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Experimental study of falling film evaporation heat transfer coefficient on horizontal tube

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ABSTRACT

The horizontal-tube falling film evaporation is a widely adopted technique in multiple-effect distillation desalination plant. It has a high heat transfer coefficient under quite small temperature difference. In this paper, an experimental equipment for horizontal-tube falling film evaporation was set up. Experiments were carried out to show how the heat transfer coefficient is affected by different parameters including heat flux, circumference direction of tubes, spray density, evaporation temperature, and experimental fluid. Results indicate that the heat transfer coefficient decreases after a little increase with growth of spray density. The heat transfer coefficient decreases along the tube circumference, but at the bottom of the tube, it shows increasing trend. In addition, a simple comparison between seawater and fresh water in heat transfer coefficient is also provided.

Keywords: Heat transfer coefficient; Horizontal-tubes falling film evaporation; Desalination; Spray density

1. Introduction

The shortage of water has become the important restrict factor of the sustainable development of society and economy. Desalination is the best acknowledged method to solve the shortage of water, because it is a kind of mature technology which can open up new water sources. There are various methods of desalination, among them, multiple-effect distillation (MED), having many advantages such as high quality product water, allowing low temperature difference, and utilization of waste heat, has become one of the major desalination technologies. MED can be divided into horizontal-tube falling film evaporation and vertical-tube falling film evaporation. For smooth tube, the heat transfer coefficient of the former one is twice of that of the latter. Hence, investigation of horizontal-tube falling film evaporation has great significance for the development of MED [1].

Several experimental and theoretical studies on falling film evaporation were reported in many applications.

About the heat flux effect: For completely wetted surface in strictly convective conditions, the heat transfer coefficient does not depend on heat flux in studies of Fujita and Tsutsui [2], Hu and Jacobi [3], and Parken et al. [4]. On the other hand, under boiling dominated conditions, the heat transfer coefficient increases with the heat flux [5–7].

About the spray density effect: Yang and Shen [7] reported that the heat transfer coefficient of falling film evaporation increased with the spray density by the experiment in which the tubes were made of one kind of Al-brass with outer diameter of 14 mm, while

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the experimental liquid was fresh water, and the range of spray density was 0–0.062 kg/m s. Xu and Ge [8] had come to the same conclusion. Her study used copper tube with outer diameter of 25.4 mm as the heating tube, seawater as the experimental liquid, and the range of spray density was 0–0.4 kg/m s). Fletcher et al. [9] found the same result with copper–nickel tube, diameter of 25.4 and 50.8 mm, experimental liquid of seawater, and spray density of 0–0.63 kg/m s). Chyu and Bergles [10,11] and Fujita and Tsutsui [2,12] obtained different conclusions, with the spray density increasing, the heat transfer coefficient decreased first and then increased after a minimum value. Chyu and Bergles [10,11] used copper tube as heating tube with the tube diameter of 25.4 mm. Fujita and Tsutsui [2,12] used copper tube with outer diameter of 25.4 mm and the range of spray density was 0.006–0.14 kg/m s.

About the temperature effect: Xu and Wang [13], Edahiro and Hamada [14], and Parken et al. [4] acquired the same conclusions that heat transfer coefficient increased with the increment of saturation temperature in their experiments.

About the liquid concentration effect: Fan [15] reported that the heat transfer coefficient did not depend on liquid concentration. His experiment used copper tube with diameter of 14 mm, fresh water and seawater as experimental liquid, and the range of spray density is 0–0.13 kg/m s. Slesarenko [16,17] found a different result that the heat transfer coefficient decreased when the liquid concentration increased. Until now, the empirical correlations describing the falling film heat transfer coefficient on horizontal tubes, such as Chyu and Bergles [10], Parken et al. [4], and Xu and Ge [8], have significant discrepancies.

Some scholars have discussed heat transfer characteristics of horizontal-tube falling film evaporation, but the results are inconformity due to the complexity of heat transfer process. In order to get a better understanding of the basic mechanisms of the horizontal-tube falling film evaporation, it should be investigated in depth. The purpose of this paper is to discuss the relationship between heat transfer coefficient and different parameters including heat flux, circumference direction of tubes, spray density, evaporation temperature, and experimental fluid.

2. Experiment process

2.1. Experiment devices

The experiment system for horizontal-tubes falling film evaporation process is shown in Fig. 1, which mainly includes water supply system, evaporation system, vacuum system, water extraction system, and instrumentation system.

The water supply system includes heating tank, feed pump, upper tank, etc.

The evaporation system includes airproof chest, spray tube, distributor, heating tube, etc.

The vacuum system includes condensers, vacuum pump, cooling water supply system, etc.

The water extraction system includes measuring cylinder, storage tank, jet pump, etc.

The instrumentation system includes flow meters, thermocouples, pressure sensors, rotameter, and computer data recorder, etc.

An illustration of the experimental apparatus used in this investigation is presented in Fig. 2. The horizontal tube assembly is placed in the cylindrical casing which is equipped with the front and back glass plate windows. The assembly consists of a feed tube, a heating tube, and four dummy tubes that are vertically set in a vertical plane. The main function of dummy tubes is to make liquid film be uniformly distributed onto the surface of heating tube on the

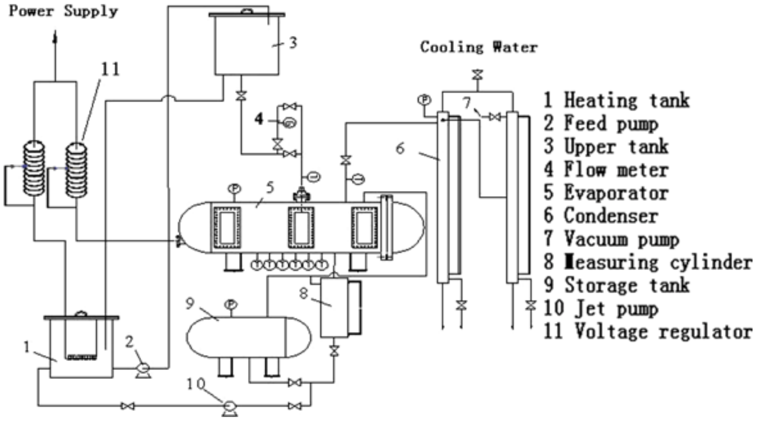

Fig. 1. Experimental system diagram.

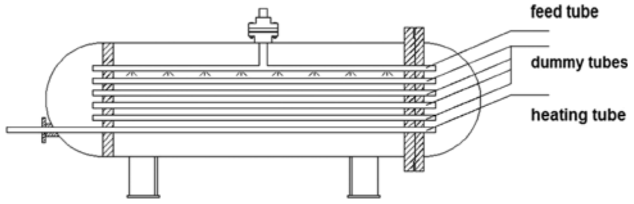

Fig. 2. The tube bundle in evaporator.

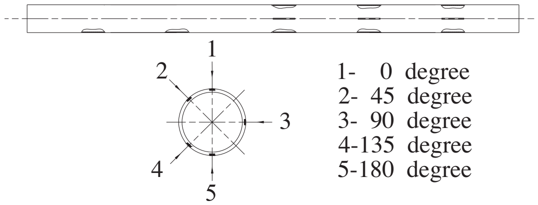

Fig. 3. Arrangements of thermocouples.

bottom. Feed tube, heating tube, and dummy tubes were all made of aluminum brass with 25.4 mm outside diameter and 0.7 mm thickness. The heating tube length is 2,000 mm with 1,600 mm effective length. The tube spacing with triangular pitch arrangement is about 2.25 times of the tube diameter. To reduce heat losses the evaporator is covered by thermal insulators. The heat loss of this experiment is less than 7%.

For the accurate controlling of the experiment process, a power adjustable electrical bar is used as the heating source to adjust the heat flux and temperature on the surface of the tube during the experiment.

The experiments were carried out at different temperatures, pressures, and spray densities. The temperatures are measured by thermocouples. Calibration of thermocouples was done before the experiment to control the maximum error within less than 0.05℃, and the error is about 2%. The surface of heating tube was formed by cutting 25 longitudinal grooves along the length direction, with each 0.3 mm deep and 0.3 mm wide. Thermocouples were bedded in the grooves, then the grooves were filled with solder and the tube surface was smoothed. Five sets of thermocouples were arranged axially on the surface of heating tube. Each set included five thermocouples, respectively, fixed from bottom of the cross-section to the top at an angular spacing of 45°. Thus, the temperatures profile in circumference direction could be observed. In the axial direction, distance between two sets of thermocouples was 350 mm. The thermocouples arrangement on the heating tube is shown in Fig. 3.

The pressures are measured by pressure sensors. The measuring range of pressure sensor is from −0.1 to 0 MPa, the precision is 0.2 kPa, and the error is less than 0.5%.

The spray densities are controlled and measured by the rotameter. The measuring range is from 100 to 1,000 L/h and the accuracy is less than 1.5%. The spray tube was made of the same material, length, diameter, and thickness as the heating tube, on the bottom of which couple of dripping holes were made to distribute liquid drops. According to "Taylor instability equation" [18], the hole diameter was 1.5 mm and the hole spacing was 20 mm. The heating tube surface was completely wetted through observation in the experiment.

Measuring signal is collected by Henghe 2300 and the LabVIEW makes data visual and to be saved.

Two fluids are used in the experiments as the evaporation mediums, which are fresh water and seawater. The fresh water for the experiment is distilled water, while the seawater is taken from Yellow Sea near Dalian (a city of northeast China) with a salinity of 3.0%.

2.2. Experiment process and method

Evaporator is the main equipment in this experiment. During the experiment, a certain vacuum degree is fixed. A vacuum pump is used both at the initial state of the system for air extraction in the experimental device and process for discharging noncondensing gas produced during the experiment. The working condition is sustained at a steady state for at least 20 min during which data are recorded.

In the experiment, feed water is heated to the saturation temperature corresponding to the pressure in the evaporator. Then it is pumped to the upper tank where the water is kept at a fixed level. The feed water flows with a steady rate by gravity and the pressure difference between outside and inside of the evaporator. The fluid is well-distributed to the heating tube outer surface via spray tubes and dummy tubes, forming continuous drops and a uniform liquid film on the heating tube surface. The heat exchange between liquid film and heating tube converts part of the liquid into vapor. Then in condenser, the vapor is condensed back to water again in order to sustain a certain degree of vacuum in the evaporator and to measure the evaporating capacity. Nonevaporated water is pumped back into heating tank again for the next circulation.

Different vacuums, corresponding to the evaporation temperature, are chosen to simulate working conditions of different effect evaporators in a MED desalination plant. The influence of spray density on the evaporative heat transfer coefficient is also recorded by changing the feed water flow rate.

3. Experiment results and discussions

In the experiment, the heating tube is plain and made of HAL77-2A aluminum brass with an outer diameter of 25.4 mm. The tube pitch between two adjacent tubes is 57 mm. The heat flux ranges from 7 to 12 kW/m^2. Evaporation temperatures are between 45 and 70℃, corresponding to the typical evaporation temperature range of MED desalination plant. The spray density is between 0.02 and 0.07 kg/(m s).

For calculating the heat transfer coefficients, the following formula is used:

$$h = \frac{Q}{A\Delta t} = \frac{q}{\Delta t} \tag{1}$$

A is constant and Q is got by measuring working voltage and current of heating tube. Δt is acquired by thermocouples (one thermocouple is located inside spray tube to get liquid temperature and the others are set on the surface of heating tube).

3.1. Effect of heat flux

Fig. 4 shows the scattered data to present the influence of heat flux of heating tube on heat transfer coefficient with fresh water as experimental fluid when evaporation temperature is 60℃ and spray density is 0.043 kg/(m s). It can be seen that the heat transfer coefficient does not change significantly with time at three different heat flux. It corroborates Fujita and Tsutsui [2] and Hu and Jacobi's [3] results. So the conclusion can be obtained in this experiment that the influence of heat flux on heat transfer coefficient is weak when heat flux ranges from 7.68 to 12.04 kW/m^2. For this reason, the heat flux is fixed at 12 kW/m^2 in the experiment.

3.2. Effect of circumferential position

Fig. 5, the fresh water experiment, shows the distribution of heat transfer coefficient in circumferential direction of heating tube, when spray density is 0.052 kg/(m s). It can be seen that the average heat transfer coefficient of heating tube increases with the evaporation temperature. At the upper portion of the tube, the local heat transfer coefficient is affected by the evaporation temperature significantly. While from 135° to 180°, the evaporation temperature has little influence on heat transfer coefficient. This is because the water evaporation on the heating tube is mainly caused by the surface evaporation rather than boiling. The increase of evaporation temperature causes the fluid viscosity to decrease, which attenuates the liquid film and reduces the heat conduction thermal resistance. In addition, it also decreases the surface tension and enhances the liquid film disturbance. All of these factors above benefit the heat transfer in the liquid film. During the falling film evaporation process, water drops impinge the top of heating tube, which can increase the disturbance of top liquid film. Therefore, the heat transfer coefficient on the upper portion is higher than that on the lower portion of the tube. When water flows further down along the surface of the heating tube, the liquid film fluctuation weakens and the liquid film thickness increases, then the heat transfer in convective state is inhibited, so local heat transfer coefficient decreases continuously. Afterward, at about 135°, the gravity effect accelerates the water flowing speed and the water flows through the heating tube. This will cause severe fluctuation of the film. Though the liquid film is normally thick at the bottom portion of the tube, the heat transfer coefficient does not decrease and even increases a little.

Fig. 6 presents the experimental result of falling film evaporative heat transfer coefficient with seawater. The evaporation temperature is 60℃ and the spray density is 0.052 kg/(m s). It can be seen from the

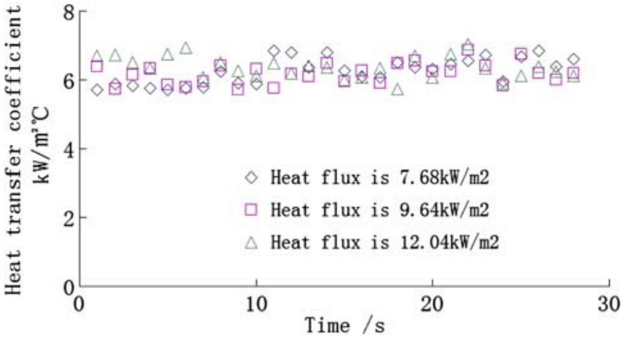

Fig. 4. Distribution of heat transfer coefficient at different heat flux.

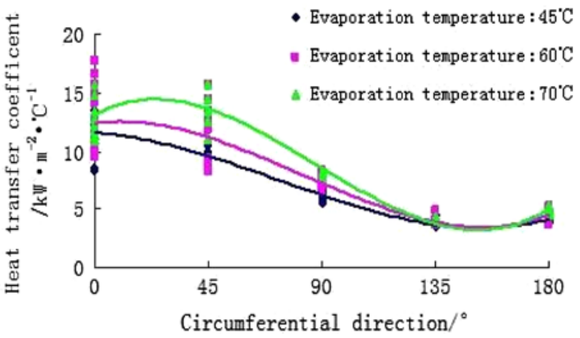

Fig. 5. Distribution of heat transfer coefficient along circumferential direction with fresh water.

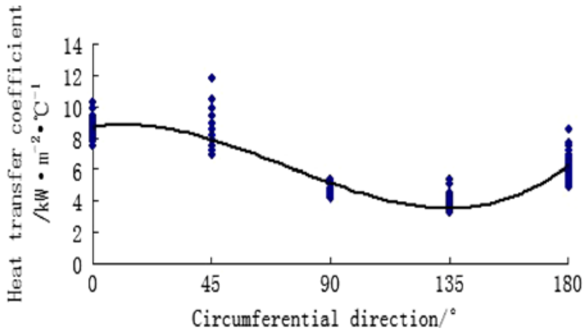

Fig. 6. Distribution of heat transfer coefficient along circumferential direction with seawater.

figure that the regular pattern is the same as fresh water. The evaporative heat transfer value of seawater is lower than that of fresh water in the same condition. For either fresh water or seawater experiment, the maximum falling film evaporative heat transfer coefficient is twice of the minimum. The conclusions in this paper are similar to results of Chyu and Bergles [10] at the circumferential range of 0–135°. But the difference appear at the bottom of tube, because there are many assumptions of analysis of Chyu and Bergles, such as the film flow is steady, the film flow is laminar, etc. while in experiment, retraction of fluid cylinder causes strong film disturbance when droplet falling off the bottom of tube of which Chyu and Bergles have not taken into account in their calculation.

3.3. Effect of spray density

Fig. 7 shows the relationship between heat transfer coefficient and spray density at different evaporation temperatures. It should be noticed that both spray density and evaporation temperature have significant influence on heat transfer coefficient. In this figure, heat transfer coefficient becomes higher during the increase of spray density. When spray density reaches about 0.06 kg/(m s), the increase of the curve slows down or even there is a declining trend afterward. The reason is that when water drops reach the surface of the tube, the higher the flow density, the stronger the liquid film disturbance, which can result in a higher heat transfer coefficient. However, the film thickness increases with the spray density simultaneously. After spray density reaches a certain amount, the increasing liquid film thickness will hinder the growth of heat transfer coefficient.

3.4. Effect of experimental fluid

Fig. 8 shows the comparison of the heat transfer coefficient of falling film evaporation with fresh water and seawater. The evaporation temperature is 60℃ and the spray density is between 0.025 and 0.09 kg/(m s). It can be seen that the heat transfer coefficients of falling film evaporation with fresh water and seawater have the same changing tendency. Both the heat transfer coefficients increase with the spray density, and maximum values appear at the spray density being around 0.06 kg/(m s).

Meanwhile, the heat transfer coefficient with seawater is generally less than that of fresh water. Since seawater has a higher viscosity than that of fresh water, the liquid disturbance of seawater is weaker than that of fresh water in the process. This result indicates that for the purpose of desalination plant design and analysis, the experimental result with fresh water is not fully suitable.

4. Comparisons with other work

In Fig. 9, the present result is compared with the results of Xu [19] and Fujita and Tsutsui [12] in dimensionless basis. The Nusselt numbers of the two curves are different from each other at the same Re number, Pr numbers, tube diameter, spray density,

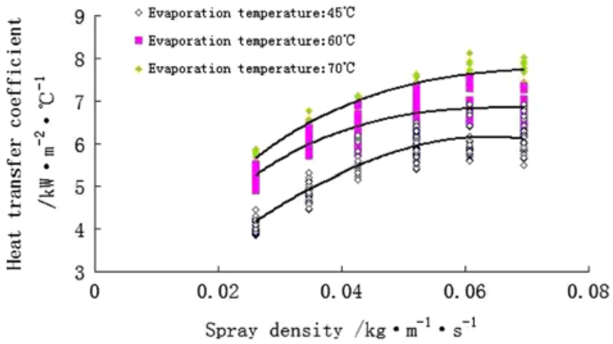

Fig. 7. Distribution of heat transfer coefficient in different spray densities with fresh water.

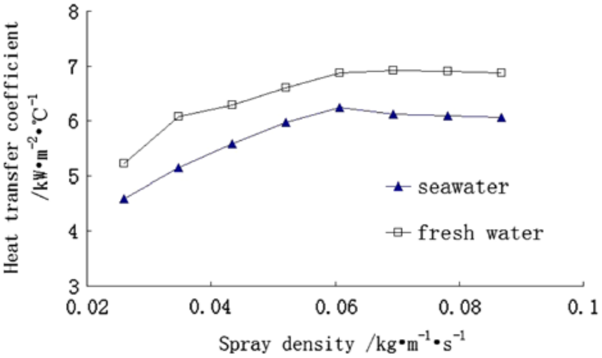

Fig. 8. Distribution of heat transfer coefficient in different spray densities for both seawater and fresh water.

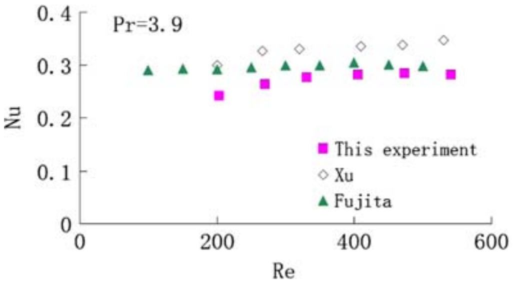

Fig. 9. Comparison of present result with the results of previous studies.

evaporation temperature, experimental fluid, and heat flux. This might be because of the different feeding heights and different experimental errors. But the trends of them are almost the same. In this experiment, Nu declines after Re = 400 and growth of Nu in Xu's result is slowdown at the same position. The correctness of above reason is validated again by this phenomenon.

$$\mathrm{Re} = \frac{4\Gamma}{\eta} \tag{2}$$

$$\mathrm{Pr} = \frac{\eta C_{\mathrm{p}}}{\lambda} \tag{3}$$

$$\mathrm{Nu} = \bar{h}\left(\frac{v^2}{g\lambda^3}\right)^{\frac{1}{3}} \tag{4}$$

Parameters mentioned above including Re, Pr, and Nu can be obtained from the Eqs. (2)–(4), respectively.

5. Conclusions

(1) In the present experiment, heat flux has little effect on the heat transfer coefficient when heat flux is from 7.68 to 12.04 $\mathrm{kW/m^2}$.

(2) The film thickness and the turbulence in the film control the heat transfer coefficient. The heat transfer coefficient increases in the beginning, then decreases, at last it increases again after a minimum value. The maximum heat transfer coefficient is about twice of the minimum.

(3) When the spray density ranges from 0.02 to 0.07 kg/(m s), the heat transfer coefficient of falling film evaporation increases with the spray density. But when the spray density reaches 0.06 kg/(m s), the increasing tendency is slowly or the heat transfer coefficient reaches its maximum value.

(4) For fresh water, the heat transfer coefficient of falling film evaporation increases with evaporation temperature.

(5) The falling film evaporative heat transfer coefficient of seawater is lower than that of fresh water.

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Nomenclature

h	—	heat transfer coefficient, $\mathrm{kW/m^2{}^\circ C}$
Q	—	thermal power, kW
q	—	heat flux, $\mathrm{kW/m^2}$
A	—	heat transfer area, $\mathrm{m^2}$
Δt	—	temperature difference, ℃
Re	—	Reynolds number
Pr	—	Planck number
Nu	—	Nusselt number
Γ	—	spray density, kg/ms
η	—	dynamic viscosity, kg/ms
C_{p}	—	specific heat at constant pressure, kJ/kg℃
λ	—	heat conductivity coefficient, W/m℃
$\bar{h}$	—	average heat transfer coefficient, $\mathrm{kW/m^2{}^\circ C}$
v	—	kinematic viscosity, $\mathrm{m^2/s}$
g	—	gravity acceleration, $\mathrm{m/s^2}$

References

[1] L. Yang, X. Chen, S. Shen, Thermoeconomic analysis of a CHP-based dual-purpose power plant, Desalin. Water Treat. 22 (2010) 371–379.
[2] Y. Fujita, M. Tsutsui, Evaporation heat transfer of falling films on horizontal tube. Part 2 Experimental study, Heat Transfer. Jpn. 24 (1995) 17–31.
[3] X. Hu, A. Jacobi, The intertube falling film: Part 2—mode effects on sensible heat transfer to a falling liquid film, J. Heat Transfer 118 (1996) 626–633.
[4] W. Parken, L. Fletcher, V. Sernas, Heat transfer through falling film evaporation and boiling on horizontal tubes, J. Heat Transfer 112 (1990) 744–750.
[5] X. Zeng, M. Chyu, Evaporation heat transfer performance of nozzle sprayed ammonia on a horizontal tube, ASHRAE Trans. 101 (1995) 317–324.
[6] S. Moeykens, M. Pate, Spray evaporation heat transfer of R-134a on plain tubes, ASHRAE Trans. 100 (1994) 173–184.
[7] L. Yang, S. Shen, Experimental study of falling film evaporation heat transfer outside horizontal tubes, Desalination 220 (2008) 654–660.

[8] L. Xu, M. Ge, Heat transfer film coefficients of falling film horizontal tube evaporators, Desalination 166 (2004) 223–230.

[9] L. Fletcher, V. Sernas, W. Parken, Evaporation heat transfer coefficients for thin sea water films on horizontal tubes, Ind. Eng. Chem. Process Des. 14 (1975) 411–416.

[10] M. Chyu, A. Bergles, An analytical and experimental study of falling-film evaporation on a horizontal tube, J. Heat Transfer 109 (1987) 983–990.

[11] M. Chyu, A. Bergles, Horizontal-tube falling-film evaporation with structure surfaces, J. Heat Transfer 111 (1989) 518–524.

[12] Y. Fujita, M. Tsutsui, Experimental investigation of falling film evaporation on horizontal tubes, Heat Transfer. Jpn. 27 (1998) 609–618.

[13] L. Xu, S. Wang, Studies on heat-transfer film coefficients inside a horizontal tubein falling film evaporators, Desalination 166 (2004) 215–222.

[14] K. Edahiro, T. Hamada, Research and development of multi-effect horizontal tube film evaporator, Desalination 22 (1977) 121–130.

[15] Y. Fan, Experimental study of falling film evaporation on horizontal tubes, Ms.D. Thesis, Dalian University of Technology, 2006.

[16] V. Slesarenko, Investigation of heat exchange during sea water boiling in a horizontal thin film desalination plant, Desalination 28 (1979) 311–318.

[17] V. Slesarenko, Thermal desalination of sea water in thin film plants, Desalination 45 (1983) 295–302.

[18] R. Bellman, R. Pennington, Effects of surface tension and viscosity on Taylor instablility, Quart. Appl. Math. 12 (1954) 151–162.

[19] L. Xu, A study on heat-transfer characteristics of falling film horizontal-tube multi-effects desalting evaporator, Ph.D. Thesis, Tianjin University, 1999.