defined the sudden drop off in heat transfer coefficients as the onset of dryout on the tube walls. Such decreases in the heat transfer coefficient were observed both on smooth [3,7] or enhanced tubes [8].

The boiling and evaporation effects on falling film evaporation make the study of the mechanism more complex, because it is difficult to separate the two effects on film evaporation when both occur in the film. Some researchers found that the heat transfer enhancement capacity of an enhanced tube is mainly due to nucleate boiling [2,8], because the enhanced surfaces often have many nucleation sites which will enhance boiling. However, few investigations have been done on enhanced tubes under the conditions of convective evaporation only. Additionally, the newly-designed enhanced tubes such as Turbo-CAB will have better heat transfer performance than for plain tubes, so investigations should be done to discover the heat transfer enhancement mechanism.

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Nomenclature

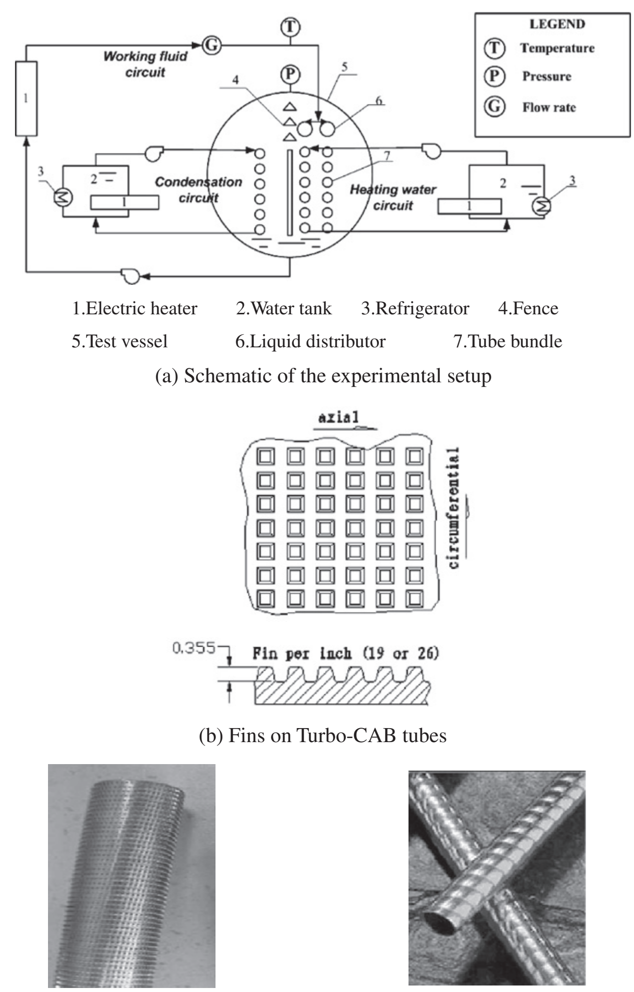
A	area, A_o based on tube O.D. diameter to fin root [m^2]
Ar	modified Archimedes number $(\sigma^3\rho^2 g(\rho-\rho_v)/\nu^4)^{1/2}$, (dimensionless)
Bo	Bond number $(\rho g H s)/\sigma$
c_p	specific heat [J kg^{-1} K^{-1}]
D	tube diameter [m]
H	fin height [m]
h	heat transfer coefficient [W m^{-2} K $^{-1}$]
L	actual effective heated length of the test tubes, [m]
L_h	wetted length of the enhanced tubes [m]
M	mass flow rate [kg s^{-1}]
Nu	Nusselt number (hL/λ), (dimensionless)
p	pressure, [N m^{-2}]
q	heat flux [W m^{-2}]
Re	Reynolds number $4\Gamma/\mu$, (dimensionless)
S	tube spacing in the bundle [m]
s	pitch length or fins spacing [m]
T	temperature [°C]
U_o	overall heat transfer coefficient [W m^{-2} K $^{-1}$]
Greek symbols	
Γ	liquid mass flow rate per unit length of tube (each side) [kg m^{-1} s^{-1}]
λ	thermal conductivity [W m^{-1} °C $^{-1}$]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ν	kinematics viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
ρ_v	vapor density [kg m^{-3}]
σ	surface tension [kg s^{-2}]
Subscripts	
i	inside of tubes
o	outside of tubes
e	enhanced tubes

Putilin et al. [9] compared the heat transfer coefficients of falling film on the longitudinally profiled tubes and those on the smooth tubes, and they got a correlation for the enhancement ratio for the local heat transfer coefficients at different angles. However, as the heat transfer coefficients reach the peak values at different transition Reynolds numbers on different tubes [10], we should consider the peak values to calculate the enhancement ratio for industry applications. So in order to guide the practical application, we have done the experiments and predictions of heat transfer enhancement capacity of these enhanced tubes on the falling film evaporation. We investigated the mean heat transfer coefficients of water falling film on three types of newly-designed enhanced tubes, i.e. Turbo-CAB (19 fpi and 26 fpi) integral-fin tubes and Korodense tubes, and the smooth tubes for reference. Tests were done in a vacuum, so few nucleation sites would exist on the tube surfaces and little gas will be contained in the nucleation sites (if there are any sites). The effects of falling film Reynolds number from about 10 to 110, the inlet temperature and flow rate of the heating water, and the evaporation pressure are investigated in this paper. Also, correlations are also given to predict the heat transfer coefficients and the enhancement ratios of these tubes.

2. Experimental method

2.1. Experimental apparatus

An experimental setup was built to investigate falling film evaporation on tube bundles in a vacuum at about 1000 Pa saturation pressure. The schematic is shown in Fig. 1(a). There are three liquid circuits in the setup: the working fluid circuit of the falling film, the heating water circuit and a condensing water circuit. The heating water inside the horizontal tubes provides the heat for film evaporation outside the tubes. The condensing water condenses the water vapor condense on the other side of the test vessel. The condenser also works to regulate the pressure in the vessel. These liquid circuits have been described in detail in the paper of Li et al. [10]. The inner diameter of the test vessel is 400 mm. The liquid distributor is a horizontal perforated integral-fin tube with 0.8-mm-holes at the top and a fin density of 26 fins per inch. As the liquid flows down from the top of the distributor, the fins help to stabilize and guide the liquid flow to the lower tubes. The distance between the distributor tube and the top tube in the bundle is 25.4 mm. One tube bundle of the setup was tested in our experiments, and the pitch of the tubes was also fixed at 25.4 mm in our tests. Before entering the distributor, the liquid has a subcooling of 0.5 °C to prevent the refrigerant from evaporating at the entrance of the vessel. In our experiments, the pressure



(a) Schematic of the experimental setup

(b) Fins on Turbo-CAB tubes

(c) Turbo-CAB-19 fpi (d) Korodense

Fig. 1. Experimental setup and the enhanced tubes. (a) Schematic of the experimental setup, (b) fins on Turbo-CAB tubes, (c) Turbo-CAB-19 fpi, and (d) Korodense.