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Experimental study of heat transfer and scale formation of spiral grooved tube in the falling film distilled desalination

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ABSTRACT

The heat transfer performance and scale formation of spiral-grooved tube in the falling film evaporator was studied experimentally compared with the conventional smooth tube. A series of experiments were performed contrastively on the two types of heat transfer tube based on a heat exchange test platform of horizontal tube falling film evaporation for desalination. The influences of various factors on heat transfer coefficients for the spiral-grooved and smooth tubes were investigated. Heat transfer experiments indicated that the heat transfer coefficient of the spiral-grooved tube can be improved by approximately 35%, comparing with the smooth tube under the same experimental conditions. The anti-scaling capability of spiral grooved tube is a little better than that of smooth tube. Their scaling layers had similar thickness under the same operation condition, and their cohesiveness with the tube was weak. Experimental findings indicated that the spiral-grooved tube was feasible for application in seawater desalination given the enhancement of heat transfer and anti-scaling characteristics.

1. Introduction

Seawater desalination is an important approach to solve the water resource shortage. At present, two mainly used methods in seawater desalination are thermally-driven multi-effect desalination (MED) and pressure-driven reverse osmosis (RO) [1]. Heat transfer tube is the core part of the seawater desalination device in the distillation method. The performance of the tube is directly related to the heat transfer efficiency, and construction cost of thermal desalination device [2,3]. To improve the performance of the heat transfer tube, an increasing number of scholars have focused on its enhancement technique by changing surface structure of tube to intensify heat transfer [4–6]. As a type of enhanced heat transfer tube, spiral-grooved tube is a specially designed heat transfer tube with external and internal convex spiral grooves made by rolling a smooth tube or subjecting it to other machining process [7]. Nowadays, researches on the spiral-grooved tube, still focus on its heat transfer characteristics with the theoretical analysis and numerical simulation methods [8,9]. And the spiral-grooved tube has been successfully applied in various fields, including chemical engineering, refrigeration, and dynamics. However, the application of this tube in the seawater desalination industry is rarely reported, and relevant experimental data are lacking [10].

Currently the key factor that limits the extensive application of spiral-grooved tubes in the seawater desalination is the scaling problem [11,12]. The scale formation and deposition on the surface of heat transfer tube is mainly influenced by two key processes: mass transfer and fluid friction [13,14]. In addition, the texture of a heat transfer tube, water quality fluctuation, control of process conditions, and generation of corrosion will strongly influence scale formation on the surface of a heat transfer tube. Hence, strengthening research on the aforementioned influencing factors will be the key to solving scaling problem on heat transfer tubes. In previous studies Rabas et al. [15,16] conducted a fouling test of spiral-grooved tubes in the condensers of 12 power plants over a long period. Their study showed that the scaling velocity of these tubes was doubled than that of smooth tubes. And during their research the cooling water used in the condensers was river water. Aroonrat et al. [17] measured heat transfer and flow characteristics of water flowing through horizontal internal spiral-grooved tubes. Their results showed that the thermal enhancement factor obtained from groove tubes was about 1.4–2.2 for a pitch of 0.5 in.; 1.1–1.3 for pitches of 8, 10 and 12 in., respectively. Wang et al. investigated the effect of different helix angles on the cycle performance of the novel 5 mm outer diameter finned tube heat exchangers for an air conditioning system [18]. Hong et al. [19]

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Nomenclature

A_s	the cross-sectional area of spiral grooved tube, m
d_e	tube equivalent diameter, m
d_i	inside diameter of spiral grooved tube, m
d_o	outside diameter of spiral grooved tube, m
G	the mass flow rate of the water sprayed outside tube bundle, kg/s
G_1	condensed water quantities of primary vapor, kg/s
G_2	condensed water quantities of secondary vapor, kg/s
h_g	enthalpy of secondary saturated steam, kJ/kg
h_w	enthalpy of saturated water at corresponding temperature, kJ/kg
K	heat transfer coefficient, kW/(m^2 ·°C)
L	length of heating zone, m
N	number of heat transfer tubes each layer
P_s	the wetted perimeter of the cross-section for spiral grooved tube, m
Q	the heat flux, kW/m^2
Q_a	the average heat transferred by the tube during evaporation, kJ
Q_1	the quantity of heat released by the primary steam, kJ
Q_2	the quantity of heat absorbed by spraying water during evaporation, kJ
T	the saturated steam temperature inside the heat transfer tube, °C
t	the temperature of liquid feeding into the evaporator, °C
ΔT	the heat transfer temperature difference between vaporization and condensation, °C
ρ	the density of condensate, kg/m^3
γ	latent heat of vaporization of primary saturated steam, kJ/kg
Γ	the spray density of the evaporator, kg/(m·s)

conducted experimental research on the heat transfer and flow characteristics in a spiral grooved tube with overlapped large/small twin twisted tapes by using air as working fluid. Zhang et al. [20] performed a study on heat transfer and pressure drop for R417A flow boiling in horizontal smooth and internally grooved tubes. And he indicated that the narrower fin root distance and the gentle slope of grooved wall are more favorable. Chang et al. [21] simulated the heat transfer network (HEN) by analyzing the influence of fouling heat resistance. Based on the research of cleaning cycle, the control method and prediction model of the fouling process of heat exchanger were obtained. Tholudin Mat Lazim carried out a CFD simulation of fluid flow and heat transfer analysis of low Reynolds number in spirally corrugated tubes with water as a working fluid. Simulation results showed there is a heat transfer enhancement range of 19.6–71.3% with appreciable pressure drop of 19.6–71.3% compared with standard smooth tube [22].

To discuss the heat transfer and scaling characteristics of spiral-grooved tubes and the feasibility of their application in seawater desalination, conducting relevant experimental research is necessary. Thus, low-temperature multiple effect distillation (LT-MED) seawater desalination of horizontal tube falling film evaporation heat transfer was first simulated on our experimental platform, using tap water as the working medium. Subsequently, spiral-grooved and smooth tubes were used as heat transfer tubes to test the influences of various parameters, such as spray density, heat flux, heat transfer temperature difference, evaporation temperature, and non-condensable gas (NCG) content, on their heat transfer performance. Afterward, spiral-grooved and smooth tubes were installed into the LT-MED seawater desalination pilot plant device, which continuously operated under practical working conditions for seawater desalination for 180 days. The scaling characteristics of the tubes were studied, and the experimental basis for the application of spiral-grooved tubes in seawater desalination was obtained.

2. Experimental study on heat transfer enhancement

2.1. Heat transfer experimental device and process

The horizontal tube falling film evaporation heat transfer experimental platform was consisted of an electric boiler, a falling film evaporator, a circulating water tank with pump, a vapor heat exchanger, a pipeline system, a vacuum pump, a metering device, a display instrument, and a data acquisition and control system. The detailed building process of this platform has been published in former article [23]. The process flow diagram of the experimental platform is shown in Fig. 1.

Experimental flow included primary side vapor circulation and secondary side feed liquid circulation. For primary side vapor circulation, low-pressure saturated vapor (also known as "fresh vapor generated"), which was produced by the vapor generator (1), passing through the wire mesh demister at the inlet of the steam pipe, entered the heat transfer tube of the horizontal tube falling film evaporator (2). Cooled by the feed water film outside the heating tube, most parts of the vapor condensed into condensation water, and then the condensed water flowed back to the vapor generator through the mass flowmeter (12). Residual uncondensed vapor entered the heat exchanger (7) for condensation, and the condensed water was drawn by the vacuum pump (11) through the mass flowmeter (9). For secondary side feed liquid circulation, the feed water in the water tank (3) entered the top of the horizontal tube falling film evaporator (2) through the circulating pump (4, 5) and formed a uniform liquid film outside the heat transfer tube through the liquid distributor. The feed water was heated until saturation by the primary vapor in the tube, and part of it was evaporated. The generated secondary vapor entered the heat exchanger (6) for condensation, and then the condensation liquid was drawn by the vacuum pump (10) through the metering device (8). The feed liquid not evaporated flowed through the tube bundle from top to bottom and then returned to the feed water tank (3).

Various parameters were measured, including temperature, pressure, flow rate, fluid level, online conductivity, and pH. Sensors on the device body and pipes were used to test temperature and pressure. Seven pipe-installed electromagnetic flowmeters were used to measure the flow rates of seawater, concentrated water, and product water. The measurement accuracy of this electromagnetic flowmeters is ±1.5%. 9 copper–constant an thermocouples were adopt to inspect the local temperature of motive steam, feed liquid, freshwater and brine in the experiments. All the thermocouples were calibrated using a constant-temperature oil bath before installation, and the overall accuracy was within ±0.1 °C. And the data of pressure at nine measuring points were arranged in the experimental device using accurate manometers with the scale range of -0.1~0 MPa, 0~0.5 MPa and 0~1 MPa, and the accuracy was 0.25%. An orifice plate flowmeter was used to measure steam flow rate with temperature and pressure compensation to ensure a measurement error of less than ±0.1%. Product water quality was monitored using an online conductivity meter and a pH meter installed on the product pump outlet. All the measured data about temperature, pressure and flow rate were recorded using a data