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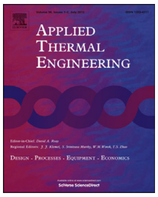

Shell-side two-phase pressure drop and evaporation temperature drop on falling film evaporation in a rotated square bundle

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HIGHLIGHTS

- Tube bundle flow resistance of steam flowing across falling-film tubes is presented.
- Effects of spray density, etc., on pressure drop and consequent temperature drop are analysed.
- A correlation for predicting the two-phase pressure drop through horizontal tube bundle is proposed.
- The new design idea on the same temperature drop in each effect evaporator is put forward.

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ABSTRACT

An experimental investigation of steam flowing across a horizontal tube bundle and related calculations on falling film evaporation in a rotated square bundle were conducted to simulate flow characteristics in a large desalination plant. The experiments and calculations were performed under saturated temperature ranging from 50 °C to 70 °C and water-spray density ranging from 0.02 kg/m·s to 0.08 kg/m·s. The intertube pressure drop and the corresponding temperature drop were presented under various operating conditions. The effects of saturated temperature, water-spray density and steam mass velocity on the pressure drop as well as on the consequent temperature drop were analysed. A correlation for predicting the pressure drop of steam flowing across the horizontal tube bundle with falling film was proposed based on the experimental results. The experimental data were reproduced within ±10%. The rotated square bundle was selected as the physical model. The fitting coefficient of pressure drop based on previous experimental data was employed for calculating the temperature drop and the pressure drop in falling film evaporation. The calculations indicated that the temperature drop caused by the pressure drop increases with increasing spray density and tube column number, but decreases with increasing saturated temperature. Based on the aforementioned analysis, a new design on a same temperature drop in each effect evaporator for multi-effect distillation evaporators is proposed.

1. Introduction

Seawater desalination provides an effective solution for solving freshwater shortages in coastal regions in China. Low-temperature multi-effect distillation (LT-MED) that employs horizontal tube falling film evaporation technology is among the most promising desalination methods with advantages such as high heat transfer coefficient at low water-spray density, low temperature and small temperature difference [1–3].

Most studies on the horizontal tube falling film evaporation process focused on its heat transfer coefficient. According to Liu [4], the heat transfer coefficient initially decreases, and then increases after a minimum value is achieved as the Reynolds number of a liquid increases. Meanwhile, others [5] reported that the heat transfer coefficient increases with the Reynolds number. Shen [6] showed the uneven distribution of the heat transfer performance within a large-scale tube falling film evaporator. However, he only considered the heat transfer coefficient distribution caused by the spray density and the condensation in the tubes. Shell-side pressure variation and its effect on heat transfer are rarely considered in previous studies. The difference in the heat transfer temperatures between the shell and the tube sides is only 2 °C–3 °C. Thus, even a small pressure variation can have a significant influence on the

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evaporation temperature, and therefore, can affect the heat transfer performance of the evaporators. For an LT-MED plant, Hisham et al. [3,7] suggested that the pressure drop in the tube bundle is an important component of the total pressure drop and a dominant parameter for calculating temperature drop.

Numerous studies on the two-phase flow through tube bundles have been published in literature. The functional relationships between the pressure drop and the relevant variables in tube bundles are determined experimentally. Ribatski et al. [8] summarised and analysed previous research on two-phase flow. They critically described the frictional pressure drop which is generally predicted using methods based on the experimental results for adiabatic air–water flows. Ishihara et al. [9] suggested a correlation approach based on the Martinelli model for representing the two-phase friction multiplier. Since then, the progress of research on the two-phase pressure drop in tube banks is primarily based on the correlations between these two variables. A number of influence factors, such as tube pitch [10], flow pattern [11] and void fraction [12,13], have been gradually involved for improving these correlations.

Previous studies on the two-phase flow focused on the mixture of gas and liquid flowing across the tube bundle. However, water and steam in a horizontal tube falling film evaporator flow in different directions. The vertical falling film flow is driven by gravity, whereas the steam flow across the tube bundle is driven by pressure difference. Hence, the pressure drop and the consequent temperature drop of the steam are not only caused by the tube bundle but also by the falling water. To date, a detailed research on tube bundle pressure drop in falling film evaporation and its effect on heat transfer remain extremely rare.

In the present study, a test bench was designed and calculations based on the experimental fitting coefficient were conducted to determine the temperature drop and the pressure drop in a large tube bundle evaporator.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The experimental system is shown in Fig. 1. The system consists of a boiler to provide steam, a temperature and pressure reducer to control saturated steam pressure and temperature, a test section, a condenser, water reservoirs, pumps and measuring instruments.

The tube bundle consists of 448 Al–brass tubes with 25.4 mm outer diameter and 500 mm length. The tube bundle exhibits a rotated square arrangement and the tube pitch is 1.3 times the outer diameter of the tube. The tube bundle contains 32 columns and 14 rows. The measuring distance is 1500 mm and the measuring points are located at the front and back ends of the tube bundle. The spray box is drilled in line along the tubes to ensure that the liquid will fall evenly on the top row tubes. The holes in each line have a diameter of 2 mm and an interval of 10 mm between them. The flow straightener is set at the entrance of the test bench to guarantee that the steam will reach the tube bundle evenly as shown in Fig. 2.

2.2. Experimental procedure

The steam is generated from the boiler, flows through the temperature and pressure reducer, through the straightener and evenly reaches the tube bundle under a required saturated temperature. After flowing across the tube bundle, the steam flows into the condenser where it condenses into liquid and is pumped back into the boiler for recycling. Meanwhile, the steady flow rate of the water is controlled by the associated pump to form a falling film on the surface of the horizontal tubes. There is a heating rod in water reservoir to guarantee the re-circulate water in saturated temperature. The experimental data of the temperature, pressure and pressure drop are recorded when the two-phase flow becomes steady. Measuring is performed under a no-evaporation condition.

The operating temperature (*T*) is set from 50 °C to 70 °C. The value of falling film flow is measured by the unilateral flow rate (spray density Γ) of 0.02, 0.04, 0.06 and 0.08 kg/m·s. The steam mass velocity (*G*) calculated by the weight of condensed water ranges from 0.39 kg/m^2·s to 1.24 kg/m^2·s. The flow area on the vertical surface across the centre of a tube column is regarded as the calculating area as shown in Fig. 3.

The sensors are calibrated before the experiment. The precision of the pressure difference sensor (GE Druck LPX9381) is ±1 Pa with a measuring range from 0 Pa to 1000 Pa. The precision of the pressure sensor (UNIK PMP5073) is 0.03 kPa with a measuring range from −0.1 MPa to 0 MPa (gauge pressure). The water flow

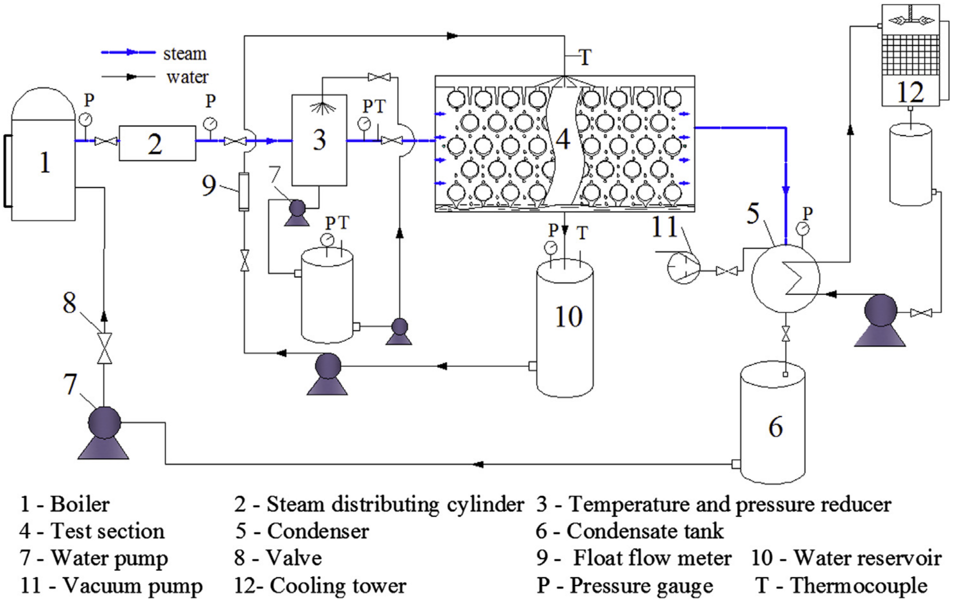

Fig. 1. The experimental schematic diagram.

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