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Characteristic study of steam maldistribution in horizontal-tube falling film evaporators

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HIGHLIGHTS

- Three-dimensional simulation on a horizontal-tube falling film evaporator.
- A distributed parameter model is established based on experimental data.
- The self-compensation characteristic is extended to various operation conditions.
- The maldistribution of steam is analyzed under various operation conditions.

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ABSTRACT

The maldistribution of steam inlet velocity of a large horizontal-tube falling film evaporator was investigated with numerical simulation using the distributed parameter model (DPM) to provide essential design of falling film evaporator. Empirical correlations were obtained through experimental studies on the falling film evaporation outside a single horizontal tube, the condensation inside the tube and the inter-tube vapor flow across a tube bundle to conduct the three-dimensional simulation of the evaporator. The maldistribution of tube-side steam on tube row and column directions were analyzed with the brine inlet salinity ranging from 30 g/kg to 60 g/kg and the brine inlet spray density from 0.05 kg/m·s to 0.09 kg/m s. The Brine boiling point elevation (BPE) and the inter-tube vapor flow resistance were taken into account in the model. Considering the self-compensation characteristic between the heat flux and steam inlet velocity of the tubes, the maldistribution of heat flux was presented to analyze the maldistribution of tube-side steam inlet velocity. The simulation results exhibit the decreasing trend of the tube-side steam inlet velocity non-uniformity along the tube row direction with the increment in the brine inlet spray density and the decrement in the brine inlet salinity. Along the tube column direction, the non-uniformity of steam inlet velocity increases with the increment of brine inlet spray density and the decrement of brine inlet salinity.

1. Introduction

The world is now facing serious water shortage problems. Fortunately, the development of low-temperature multi-effect distillation (LT-MED) system during recent years provides a promising technology to supply large quantity of fresh water [1]. The horizontal-tube falling film evaporator shows distinct advantages, which includes high heat transfer coefficient, the maximum use of available temperature difference, positive venting, good vapor separation, minimum pressure drop, etc., over other evaporators such as the forced-circulation evaporators or vertical-tube falling film evaporators. Therefore, the LT-MED system has the most extensive applicable capacity in desalination plants and other relative fields.

The horizontal-tube falling film evaporator for desalination features the tubes set horizontally with in-tube cooling and external evaporating thin films. For many previous studies, their analyses for heat exchangers were carried out based on the equal flow rate at the inlet of parallel channels [2,3]. For the thermal calculation and the design of a large falling film evaporator, the assumption of uniform steam inlet velocity lead to a certain deviant from the real heat load of the evaporator. The maldistribution of the refrigerant on the tube side has been studied in the air-to-refrigerant heat exchangers [4–6]. In their experimental or

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Nomenclature

BPE	boiling point elevation of brine, °C
D	diameter of tube, m
F	heat transfer area, m^2
G	steam or vapor mass flow rate, kg/s
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
L	tube length, m
m	mass flow rate, kg/s
N	grid number
N_e	tube column number that the inter-tube vapor has passed across
$N_{\mathbf{row}}$	total grid number along the tube row direction
$N_{\mathbf{col}}$	total grid number along the tube column direction
$N_{\mathbf{len}}$	total grid number along the tube length direction
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Δp	pressure drop, Pa
Δp_{total}	steam pre and aft pressure drop inside the tube, Pa
q	heat flux, W/m^2
r	latent heat, J/kg
Re	Reynolds number
S	local brine salinity, g/kg
T	temperature,°C
ΔT	temperature difference, °C
v	tube-side steam inlet velocity, m/s
v_e	the inter-tube vapor velocity, m/s
v_{st}	tube-side steam local velocity, m/s
x	vapor quality
row, **col**, **len**	space coordinates along the tube row, column and length directions

Greek symbols

Γ	local brine spray density, kg/m·s
η_q	heat flux percentage
η_v	tube-side team inlet mass flow rate percentage
λ	thermal conductivity, W/m K
μ	dynamic viscosity, N s/m^2
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s

Subscripts

1	first tube pass
2	second tube pass
br	brine on the evaporation side
c	the condensation side
e	evaporation side/Vapor on the evaporation side
i	grid number along the tube row direction
inlet	parameters at the inlets
j	grid number along the tube column direction
l	liquid on the condensation side
outlet	parameters at the outlets
ref	reference values
st	steam on the condensation side
z	grid number along the tube length direction

analytical work, the gravity is an important force that affects the distribution in vertical branch tubes. For horizontal-tube falling film evaporators, the tubes are connected by headers at each end. These parallel tubes have the same value of fore and after pressure drop. Due to the maldistribution of parameters including the liquid physical properties, the temperatures, temperature differences, etc. the total heat flux varies from tube to tube. The tubes with higher heat flux absorb more steam to keep the pre and after pressure balance on the tube side. Recently, Hou [7] conducted a two-dimensional simulation on a large horizontal-tube falling film evaporator presenting the maldistribution of tube-side steam inlet velocity along the tube row direction. The non-uniformity of many thermal parameters within the inner space of the evaporator has been experimentally or analytically studied by previous researchers. According to the experimental work of Zeng [8], when all the tube surfaces are wet, the upper tubes exhibited higher heat transfer coefficients than the lower tubes. His later experimental results [9] indicated a more pronounced maldistribution of the heat transfer coefficient alone the square-pitch bundle than the triangular-pitch bundle in a falling film evaporator. Moeykens et al. [10,11] found better evaporation performance in the first row than other rows with HFC-134a, while the thermal performance increased from row to row with HCFC-123. Liu et al. [12] conducted experiments on water evaporating from plain tubes. Their results demonstrated that lower tubes had slightly higher heat transfer coefficients than those of the top tubes. They regarded the potential reason as the increase of turbulence in the tube row direction. Roques [13] presented the heat transfer results on a plain tube bundle and enhanced tube bundles. The heat transfer coefficients were found scatter among tubes from top to bottom with no significant discrepancy on any individual tube. This work was later extended by Habert [14]. Through his experimental study for plain tubes, similar scatter of heat transfer coefficient among tubes were obtained except tube 4 and 5 for higher heat transfer coefficient. He explained this phenomenon as the liquid splashes for adjacent upper tubes. Chen and Kocamustafaogullari [15] experimentally and numerically demonstrated the potential of coupling external falling-film evaporation with internal steam condensation to achieve overall heat transfer coefficients distribution along the tube peripheral, axial and tube row directions. Recently, some numerical simulations using distributed parameter model (DPM) had been carried out to predict the thermal and hydrodynamic performance in the inner space of a falling film evaporator. Yang et al. [16] used DPM to investigate the influence of tube pass arrangements and the dry patch area on the heat transfer performance of the falling film evaporators. Shen et al. [17] studied the overall heat transfer coefficient distribution along the tube row and length direction in a falling film evaporator with the operation liquid of fresh water. Hou et al. [7] recently simulated a practical horizontal-tube falling film evaporator with the working liquid of brine. A two-dimensional analysis was presented to study the maldistributions of various parameters including heat transfer coefficient, brine salinity and tube-side steam inlet velocity, etc. Although previous studies has considered the maldistributions of thermal parameters in the air-refrigerant heat exchangers or the falling film evaporators, the maldistribution of tube-side steam inlet velocities under different operation conditions had been barely considered in large falling film evaporators. In this paper, a comprehensive distributed parameter model was developed to simulate the heat transfer and flow characteristics within the horizontal-tube falling film evaporator based on the data from three experimental studies. To better analyze the non-uniform distribution of steam inlet velocity, the maldistribution of tube-side steam inlet velocity along the tube row direction was defined as the ratio of the averaged steam inlet