Applied Thermal Engineering 70 (2014) 477–485

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Numerical investigation of falling film evaporation of multi-effect desalination plant

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HIGHLIGHTS

- Numerical study of falling film evaporator using multiphase flow is performed.
- Increase of temperature difference increases vaporization rate.
- Heat transfer coefficient for vertical arrangement is larger than horizontal one.
- The pressure drop increases with increase of temperature difference.

ARTICLE INFO

Article history:
Received 11 March 2014
Accepted 12 May 2014
Available online 29 May 2014

Keywords:
Falling film evaporator
Two-phase flow
Desalination
MED
Computational fluid dynamics

ABSTRACT

In this study, a numerical investigation is performed to improve the heat transfer and pressure drop of falling film evaporator using multiphase flow formulations in Eulerian–Eulerian approach. A finite volume method code is used for solving the governing equations including continuity, energy and Reynolds averaged Navier–Stokes equations (RANS) with the $k-\varepsilon$ turbulence model. Also, the heat and mass transfer during the phase change is taken into account. The effects of temperature difference, arrangement of tubes and tube pitch on the average heat transfer coefficient, the net vapor production and pressure drop across the tube bundles are presented. The results show that increase of temperature difference increases vaporization rate, heat transfer coefficient and pressure drop along the tube bundle. It is also found that the heat transfer coefficient for vertical arrangement of tubes is larger than that of horizontal arrangement.

1. Introduction

Falling film evaporators have been widely used in chemical, refrigeration, petroleum refining, desalination and food industries. They are attractive principally due to high heat transfer coefficient at low film flow rates, low evaporation temperature and small temperature differences. Thus, the cost and the space required for the facilities can be reduced when compared against flooded evaporators [1].

The design of the falling film evaporators is such that the feed enters the top of the evaporator and is distributed to the tube side of the heat transfer tubes. The feed flows down the tubes as a film from which water is evaporated. At the bottom of the tubes, the remaining liquid film detaches from the tubes. The liquid phase is separated from the water vapor in the separator and the water vapor is condensed in the condenser, drawing a vacuum. When processing heat sensitive materials, the evaporator is normally run under vacuum which lowers the boiling temperature of the product. There are practical, rather than process, limitations to the height of a falling film evaporator. Evaporators are normally constructed off-site. The size of the evaporator that can be transported to the site is often limited by the roads, bridges and corners of the road to the site. Due to the small temperature drop across the falling film, giving low rates of evaporation, it is common to use multi-pass falling film evaporators. This involves returning the product stream to the top of the evaporator and running it down to another set of tubes in the same evaporator effect (stage). It is also common to use several evaporator effects to fully concentrate the product; the current generation of falling film evaporators use three or four effects [2–4].

The complexity of the two-phase flow in a tube bundle presents important problems in the design and understanding of the physical phenomena taking place. The working conditions of an evaporator depend largely on the dynamics of the two-phase flow that

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http://dx.doi.org/10.1016/j.applthermaleng.2014.05.039
1359-4311/

in turn influence the heat exchange and the pressure drop. A characterization of the flow dynamics, and possibly the identification of the flow pattern in tube bundle, will lead to a better understanding of the phenomena and reveal the mechanisms governing the heat transfer process in a tube bundle. In general, the performance of falling film evaporators is affected by many parameters of horizontal tube bundles as well, such as tube size, tube surface geometry, tube arrangements, tube location, liquid film flow rate, heat flux, vapor flow and liquid properties.

Despite numerous theoretical and experimental studies [5–9], reliable model for predicting the fluid flow and heat transfer in the falling-film horizontal-tube evaporator is still not available.

Thome et al. [10,11] defined the sudden drop off in heat transfer coefficients as the onset of dryout on the tube walls. A review of falling film evaporation on single tubes and tube bundles is presented by Thome [12]. Both plain and enhanced tubes are addressed in his survey plus the effects of lubricating oil on heat transfer. He concluded that the enhanced tubes provide a very high level of heat transfer augmentation for falling film evaporation on horizontal bundles, and sharply reduce the required refrigerant charge compared to flooded evaporator designs. Habert and Thome [13,14] performed falling-film evaporation measurements on a single tube row bundle and a three-row tube bundle to obtain local heat transfer coefficients. They observed that in a single-row configuration, the heat transfer coefficient is mostly constant for a given heat flux in the plateau region until the onset of dry-out is reached, followed by increasing dry-out of the surface with a rapid decrease of the heat transfer toward the vapor-phase heat transfer value at complete dry-out. They also concluded that the bundle effects were detrimental to thermal performance. They discussed the hydrodynamics of the liquid film appeared to be the key parameter and flow is actually a bubbly two-phase flow, not a liquid film. Hou et al. [15] used a comprehensive distributed parameter model for simulating the steady-state performance of a practical horizontal-tube falling-film evaporator. Based on their 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. Also the mass and heat flux of steam are mutually matched, indicating that the self-compensation characteristic appears among the tubes.

Chen et al. [16] investigated the film characteristics outside the tubes in horizontal-tube falling film evaporator, numerically. Their numerical simulation results showed that, at the fixed fluid flow density, the liquid film is thicker on the upper and lower tube and the thinnest liquid film appears at angle of about 120°. The results also indicated that, when the fluid flow density decreases to a certain value, the local dry-out spot on the surface of the tube would occur.

In large MED plant in which the total number of tubes in each effect is enormous the effect of pressure drop becomes a disturbing problem due to high vaporization rate. Therefore the need for improve of pressure drop with the least decrease in heat transfer coefficient and vaporization rate is vital. The literature reviews show that the above mentioned issue is still an important problem in large MED industries.

As discussed above, there are practical limitations to the height and width of a falling film evaporator. Obtaining the maximum possible heat transfer coefficient with relevant minimum pressure drop for a particular volume and required material of a falling film evaporator is of the most interest. In this study, a numerical investigation is performed to improve the heat transfer and pressure drop of falling film evaporator using multiphase flow formulations in Eulerian–Eulerian approach.

2. Mathematical formulation

The layout of the tube bundle is shown schematically in Fig. 1. In falling film process, water is distributed on the top of tube bundles. As water flows around the hot tubes, heat conveys from the tube to the fluid. During this process, the temperature of the liquid increases and some parts of liquid may be evaporated. So, there are two phases, i.e. the liquid phase as well as the vapor phase. The computational domain, the relevant grid and boundary conditions are illustrated in Fig. 2. Due to the symmetry of the tube bundle and neglecting the wall effects, only a horizontal period of the tubes will be simulated.

In this study, two types of arrays, horizontal (Fig. 3(a)) and vertical (Fig. 3(b)), and a single value of tube diameter, $D = 28.57$ mm, are considered for the simulation. As shown in Fig. 3 in horizontal tube bundle H > V and in vertical tube bundle H < V. These two different types of tube bundle imply two different mechanisms, in which the produced vapor can exit the tube bundle domain via demisters. Parameter S is the pitch of the tubes.

Two values for the pitch of tubes are examined to evaluate the overall heat transfer coefficient of the tube bundle.

The governing equations consist of continuity, momentum and energy equations for liquid and vapor phases in Eulerian–Eulerian approach, which are presented as:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_p) = s_p \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_p \rho_p \vec{v}_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_p \vec{v}_p) = -\alpha_p \nabla P + \nabla \cdot \bar{\bar{\tau}}_p + \alpha_p \rho \vec{g} + F_p \tag{2}$$

where t is the time, α is volume fraction, v is velocity, P is pressure. The index p is phase indicator. The two terms s_p and F_p stands for mass and momentum source terms. Also $\bar{\bar{\tau}}$ is stress tensor and g is gravitational acceleration.

The energy equation for each phase is also expressed as:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p h_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_p \cdot h_p) = -\alpha_p \frac{\partial P_p}{\partial t} + \bar{\bar{\tau}}_p : \nabla \vec{v}_p - \nabla \cdot \vec{q}_p + se_p \tag{3}$$

where h and se_p are enthalpy and energy source term, respectively.

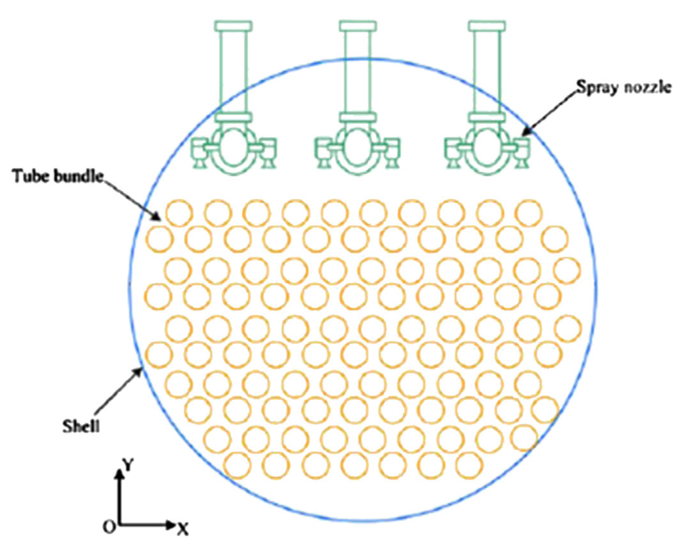

Fig. 1. Schematic of an industrial tube bundle.