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An Experimental study on Flow and Heat Transfer Characteristics of Oily Water Falling Film on Horizontal Tubes

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ABSTRACT

In order to study the falling film flow process outside the horizontal circular tube, experiment is adopted in this paper to investigate the effects of liquid spray density and spray temperature on the liquid film flow pattern transformation and pattern distribution. Meanwhile, the temperature distribution characteristics of the horizontal tubes are analyzed. The high-speed camera was used to photograph the flow pattern of the liquid film, and the K-type thermocouples were used to measure the tubes wall temperature. The results show that (1) as the spray density increases, the liquid film is converted from a droplet flow to a columnar flow and then to a sheet flow; (2) the critical spray density of the flow pattern conversion will reduce with the spray liquid temperature increasing; (3) the critical spray density of 10% glycerol solution for flow pattern conversion is bigger than that of water; (4) the tube wall circumferential temperature increased with the increase of spray density, and the tubes wall circumferential temperature decreased with the increase of the circumferential angle in the range of the circumferential angle from 0° to 135° and rose slightly from 135° to 180°; (5) the tube wall circumferential temperature of water is higher than that of the 10% glycerol solution.

Keywords: oily wastewater, falling film, flow pattern, heat transfer characteristics, horizontal tube

NONMENCLATURE

T	Temperature, °C
T_i	Spray temperature, °C
C_p	Specific heat at constant pressure, $J·kg^{-1}·K^{-1}$
μ	Dynamic viscosity, Pa·s
σ	Surface tension, $N·m^{-1}$
ρ	Density, $kg·m^{-3}$
Γ	Spray density, $kg·m^{-1}·s^{-1}$
R	Radii, mm
Φ	Diameter, mm
L	Interval of holes centre,mm
ϑ	Circumferential angle, °

1. INTRODUCTUON

With the continuous development of industrial technology, the correct and reasonable discharge and utilization of oily sewage has gradually become the focus of sewage treatment. The source of oily sewage is extensive, mainly reflected in petroleum production, chemical industry, steel and machinery manufacturing industry. Sewage source heat pump (SSHP) system can not only improve the utilization efficiency of heat energy in sewage, but also realize the effect of energy saving by recovering the heat energy in oily sewage. The safe and efficient operation of the SSHP system depends on the selection and heat transfer effect of the sewage heat exchanger. Among many types of heat exchangers, the spray heat exchanger has been widely concerned and applied because of its high heat transfer efficiency, small heat transfer volume and good operation under the condition of serious scaling so that

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it is widely used in medicine, chemical industry, biochemical engineering, waste liquid recovery, seawater desalination and other fields[1]. The typical flow of the spray heat exchanger is the falling film flow outside the horizontal tube. Therefore, studying the falling film flow and heat transfer characteristics of the spray heat exchanger is the basis of designing and strengthening heat transfer. During the falling film flow, the distribution of the liquid film and the quality of film formation on the wall of the heat exchange tube will directly affect the heat exchange efficiency of the heat exchanger. Therefore, in order to obtain a better liquid film distribution and higher heat exchange efficiency, A large number of studies on the falling film flow process and heat transfer characteristics of liquid flow outside the tube have been conducted.

Fujita et al.[2] added two new flow patterns based on the basic flow pattern: special trickle flow and disturbed column flow. Wang et al.[3] found that the transitional Reynolds numbers increase with an increase in the orifice spacing at a fixed orifice diameter; transitional Reynolds numbers also increase with an increase in the orifice diameter at a fixed orifice spacing-to-diameter ratio. Yan et al.[4] pointed out that the arrangement of nozzles induces significant impact on the fluid flow and heat transfer characteristics of the test tubes. The nozzles pitch is a key parameter, which allows film bonding and can be considered as a controlling parameter for heat transfer enhancement and the flow structure. Zhao et al.[5] elucidated the importance of surface tension in calculation and the effects of film flow rate, tube diameter, liquid distributor height and inlet liquid temperature on the flow field and film thickness. Pu et al.[6] explored the flow and heat transfer characteristics of falling film evaporation on a circular tube and flat tubes. It is confirmed that the liquid film becomes thinner and thinner as height-width ratio increases. Jige et al.[7] clarified the effects of film Reynolds number, heat flux, saturation temperature, and refrigerant properties on the heat transfer. Gstoehl et al.[8] described a new optical method for the non-intrusive measurement of falling film thickness on the perimeter of horizontal tubes and compared with Nusselt's[9] formula. Sun et al.[10] proposed that the liquid film of water outside the horizontal pipe is unevenly distributed, and the thickness of the liquid film depends on the spray density and the value of the circumferential angle. Zhang et al.[11] showedthat the film thickness of the corrugated tube increases with the increasing of the film Reynolds number, which is the thinnest from 90° to 120°. It decreases as the tube spacing increases and increases with the tube diameter and corrugated radius. Giannetti et al.[12] showed the importance to operate at reduced mass flow rates with a thin uniform film, which required add tension-active additives to realize this condition. Liu et al.[13] found that the increase of viscosity can retard the droplets falling and the decrease of surface tension can predate the appearance of the droplet detaching. Ben Jabrallah et al.[14] proposed that the heat and mass transfer can be intensified by increasing the temperature of the water feed or by decreasing flow rate. Hassani et al.[15] studied the performance of mass transfer models for heat transfer coefficient, film thickness, bubble generation and liquid super-heating. Manouchehri et al.[16] showed that heat exchanger effectiveness is linked to fluid inlet temperatures, and that increases in either of these temperatures would lead to an increase in effectiveness. Moreover, in previous studies [17, 18], it was reported that the oil content in the wastewater had a critical effect on fluid physical properties and the flow and heat transfer characteristics of spray falling.

It can be seen that most of the studies on the falling film flow outside the horizontal tube are pure liquid solution, and there is few study of oily sewage on the film distribution, flow pattern and heat transfer characteristics. Therefore, in this paper, an oily sewage source heat pump was designed and experiments were carried out to study the flow process and heat transfer characteristics of the falling film over the horizontal circular tube. The influence of water and 10% glycerol solution on the liquid film distribution and heat transfer coefficient at different spray densities, spray temperatures and oily content were investigated.

2. METHODOLOGY

2.1 Experimental setup

As shown in Fig. 1, the experimental setup was a self-designed sewage source heat pump (SSHP) system, which mainly consists of compressor, condenser (plate heat exchanger), drying filter, thermal expansion valve, flow meter, rotary flowmeter, spray heat exchanger and evaporator (shell-and-tube heat exchanger).

*R*245*fa* was used as refrigerant of the SSHP. The flow rate was controlled and measured by the water pump and flowmeter. Temperature and pressure sensors were placed at different positions of the experimental setup to monitor the system operating. In front of the heat transfer tube, A high-speed camera was placed to capture the flow phenomenon and photograph the film pattern on the side of the tube.

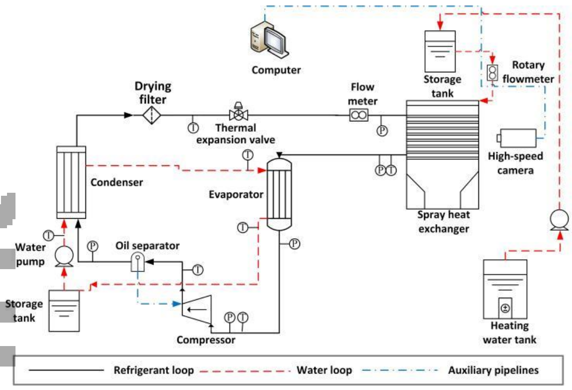


Fig.1 Experimental installation and process of falling film flow

2.2 Spray heat exchanger

The spray heat exchanger was the falling film test section, as shown in Fig. 2. The spray heat exchanger consists of a liquid distributor and two heat transfer tubes. Twelve liquid distribution holes with a diameter of 3mm and interval of 5 mm are designed on the bottom of the liquid distribution tube. Two horizontal tubes with diameter of 25.4 *mm* were placed under the liquid distribution tube. The distance between the three tubes are 3 and 13 mm, respectively, as shown in Fig. 2(b).

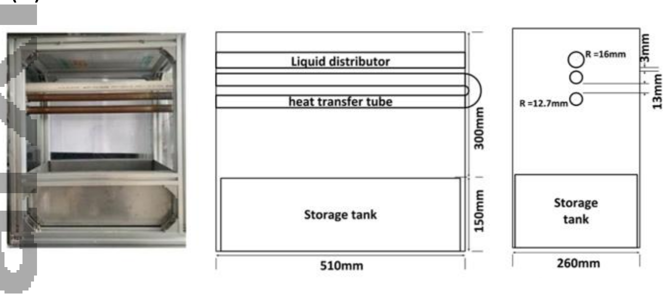


Fig.2 Structure and size of spray heat exchanger

2.3 *Experiment method*

The sewage wastewater was simulated using mixture of water and glycerol in the experiments. In this study, two types of fluid with different concentrations of glycerol were used, 0% namely pure water and 10% type. The physical properties of the liquid are shown in Table 1.

Table 1 Physical properties of liquid

Liquid	T (°C)	ρ ($kg·m^{-3}$)	C_p ($J·kg^{-1}·K^{-1}$)	μ ($10^{-5}Pa·s$)	σ ($10^{-3}N·m^{-1}$)
	46	989.74	4174	59.204	68.46
Water	55	985.65	4176	50.91	66.95
	65	980.5	4178	43.745	65.25
10%	46	1011.25	4063	73.84	68.34
glycerol	55	1007.41	4057	62.75	66.76
solution	65	1002.57	4049	53.75	64.97

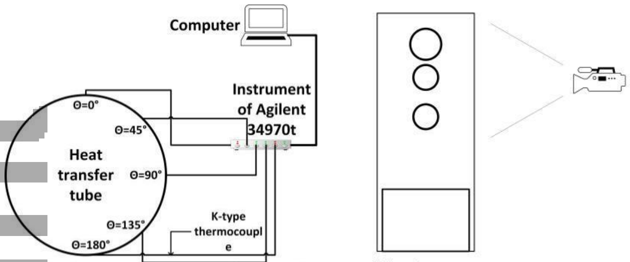
According to previously related studies [17, 19], the spraying temperature were determined at 3 levels, and the spray density were set at 6 levels, as shown in Table 2. Before the experiment, the heat transfer tubes were washed with alcohol and dried. Heating water tank provided sewage wastewater at a specified temperature and the rotary flowmeter were used for controlling the spray density to meet the experiment parameters. The sewage wastewater flowed out through the liquid distributor and reached the heat transfer tubes then it forms a liquid film on the tube. The liquid film exchange the heat with the refrigerant *R*245*fa* at the heat transfer tube, thereby, the heat transfer achieved.

Table 2 Experimental condition

Flow fluid	Spray temperature (°C)	spray density ($kg·m^{-1}·s^{-1}$)
Water	46	
Water	55	
Water	65	0.027, 0.055, 0.082,
10% glycerol solution	46	0.109, 0.137, 0.164
10% glycerol solution	55	
10% glycerol solution	65	

2.4 Temperature acquisition and liquid film observation

The utilized data acquisition system for temperature measurement is consist of a data acquisition unit: Agilent 34970t. It is connected to the thermocouple and transmitted the measured wall temperatures to the computer. The K-type thermal couples were placed at five different circumferential positions around the heat transfer tube (0°, 45°, 90°, 135° and 180°) to measure the tube surface temperature, as shown in Fig. 3(a). The measuring range of thermal couple was -20°C to 400°C and had an accuracy of ±0.5°C. Meanwhile, the high-speed camera (UI-3040CP-C-HQ) was placed directly in front of the falling film chamber to record the falling film flow pattern, as shown in Fig. 3(b). The pixel of the high-speed camera was set to 1448×1086. Since the flow pattern between the tubes was not just a concept for a certain unit or a certain moment, but a collection of multiple unit pattern within a stable period of time, each experiment recorded 15 seconds video of liquid film flow, and then captured the picture with a clear footage and liquid film continuously and stably for more than 5 seconds as the liquid film flow pattern in this experiment.



(a) Temperature acquisition view (b) Film pattern capture view

Fig.3 Temperature acquisition and liquid film observation

2.5 Definition of liquid film pattern

Droplet flow: the droplet is the only flow pattern between tubes.

Droplet-Column flow: mixed pattern of droplet and columnar between tubes.

Column flow: the column is the only flow pattern between tubes.

"Γ" shape flow: transition pattern of column to sheet transition, which is similar to the "Γ".

Column-Sheet flow: the mixed pattern of column and sheet between tubes.

Sheet flow: the flow pattern between the tubes is continuous liquid film.

3.Results and discussion

3.1 Falling film flow characteristics

Fig.4 shows the process of liquid film evolution with different spray densities, where T_i=55°C. As can be seen in Fig.4(a), due to the low initial spray density, the liquid falls downward and forms a droplet flow. Then as the spray density increases, it can be seen in Fig.4(b) that the liquid film develops into a column flow. After that, when the spray density increased to 0.082 kg·m^{-1}·s^{-1}, the liquid film gradually evolved into multiple column flows, as showed in Fig.4(c). As seen in Fig.4(d), the liquid film at the bottom of the tube was thickened with spray density increases, and film flow pattern developed into "Γ" shape flow. It can be seen in Fig.4(e) and Fig.4(f), the flow pattern evolved into a column-sheet flow and then developed into a sheet flow.

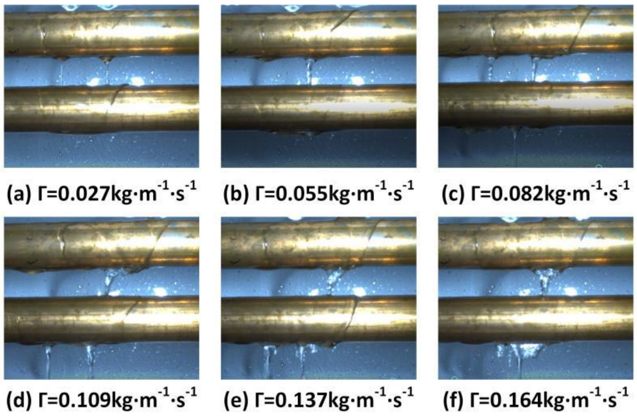


Fig.4 Falling film flow pattern at different spray densities

It is observed from Fig. 5 that, for Γ=0.027 kg·m^{-1}·s^{-1}, the liquid film pattern of water at 46°C is droplet flow, however, at 55°C and 65°C the liquid film pattern of water is column flow. For Γ=0.082 kg·m^{-1}·s^{-1}, the liquid film pattern of water is column flow at 46°C,55°C and 65°C. For Γ=0.137 kg·m^{-1}·s^{-1}, column flow was observed for T_i=46°C, while sheet flow was observed for T_i=55°C and 65°C. For Γ=0.164 kg·m^{-1}·s^{-1}., the flow pattern for T_i=46°C also changed to column-sheet flow. This indicates as the temperature increases, the width of sheet flow becomes larger.

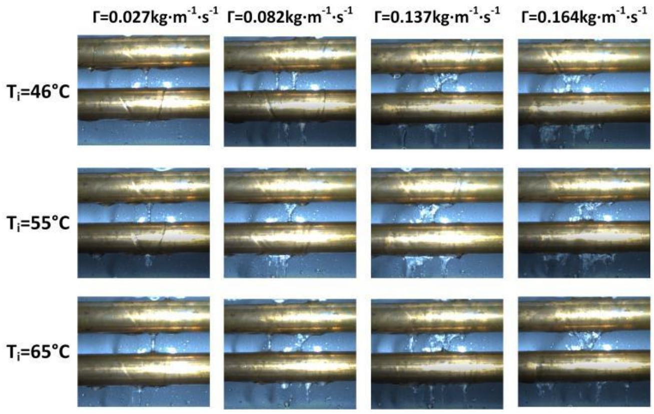


Fig.5 Falling film flow pattern of water at different temperatures and different spray densities

Fig.6 shows that the liquid film flow pattern of 10% glycerin solution at 46°C and 55°C is droplet flow and at 65°C the liquid film is columnar flow when the Γ=0.027 kg·m^{-1}·s^{-1}. For Γ=0.082 kg·m^{-1}·s^{-1}, at 46°C and 55°C the liquid film flow pattern changed from droplet flow to column flow while the liquid film at 65°C developed into the "Γ" shape column flow. For Γ=0.137 kg·m^{-1}·s^{-1} and Γ=0.164 kg·m^{-1}·s^{-1}, the liquid column became wider. However, neither column-sheet or sheet flow were observed. This indicates the higher viscosity of 10% glycerin solution postponed the transformation of flow pattern from column to sheet flow. Besides, as the temperature increases, the width of the colum flow becomes larger due to the reduction in viscosity at higher temperature.

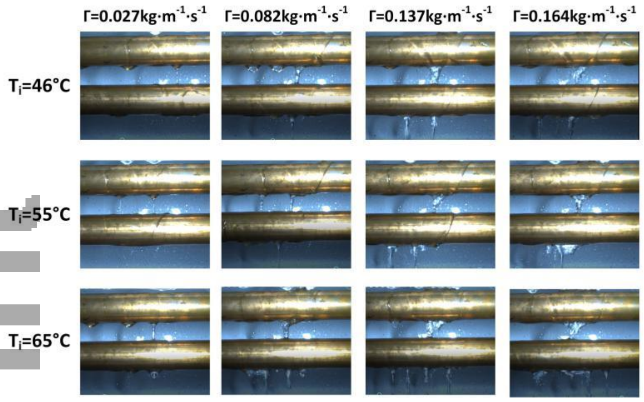


Fig.6 Falling film flow pattern of 10% glycerin solution at different temperatures and different spray densities

Fig.7 shows the comparison of flow pattern of water and 10% glycerin solution at 55°C. It can be seen that at the same temperature and spray density, the area of the water liquid film spreading on the tube wall is larger and more uniform, which can be shown in the red circle in the Fig.7. This is due to the viscosity of the glycerol solution is higher than water. Hence, the higher viscous on the tube wall reduce the flow rate, making the liquid film more difficult to spread than water. As a result, the critical spray density leading to flow pattern transformation of glycerol solution is higher than that of water.

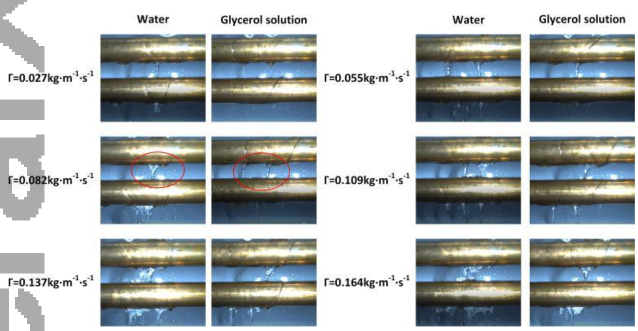
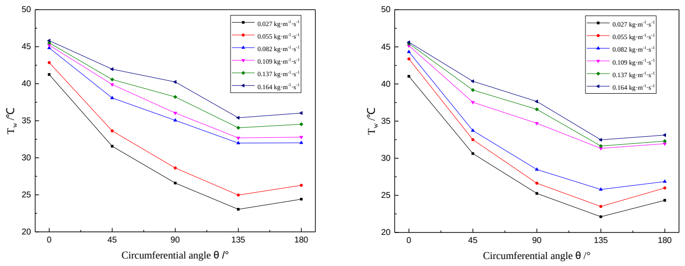


Fig.7 Comparison of flow pattern of water and 10% glycerin solution at different spray densities at 55°C

3.2 Falling film heat transfer characteristics

3.2.1Temperature distribution of tube wall

Fig.8 shows the circumferential temperature distribution of the tube wall when the spray liquid temperature is 46°C. As can be seen from Fig.8, at the same spray temperature, the higher the spray density, the higher the wall temperature at the same circumferential angle. It indicates that within the scope of the experiment, increasing the spray density can strengthen the falling film evaporator heat transfer process. It also can note that the tube wall circumferential temperature decreases with the increase of the circumferential angle in the range of the circumferential angle from 0° to 135°. The reason is that when the liquid film spreads on the tube wall, it exchanges heat with the refrigerant and causes the liquid film temperature to decrease. The tube wall temperature rises slightly with the increase of the circumferential angle in the range of the circumferential angle from 135° to 180°. This is because the liquid accumulates at the bottom of the heat exchange tube and forms a vortex, which strengthens the mixture of the inside cold fluid and the external hot fluid and increases the temperature difference between the inside and outside of the tube wall, so that the process of heat exchange is strengthened.

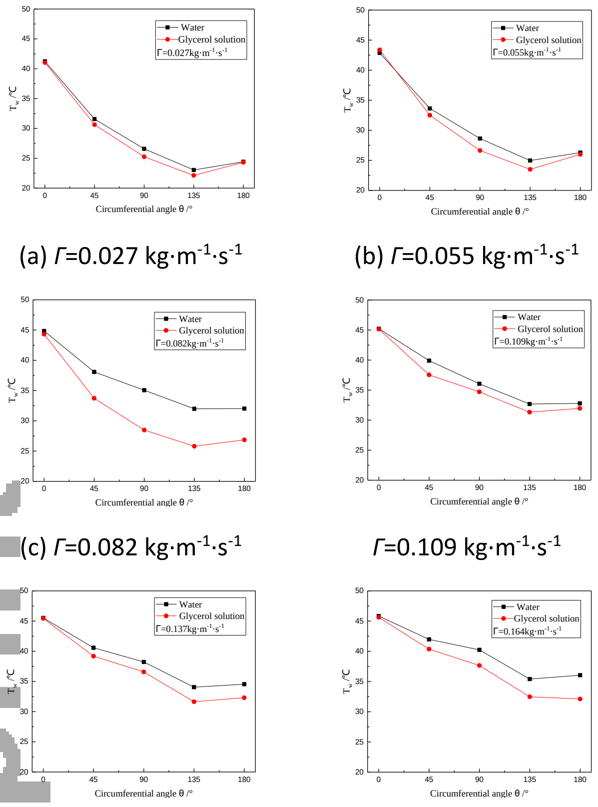


(a) water-heat transfer tube (b) glycerol solution-heat transfer tube

Fig. 8 First tube wall circumferential temperature distribution

3.2.2 Influence of spray density on the tube wall temperature

Fig.9 compares tube wall circumferential temperature distribution of water and 10% glycerol solution. It can be seen from Fig. 9 that under the same experimental conditions, the tube wall circumferential temperature of water is higher than 10% glycerol solution. It illustrates that the falling film flow heat transfer effect of water is better than glycerol solution under the same experimental conditions. This is because the viscosity of glycerol solution is higher than water and the isobaric specific heat capacity is smaller than water, so that has a low heat exchange intensity.



(a) Γ=0.027 kg·m^{-1}·s^{-1} (b) Γ=0.055 kg·m^{-1}·s^{-1}

(c) Γ=0.082 kg·m^{-1}·s^{-1} Γ=0.109 kg·m^{-1}·s^{-1}

Γ=0.137 kg·m^{-1}·s^{-1} Γ=0.164 kg·m^{-1}·s^{-1}

Fig.9 Comparison of circumferential temperature between water and 10% glycerol solution

4.Conclusions

In this paper, experimental study was carried out to investigate the falling film flow characteristics and heat transfer characteristics of horizontal tubes. The influence of the spray liquid temperature, spray density and glycerin content on falling film flow pattern and tube wall temperature distribution were studied, and the following conclusions can be obtained.

(1) Under the same temperature, as the spray density increases, the liquid film is converted from a droplet flow to a columnar flow and then to a "Γ" shape flow. Finally, it evolves into a column-sheet flow and then develop into a sheet flow

(2) The critical spray density of the flow pattern conversion will reduce with the spray liquid temperature increasing.

(3) The viscosity of the 10% glycerol solution is bigger than that of water, so that the flow resistance outside the tube wall is larger and the flow rate is smaller. Therefore, the critical spray density for flow pattern conversion is bigger than that of water.

(4) Under the same spray temperature, the tube wall circumferential temperature increased with the increase of spray density. The tube wall circumferential temperature decreased with the increase of the circumferential angle in the range of the circumferential angle from 0° to 135° and rose slightly from 135° to 180°.

(5) Under the same experimental conditions, the viscosity of glycerol solution is higher than water and the isobaric specific heat capacity is smaller than water so that the tube wall circumferential temperature of water is higher than that of the 10% glycerol solution.

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REFERENCE

[1] A. Maciver, S. Hinge, B.J. Andersen, J.B. Nielsen. New trend in desalination for Japanese nuclear power plants, based on multiple effect distillation, with vertical titanium plate falling film heat transfer configuration. Desalination, 2005, 182: 221–228.

[2]Y. Fujita, M. Tsutsu.i. Evaporation heat transfer of falling films on horizontal tube-part 2, experimental study. Heat Transfer, 1995, 24(1): 17-31.

[3] X.F. Wang, M.G. He, K. Lv, et al. Effects of liquid supply method on falling-film mode transitions on horizontal tubes. Heat Transfer Engineering, 2013, 34(7): 562-579.

[4]W.M. Yan, C.W. Pan, M. Ghalambaz. Experimental study on fluid flow and heat transfer characteristics of falling film over tube bundle. International Journal of Heat and Mass Transfer, 2019, 130: 9–24.

[5]C.Y. Zhao, W.T. Ji, et al. Hydrodynamic behaviors of the falling film flow on a horizontal tube and construction of new film thickness correlation. International Journal of Heat and Mass Transfer, 2018, 119: 564–576.

[6]L. Pu, Q. Li, X.Y. Shao, et al. Effects of tube shape on flow and heat transfer characteristics in falling film evaporation. Applied Thermal Engineering, 2019, 148: 412–419.

[7] D. Jige, H. Miyata, N. Inoue. Falling film evaporation of R1234ze(E) and R245fa on a horizontal smooth tube[J]. Experimental Thermal and Fluid Science, 2019, 105: 58–66.

[8]D.Gstoehl, J.F. Roques, et al. Measurement of falling film thickness around a horizontal tube using a laser measurement technique. Heat Transfer Engineering, 2004, 25(8): 28-34

[9] Nusselt. Die oberflachenkondensation des wasserdamqfes. Zeitschrift Verein Deutscheringenieure, 1916, 60: 541-546, 569-575.

[10] F. Sun, S.L. Xu, Y.Gao. Numerical simulation of liquid falling film on horizontal circular tubes. Frontiers of Chemical Science and Engineering, 2012, 6(3): 322-328.

[11] Y.S. Zhang, D.W. Wang, Y. Liu, et al. Distribution characteristics of falling film thickness around a horizontal corrugated tube. International Journal of Heat and Mass Transfer, 2020, 154: 119773.

[12]N. Giannetti, A. Rocchetti, et al. Irreversibility analysis of falling film absorption over a cooled horizontal tube. International Journal of Heat and Mass Transfer, 2005, 88, 755–765.

[13]S.L. Liu, et al. Experimental study on droplet flow of falling film between horizontal tubes[J]. International Journal of Multiphase Flow, 2019, 118: 10–22.

[14]S. Ben Jabrallah, A.S. Cherif, et al. Experimental study of the evaporation of a falling film in a closed cavity. Desalination, 2005, 180: 197-206.

[15] M. Hassani, R. Kouhikamali. Heat and mass transfer modeling of R-245fa and R1233zd(E) with concurrent boiling and convective evaporation in falling film applications. International Journal of Refrigeration, 2020, 117: 181–189.

[16] R. Manouchehri, M. R. Collins. An experimental analysis of the impact of temperature on falling film drain water heat recovery system effectiveness. Energy and Buildings, 2016, 130: 1–7.

[17] J. Hao, Y. Xu, T. He, N. Mao, M. Song, J. Tang. Numerical study on heat transfer of oily wastewater spray falling film over a horizontal tube in a sewage source heat pump. International Journal of Heat and Mass Transfer, 2019, 142, 118423.

[18] N. Mao, J. Hao, Y. Xu, M. Song, J. Tang. A numerical study on non-uniform characteristics of spray falling heat transfer over horizontal tubes in an oily sewage source heat pump. International Journal of Heat and Mass Transfer, 2020, 154: 119679.

[19] N. Mao, J. Hao, T. He, Y. Xu, M. Song, J. Tang. Unsteady heat transfer properties of spray falling over a horizontal tube in an oily sewage source heat pump. Applied Thermal Engineering, 2020, 179, 115675.