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# Heat transfer characteristics of steam condensation flow in vacuum horizontal tube

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ABSTRACT

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/($m^2$ 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.



## 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.

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**Nomenclature**

| | | | |
|---|---|---|---|
| $c_p$ | constant pressure specific heat, kJ/(kg °C) | *Greek symbols* | |
| $D$ | diameter, m | $\Delta$ | difference |
| $F$ | effective heat transfer area, $m^2$ | $\theta$ | angle |
| $G$ | mass flow rate, kg/($m^2$ s) | | |
| $h$ | heat transfer coefficient, W/($m^2$ K) | *subscripts* | |
| $m$ | mass flow rate, kg/s | c | cooling water |
| $L$ | length, m | in | inlet |
| $Q$ | heat transfer rate, W | out | outlet |
| $q$ | heat transfer rate per meter, W/m | s | steam |
| $T$ | temperature, °C | w | wall |

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.

## 2. Experimental apparatus

Fig. 1 shows the schematic diagram of the experimental apparatus. The water is heated to saturation temperature and then evaporates to steam in an evaporator which electric power is 12 kW. The steam flows through four identical test sections. All or part of steam condenses into water and releases latent heat in the test sections. There is a quartz glass tube with the same inner diameter of test tube after each test section. The flow pattern can be observed through the quartz glass tube. The steam and condensation water flow together into the steam-liquid separator which is connected to the last test section. Due to the gravity, condensation water leaves in the separator while steam enters into two double-pipe condensers, where the steam is condensed completely by cooling water. In the end, all the condensation water is collected into the water tank. A vacuum pump connected to the second condenser enables the experimental system to achieve and maintain vacuum state. A water pump and a cooling water tank provide cooling water at constant temperature for four test sections respectively.

The total length of the test tube is 8 m. For lower the increment of cooling water temperature, the main experimental apparatus is divided into four identical test sections. Each test section is a double-pipe heat exchanger. The inner tube is made of aluminum brass, which is also used in desalination plant. The inner diameter is 18 mm and effective heat transfer length is 1.8 m. The outer tube is made of stainless steel, with an inner diameter of 35 mm. The steam flows and condenses in the inner tube while the cooling water counter currently flows in annular area and takes away the condensation latent heat.

A cross section is selected to place the thermocouples in each heat exchanger. The position is in the middle of the test section. There are 6 tiny grooves on the outer wall of test tube at the cross section. A T-type thermocouple is welded in each groove, and then the surface is polished smoothly. The condensate is collected at the bottom of tube, so the temperature change at the bottom is bigger than at the top. In order to obtain the tube wall temperature accurately, thermocouples are distributed from the bottom up circumferentially at 0°, 20°, 40°, 60°, 90° and 180° of the tube. The cooling water temperatures at the inlet and outlet of each test section are measured by T-type thermocouples. All the thermocouples were calibrated by a thermostatic water bath with the accuracy of 0.1 °C. The liquid level meters were equipped in the separator and condensers, so the mass flow rate of steam and the condensation water can be measured. The mass flow rate of cooling water in each test section is measured by rotameter with an accuracy of 10 L/h. The absolute pressure in evaporator and the inlet and outlet of the whole test tube are measured by pressure transducers, which precision is ±28 Pa. Pressure drop of steam condensation