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Numerical simulation and performance analysis of horizontal-tube falling-film evaporators in seawater desalination ☆

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ABSTRACT

A comprehensive distributed parameter model for simulating the steady-state performance of a practical horizontal-tube falling-film evaporator has been developed and validated. This model is capable of predicting the distributions of thermal parameters in the tube-side and shell-side, which provide important information of heat and mass exchange processes. The fluid flow and heat transfer characteristics in tubes are analyzed in detail. The computational time is reduced significantly in comparison with the Computational Fluid Dynamics. Based on the numerical results, it is found that the steam is not evenly distributed in the horizontal tubes of each tube pass, which is favorable for parallel channels with uneven heat fluxes. The mass and heat flux of steam are mutually matched, indicating that the self-compensation characteristic appears among the tubes. In addition, the overall heat transfer coefficient reaches the maximum value of about 3300 W/m^2 K at the entrance region of each tube pass, and then decreases gradually along the flow direction. As liquid film falls downward from tube to tube, the liquid flow rate of seawater continually decreases from 0.063 kg/ms to 0.04 kg/ms with the corresponding salinity gradually increasing from 36 g/kg to 56 g/kg.

1. Introduction

The world is becoming increasingly aware of critical limitations in the availability of fresh water due to population growth and changes in weather conditions. Rapid developments have occurred recently in the low-temperature multi-effect distillation desalination system, which provides a promising technology for supplying large quantities of fresh water [1,2]. The falling-film horizontal-tube evaporator (FHE) has been extensively utilized in this system and playing important roles because of many advantages such as high heat transfer rates at low liquid flow rates and small temperature differences.

Despite numerous theoretical and experimental studies [3–7], a reliable model for predicting the fluid flow and heat transfer in the FHE is still not available. Integrated parameter model (IPM) has been widely used in designing the FHE, which is mainly based on empirical knowledge. Average values are used to represent the varying thermal parameters in the whole computational domain, so IPM poses inherent difficulty in characterizing the parameters of every point in the evaporator. Clearly, it is not possible to provide a better understanding of the overall performance and gain deeper insight into the local heat and mass transfer. Moreover, Computational Fluid Dynamics (CFD) has been developed in the last decade. However, this method requires massive computational burden, because of the complexity of generating the computational grids and the difficulty in solving the partial differential equations. This shortcoming has hindered the application of the CFD to the design and optimization of the heat exchanger, especially for the FHE. To overcome the drawbacks of the IPM and CFD, the distributed parameter model (DPM) has been proposed. The heat exchanger is divided into elements and the thermal parameters in each element are considered to vary. The main merit of the DPM is that the parameter distribution over distance is detailed and the moving two-phase interface is clearly defined. Therefore, DPM can yield accurate results against the IPM, and can rapidly perform the simulation in comparison with the CFD.

The novel DPM has been considered as a powerful tool in the analysis of heat exchangers [8–12]. However, there has been little literature focusing on the performance evaluation of the FHE by using the DPM. Motivated by this need, a general DPM is established for simulating steady-state performance of the FHE, which is capable of predicting the distributions of thermal parameters in the tube-side and shell-side. The complex working process is displayed graphically. The related heat and mass exchange is analyzed to reveal fluid flow and heat transfer characteristics in the evaporator.

2. Distribution parameter model

2.1. Physical model

The structure of a practical FHE is illustrated in Fig. 1(a) and (b). The FHE is a typical one-shell-pass and two-tube-passes heat exchanger, which basically consists of a bundle of horizontal tubes connected by

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Nomenclature

A	heat transfer area, m^2
a_1, a_2, a_3	empirical constants
b_1, b_2, b_3, b_4	empirical constants
D	diameter of tube, m
G	mass flux, kg/m^2 s
g	gravitational acceleration, m/s^2
h	convective heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of working fluid, J/kg
i	row number, or specific enthalpy, J/kg
l	length, m
m	mass flow rate, t/h
M_z	element number in the Z direction
n	total number of rows
Nu	Nusselt number
Pr	Prandtl number
p	pressure, kPa
Δp	pressure drop, Pa
Δp_{frict}	frictional pressure drop, Pa
Δp_{mom}	momentum pressure drop, Pa
Δp_{static}	static pressure drop, Pa
Δp_{total}	total pressure drop, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
Re	Reynolds number ($2\Gamma/\mu_L$)
s	salinity, g/kg
T	temperature, K
t	temperature, °C
U	overall heat transfer coefficient, W/m^2 K
u	velocity, m/s
x	vapor quality
X, Y, Z	space coordinate

Greek symbols

Γ	total liquid flow rate on the tube per unit length, kg/ms
ε	void fraction
η	percentage
λ	thermal conductivity, W/mK
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
Ω	variable
Φ^2_{LO}	two-phase multiplier

Subscripts

f	fluid
h	heat flux
i	inner part
in	inlet
L	liquid
m	mass flux
o	outer part
out	Outlet
V	vapor
w	wall

headers at each end. The shell-side seawater is introduced through spray nozzles to the top of the bundle and falls from tube to tube. The heating steam condenses inside the tubes to release its latent heat to heat the feed seawater outside the tubes from the intake temperature to the saturation temperature. The saturated film evaporates over the outside surface of the tubes and vapor is generated in the shell-side.

To simplify numerical simulation while still keep the basic characteristics of the process, the following assumptions are adopted: (1) the film flow is steady and the influence of vapor shear stress on the liquid film is neglected; (2) crossflow effects of vapor flow on film flow modes between tubes are neglected; (3) effects of fouling resistance on heat transfer are neglected; (4) uniform liquid distribution of feed seawater is achieved on the top row of tubes in the bundle.

2.2. Grid generation

Uniform grids throughout the calculation domain are adopted, which coincide with the flow passages. The tubes are normally arranged in three dimensions and correspondingly divided into a three-dimensional network with identical elements. The element number in the Z direction can be arbitrary, while the subdivisions in the X and Y directions must be the same with the arrangement of the tubes. This grid generation method has the following advantages: (1) the grid size is equal to the characteristic dimension of the practical FHE so that the research achievements are available to be directly applied; (2) the drastically-reduced number of grids leads to a considerable saving in computational time.

2.3. Governing equations

In the analysis of the element, the overall heat transfer rate Q can be calculated from:

$$Q = UA_{\text{o}}\left(T_{\text{f,i}} - T_{\text{f,o}}\right) \tag{1}$$

$$U = \frac{1}{\frac{1}{h_{\text{i}}}\frac{D_{\text{o}}}{D_i} + \frac{D_{\text{o}}}{2\lambda}\ln\frac{D_{\text{o}}}{D_{\text{i}}} + \frac{1}{h_{\text{o}}}} \tag{2}$$

where U is the overall heat transfer coefficient. Since the thermal resistance of the tube wall is a known quantity, the evaporation coefficient and condensation coefficient become the major contributors to the overall heat transfer coefficient. The subcooled liquid film outside the tubes is heated to saturated state and different flow regions of steam exist inside tubes (two-phase regions and single-phase regions), which results in the overall heat transfer coefficient varying over a great range at different locations. Consequently, the model is divided into two modules: steam side module and seawater side module.

2.3.1. Steam side module

The governing equations of mass, momentum and energy can be expressed as follows:

$$G_{\text{in}} = G_{\text{out}} \tag{3}$$

$$p_{\text{out}} = p_{\text{in}} - \Delta p_{\text{total}} \tag{4}$$

$$Q_{\text{i}} = G_{\text{in}}A_{\text{i}}(i_{\text{in}} - i_{\text{out}}) = h_{\text{i}}A_{\text{i}}\left(T_{\text{f,i}} - T_{\text{w,i}}\right) \tag{5}$$

where the total pressure drop Δp_{total} and the convective heat transfer coefficient h_{i} are calculated by the following correlations, respectively.

In the two-phase regions, the convective heat transfer coefficient is calculated using the Chato correlation [13]:

$$h_{\text{i}} = \Omega\left[\frac{\rho_{\text{L}}(\rho_{\text{L}} - \rho_{\text{V}})g\lambda_{\text{L}}^3 h_{\text{fg}}}{\mu_{\text{L}}D_{\text{i}}\left(T_{\text{f,i}} - T_{\text{w,i}}\right)}\right]^{1/4} \tag{6}$$