Heat transfer characteristics of steam condensation flow in vacuum horizontal tube

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The heat transfer characteristics of steam condensation flow in a vacuum horizontal long tube were studied experimentally when the saturation temperature varies from 50 to 70 °C, mass flow rate is no more than 11 kg/(m² s) and temperature differences between steam and cooling water are 3, 5 and 7 °C respectively. The results of experiments indicate that the steam temperature decreases and the condensation temperature difference decreases first and then increases along the flow direction. The effects of mass flow rate and total temperature difference on temperature distribution are also discussed in the paper. The condensation heat transfer coefficient increases first and then decreases along the flow direction. The heat transfer coefficient increases with mass flow rate in most cases, but may decrease in the first section at high mass flow rate. The heat transfer coefficient also increases with saturation temperature and decreases with condensation temperature difference. The heat transfer rate decreases along the flow direction and increases with mass flow rate.

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1. Introduction

Many countries in the world have suffered from a shortage of natural fresh water. The seawater desalination is an effective method to solve the shortage of water resources in offshore area. In the numerous seawater desalination methods, low temperature multi-effect evaporation (LT-MEE) technique has the significant advantages on utilizing low temperature heat sources, low energy consumption, high desalinated water quality and stable operation [1,2]. In the process of LT-MEE desalination, the steam is condensed into water in horizontal tubes, which provides heat source for seawater evaporation outside the tube. In-tube condensation is also widely used in various industrial fields, such as nuclear power and chemical engineering and refrigeration.

Cavallini et al. [3] proposed a review of refrigerants condensation inside and outside smooth and enhanced tubes in 2003. A lot of experimental research were mentioned and summarized in the review. Later, Miyara [4] reviewed condensation of hydrocarbons inside and outside tube and in plate heat exchanger. An intensive review of various aspects of condensation in tube was proposed by Dalkilic and Wongwises [5], including the heat transfer, flow pattern, void fraction and pressure drop. Zhang et al. [6] reviewed 28 condensation heat transfer correlations in horizontal channels and compared them with 2563 experimental data points.

The steam and tube wall temperature distributions along flow direction in a horizontal tube with heat transfer length of 3.0 m and inner diameter of 27.5 mm when the inlet pressure is 0.2 MPa is shown in Wu and Vierow's study [7]. Both the steam and tube wall temperature decrease along the flow direction. Similar distributions are also measured in a tube with the length of 1.75 m at the pressure 0.1 MPa by Ren et al. [8]. But there is little research on the temperature distribution in a continuous horizontal long tube in vacuum state and the effect of mass flow rate on the temperature distribution.

During the condensation in a horizontal tube, the flow patterns are dominated by gravity and shear force. When the mass flow rate is low, the shear force between steam and condensation liquid is rather small. The steam condenses into liquid on the inner tube wall and forms the liquid film. And the condensate is collected in the bottom of the tube, presenting stratified flow pattern, which is controlled by gravity force. The dominant heat transfer mechanism in this flow pattern is conduction across the film at the top of tube [9]. This type of condensation is commonly referred to as film condensation, which can be analyzed by the classical Nusselt theory [10]. Based on the experimental data, Thome [11] proposed a new condensation model with the assumptions of two types of heat transfer mechanisms occur in the tube: film condensation at the top of tube and convective condensation at the bottom.
The main factors affecting the condensation heat transfer coefficient are mass flow rate, vapor quality, saturation temperature and temperature difference. The condensation of steam and various kinds of refrigerants have been studied extensively. A lot of experimental results [12–17] show that condensation heat transfer coefficient increases with the increase of mass flow rate and vapor quality. But there are some different conclusions in special cases. Dobson [9] and Cavallini et al. [18] considered that the heat transfer coefficient has no obvious relationship with vapor quality during low mass flow rate and it increases with vapor quality during high mass flow rate. Yan’s experiment [19] shows that the mass flow rate has less effect on heat transfer coefficient when the vapor quality is low. The saturation temperature influences on the physical properties, for example, the density, viscosity and thermal conductivity of vapor and liquid, then affects the heat transfer coefficient. With the change of saturation temperature, some physical properties of steam and refrigerants show a different variation tendency. For refrigerant [14,18,19], heat transfer coefficient decreases with saturation temperature in most cases. But there are some special cases. Hossain et al. [13] pointed out that saturation temperature has no effect on heat transfer coefficient when the mass flow rate is low, because the heat transfer mechanism is forced convection, not the free convection. For steam [20], heat transfer coefficient increases with saturation temperature. The temperature difference affects the heat transfer coefficient primarily by influencing the condensation rate and film thickness. Cavallini’s experiment [18] shows that heat transfer coefficient has no relationship with temperature difference when the mass flow rate is high while it decreases with temperature difference when the mass flow rate is low and the dominant force is the gravity. Dobson and Chato [9] pointed out that large temperature difference leads to thicker condensation film and smaller heat transfer coefficient when the flow pattern is stratified while the temperature difference has less effect on heat transfer coefficient when the flow pattern is annular. The research of Yan and Lin [19] shows that the condensation rate is proportional to heat flux when the mass flow rate is constant, and the heat transfer coefficient decreases with heat flux.

In the LT-MEE desalination plant, steam condensation has the characteristics of high vacuum, low mass flow rate and small temperature difference. The density of steam is very small in vacuum state, so the mass flow rate is rather small although the steam velocity is high. The steam saturation temperature is more sensitive to the pressure in vacuum state. So the flow resistance of steam condensation can significantly affect the steam saturation temperature, and thereby affects the temperature difference and heat transfer coefficient. This paper studies the heat transfer characteristics of steam condensation in vacuum horizontal tube by experiment.

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