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Microscopic mechanisms of heat transfer in horizontal-tube falling film evaporation

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HIGHLIGHTS

- Microscopic mechanisms of heat transfer in horizontal-tube falling film evaporation are proposed.
- The enhanced microscopic heat transfer in the upper tube is the result of a recirculation flow.
- The convection effect is closely related to the velocity profile.

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ABSTRACT

Complex heat and mass transfer phenomena in horizontal-tube falling film evaporators are areas of intense research due to their increasing predominance in thermal desalination industries. To better understand the microscopic mechanisms of heat transfer, a computational fluid dynamic model using the Volume of Fluid (VOF) was developed to simulate horizontal-tube falling film evaporation. The temperature and velocity profiles were determined as part of the solution of the governing equations. The numerical model predicted the local dimensionless temperatures, normal and tangential velocities, and heat transfer coefficients within thin liquid film around a tube for varying Reynolds numbers. Profiles of dimensionless temperatures around the tube prove that both conduction and convection contributes microscopic mechanisms to heat transfer in the liquid film. A laminar sub-layer is found to exist and dominate the heat transfer resistance within the film. A recirculation flow observed at an inclination angle of 5° accounts for the enhancement in the microscopic mechanism of heat transfer. The convection effect decreases with increasing inclination angle due to the decreasing normal velocity and increases with increasing *Re* due to the thinning laminar sub-layer.

1. Introduction

Horizontal-tube falling film evaporators have been increasingly predominant in thermal desalination industries due to their high heat transfer efficiency, small temperature difference and thin liquid film. The complex heat and mass transfer phenomena in falling film evaporation, which result from the inherently coupled nature between heat transfer processes and dynamic interactions in both liquid and vapor phases, have received substantial attention to obtain reliable knowledge of falling film evaporation.

A large body of experimental research on heat transfer performance and two-phase flow dynamics in falling film evaporation has been investigated. Given that flow modes have an important effect on falling film heat transfer coefficients and appearance of dry patches, different flow patterns [1,2] were presented and correlations of transitions between flow modes [3,4] were proposed. The presented flow mode maps constructed solely on visual observations do not agree in a reasonable way because the flow mode identifications are determined by subjective judgements. Experiments were conducted to determine the threshold Reynolds numbers for film breakdown at varying heat fluxes and flow rates due to its significantly adverse effect on heat transfer coefficients [5,6]. Among proposed flow modes, dry patches caused by the film breakdown may occur under the droplet flow mode if the distance between droplet active sites, which depends on the flow rates and inter-tube space, is not minimized.

The experimental study on heat transfer coefficients of falling film evaporation were carried out as a function of heat flux, saturation temperature, flow rates and nozzle height [7–10]. A great number of experiments were focused on the comparison of heat transfer performance between plain tubes and enhanced tubes [11–13]. Although the use of the enhanced tubes improves heat transfer coefficients, practically, scaling is more likely to occur on the enhanced surface due to the breakdown of the very thin film in desalination falling film evaporators. Based on a large amount of experimental data bank, a great number of

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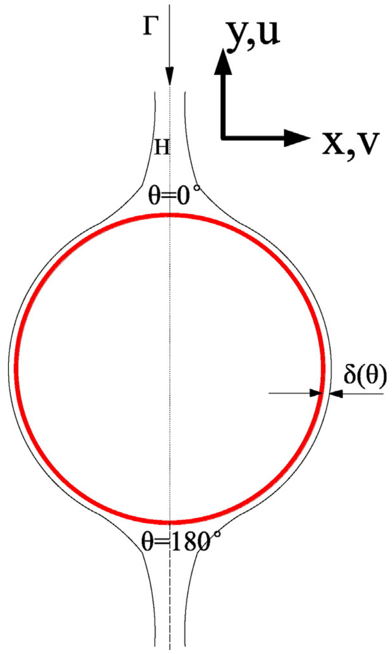

Fig. 1. Schematic of film flow around a horizontal tube.

empirical correlations have been developed [14–16]. Since the experimenters concentrated mostly on adjusting empirical coefficients in their correlations, the accuracy of the predictions is limited to restrictive conditions. Thus, the correlation predictions agreed with each other poorly. Most of the experimental research has focused on given parameters' effects on overall heat transfer performance with little attention paid to local dynamics and heat transfer, even though deep insight into the dynamic interactions of two-phase flow and microscopic mechanisms of heat transfer could be gained from these local parameters. This can be partially attributed to the challenge in measuring the local conditions within thin liquid film around tubes.

Significant efforts have been made to theoretically analyze and model the heat and mass transfer phenomena of falling film evaporation. It is agreed by most theoretical researchers that the heat transfer coefficient of falling film evaporation depends on the analysis of flow regions [17, 18], but the number of classified flow regions and their distribution around the tube are contested. In addition, investigations on the governing equations, boundary conditions, assumptions and solution methods have been performed [19–23]. Investigators have attempted to simulate realistic flow conditions by including a variety of assumptions in their models. The assumption of a laminar flow rarely occurs in falling film evaporation even at very low Reynolds numbers. Furthermore, the temperature is assumed to be linear within liquid film, which means that conduction dominates convection. It is also assumed that the velocity profiles are linear in the thermal boundary developing layer [24–26] and parabolic for laminar films in both the adiabatic and isothermal wall cases [27]. The local evaporation rates based on these assumptions are generally lower than the experimental data and the calculated interface conditions are divergent. The conflicting conclusions are due to the fact that the hydrodynamics of falling film are priori assumptions in the previous simulation. However, the experimental evidence proves that heat and mass transfer are inextricably linked with the fluid motions. Thus, the hydrodynamics should be calculated in a coupled manner with heat and mass transfer processes rather than a priori. Few of the existing models account for the transverse velocities across the film in a comprehensive manner. These velocities may play an important role in determining the heat transfer mechanism of falling film evaporation.

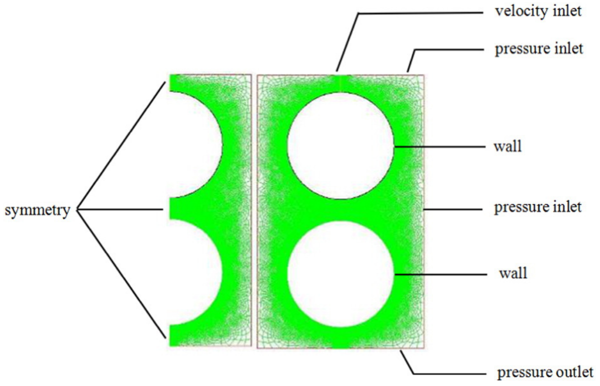

Fig. 2. Schematic of a meshed model with boundary conditions.

Table 1
CFD settings

Fluent settings	Parameters
Simulation	VOF
Primary phase	Air
Pressure velocity coupling	PISO
Discretization pressure	PRESTO
Volume of fraction	Geo-reconstruct
Discretization momentum	Second order upwind
Discretization energy	Second order upwind
Time step size	0.00005 s
Evaporation model	Mass transfer (UDF)

Although a great deal of research on falling film evaporation in both the modeling and experimental fields has been done, there still exists a need to further develop existing modeling technologies to investigate key deficiencies. The conflicting conclusions on the experimental parameters and heat transfer performance in liquid film are due to the lack of local hydrodynamics. Given the difficulties associated with experimentally measuring local velocity, temperature and film thickness in very thin liquid film, simulation work plays an important role in the exploration of microscopic heat and mass transfer phenomena in horizontal tube falling film. The above-mentioned simulation deficiencies suggest that the existing models can be improved by deriving the temperature and velocity profiles rather than assuming them. In this study, a computational fluid dynamic model using the VOF method was developed to predict the profiles of local temperature, velocity, film thickness and heat transfer coefficient within liquid film. The microscopic heat transfer mechanism was obtained by analyzing the microscale heat and mass transfer in two-phase falling film flow.

2. Numerical model formulation

2.1. Physical model

Seawater with a constant flow density of Γ and a uniform temperature falls on the top of a horizontal tube at a height of H as show in Fig. 1. The liquid jet flows around both sides of the tube to form thin film under the

Table 2
Physical parameters

Physical parameters	Values
Water inlet width	1 mm
Tube diameter	25.4 mm
Impingement height	5 mm
Water inlet velocity	0.071–0.15 m/s
Inlet volume fraction	Vapor phase 1
Inlet water temperature	331.15–334.15 K
Saturation pressure	19,923 Pa
Saturation temperature	333.15 K
Tube wall temperature	335.15 K