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Technical Note

Heat transfer performance of lithium bromide solution in falling film generator

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ABSTRACT

An experimental investigation of vertical in-tube falling film heat transfer with different heat fluxes and concentrations of lithium bromide solution were conducted. The experiments show that the heat transfer coefficient increases with the decrease of inlet concentration and significantly increase with heat flux increase. An experimental correlation of falling film heat transfer coefficient is obtained:

$$h_m = 129.7712 W_{in}^{-0.8058} q_w^{0.2422} Re^{-0.0856}$$

The comparison of falling film generator with immersed tube generator shows that the heat transfer coefficient is 4.37 times higher than that of immersed tube generator, which can significantly reduce the volume of the falling film generator. The volume of falling film generator is only 52.1% of the volume of immersed tube generator.

1. Introduction

When a gas medium from waste heat sources flows in the tubes of immersed tube generator of lithium bromide absorption chiller, the gas convection heat transfer process inside the immersed tube is the dominant thermal resistance of immersed tube generator. Currently, the heat transfer enhancement through extended area inside tubes is quite difficult. In order to more effectively design the lithium bromide absorption chiller, more heat transfer area is needed to achieve the required heat transfer in the immersed tube generator. The lower heat transfer coefficient and heat flux will result in use of an extra heat transfer tube, which has a larger generator volume. The higher liquid column in the generator is caused by the larger generator volume. In turn, this will worsen the heat transfer performance of generator. To increase the heat transfer performance and design a more compact generator, a vertical in-tube falling film heat transfer [1] is experimentally investigated in this paper. The falling film lithium bromide solution inside the vertical tubes is heated by heat source of gas flowing across the tubes with extended fins along the outer surface. The heat transfer performance of generator can be significantly enhanced by incorporating the finned surface on the outside of the vertical tubes.

Falling film heat transfer has been widely utilized in the chemical engineering and desalination industries. Relevant research has been performed in this area; however, most research previously conducted is analytical. There are comparatively few experimental investigations performed on this type of heat transfer [2]. Chun and Seban [3] conducted falling film evaporation heat transfer experiments of water on the outside surface of vertical tube and published important experimental data. So far, the experimental data have been used by many investigators to validate the theoretical simulations of falling film heat transfer. In Struve's [4] experiment of R11 refrigerant, falling film evaporation inside vertical tube, the relations of local heat transfer coefficient and heat flux, velocity and local thickness of falling film are correlated. The heat transfer test of water falling film inside a vertical tube carried out by Fujita and Ueda [5] shows that increasing *Re* number of laminar falling film flow results in an insignificant decreasing of the heat transfer coefficient. Chen et al. [6] investigated the effect of falling film mass transfer to the heat transfer coefficient; the results reveal that the effect is determined by the range of "Bubble Point" temperature of lithium bromide solution, i.e., the concentration of lithium bromide solution is the key factor to the heat transfer coefficient. Philipp Adomeit etc. [7] measured the velocity distribution, thickness and surface wave of water falling film through particle image velocity (PIV). This research also demonstrates that the falling film can have a higher heat transfer coefficient in lower heat flux.

The performance of lithium bromide falling film evaporation heat transfer is seldom found in literature. In order to better understand the characteristics of lithium bromide falling film evaporation process, an experimental test of laminar falling film evaporation for lithium bromide solution is carried out in this research under the conditions of heat flux q_w = 1025 kW/m^2–25 kW/m^2 and inlet concentration of lithium bromide solution W_{in} = 49.5–58%.

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Nomenclature

A	area, m^2
h	heat transfer coefficient, W/(m2·K)
H	enthalpy, J/kg
K	overall heat transfer coefficient, W/(m2·K)
L	tube length, m
M	mass flow rate, kg /s
m	weight, kg
N	number of the heat transfer tubes
P	pressure, Pa
q	volume flow rate, ml/s
q_w	heat flux, W/m^2
Q	heat flow rate, W
R	radius, m
Re	Reynolds number
S_f	fine spacing, m
T	temperature, K
V	volume, m^3
W	concentration of the solution,%

Greek letters

Γ	mass flow rate per unit tube circumference of the inner wall, kg/(m s)
δ	thickness, mm
ε_r	relative error
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s

Subscripts

f	fin
g	gas
i	inside surface
in	inlet
l	heat loss
m	solution film, mean
o	outside surface
out	outlet
s	steam
t	tube wall

2. Experimental setup and condition

2.1. Experimental setup

Fig. 1 is the diagram of the experimental setup for vertical in-tube falling film evaporation heat transfer test of lithium bromide solution. To prevent corrosion 1Cr18Ni9Ti stainless steel is used as the test tube and container of lithium bromide solution. The falling film evaporation test tube has an outside diameter of Φ25 mm with 2 mm wall thickness and heating length of 760 mm. There are 12 insulated NiCr–NiSi thermocouples of Φ0.2 mm diameter are mounted on the isothermal surface of test section and each thermal couple keeps more than 20 mm touched length on the wall. The spacing between thermal couples is 60 mm in axial direction and 90° along circumferential direction. In the upper container the saturated state of lithium bromide solution is maintained by an electric heater and the saturated temperature is also monitored by a thermocouple. The temperature signals from the thermocouples are recorded by a computer through Agilent 34970A.

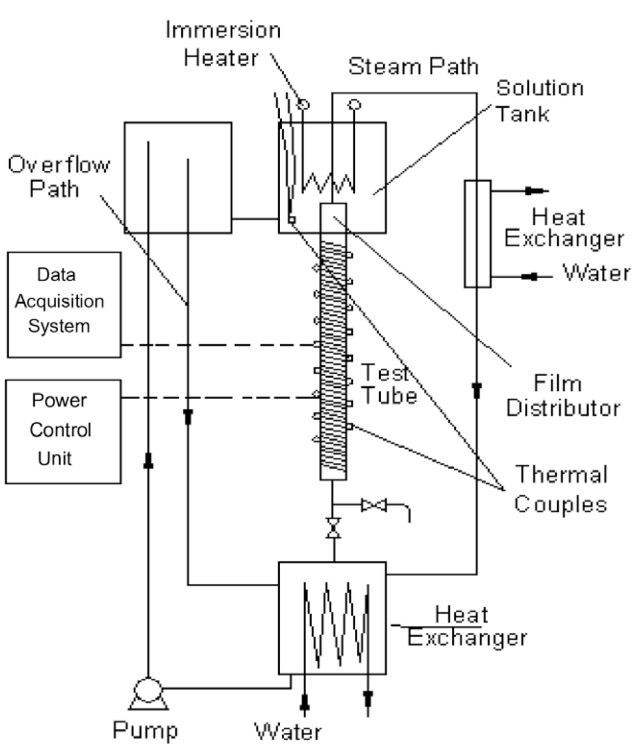

Fig. 1. Experimental setup.

Fig. 2 shows the schematic of the film spreader. The steam and liquid solution is sealed hermetically by two matching conical surfaces and spread in the gap between the film spreader and the annular tube. The film flows downward along the wall inside the test tube. The perpendicularity of test tube is calibrated to ensure uniform film spreading along the circumference. The mass flow rate is controlled through adjusting the level of liquid solution in the upper container and the falling film is heated by an electric heater wrapped on the outer surface of test tube.

2.2. Experimental conditions

The experimental conditions are listed in Table. 1.

3. Experimental results

In the falling film evaporation experiments, it is essential to keep the liquid film on the tube wall stable and to have uniform film thickness. If the film spreader is not perpendicular to the table or the annular gap is partially blocked, the wall of the test tube would locally dry out because of uneven film spreading and the temperature around the dry area on the wall will higher than the temperature around the wet area. Therefore, the wall temperature is monitored through the thermal couples attached on the wall before the test. When the temperature differences between the thermocouples exceed a certain value, the annular gap has to be cleaned and the perpendicularity of film spreader and test tube has to be calibrated to maintain uniform film spreading. In the experimental test the recorded parameters include the inlet flow rate and temperature of lithium bromide solution, the outside wall temperatures of test tube, the outlet temperature of lithium bromide solution and the input heat through electric heater.

The energy balance is also performed before conducting the test to ensure the reliability of the experimental data. The heat loss is

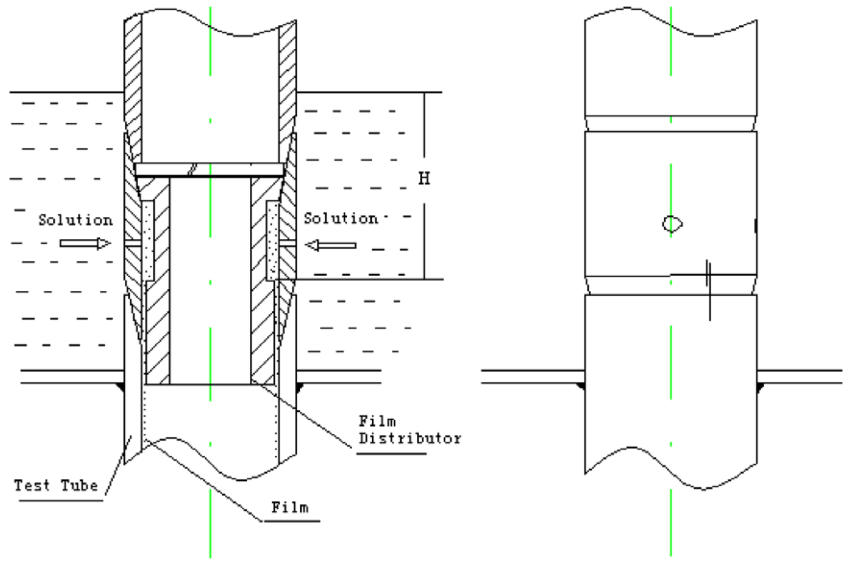

Fig. 2. Schematic of film spreader.

Table 1
Experimental conditions.

Item	Symbol (unit)	Value
Inlet concentration	W_{in} (%)	49.5–58
Heat flux	q_w (W/m^2)	10,000–25,000
Volume flow rate	q (ml/s)	7–14
Pressure	P (Pa)	9725

calculated by Eq. (1), which is derived from mass and heat energy balance equations.

$$Q_l = Q_o + M_{out}(H_s - H_{out}) + M_{in}(H_{in} - H_s) \quad (1)$$

where Q_o is heat input, M_{in} is inlet mass flow rate and M_{out} is the outlet flow rate. The inlet mass flow rate M_{in} is obtained from the measured the mean volume flow rate and corresponding density of solution. And the outlet flow rate M_{out} is obtained through the mass equilibrium calculation under the outlet temperature of solution.

The calculated heat losses from Eq. (1) are less than 4.2% of heat input. According to qualitative analysis, the relative error is large when the heating load is low and the working temperature is high. In the experiments, the heat loss from the surface of insulation wrapped on the outside surface of test tube is also calculated by using the natural convection heat transfer correlation in finite space. For the condition of lowest heat input 501.51 kW and 26.1 °C ambient temperature, the measured surface temperature of insulation is 34.5 °C and the heat loss is $Q_l = h_o A_o \Delta t$ = 16.369 W which is only 3.3% of the heat input. This result is very close to the calculated heat losses from Eq. (1). It can be concluded that the experiment design is reasonable. Based on the accuracy of instruments used in the test and test range of parameters, the relative discrepancy of average heat transfer coefficient for falling film evaporation in the tube from error analysis is as follows:

$$\varepsilon_r(h) = \varepsilon_r(Q_o) + \varepsilon_r(A) + \varepsilon_r(\Delta T) = 0.65\% \quad (2)$$

where $\varepsilon_r(Q_o)$ is relative error of heat input, $\varepsilon_r(A)$ is relative error of area, $\varepsilon_r(\Delta T)$ is relative error of temperature measurement on the outside surface of test tube. We can calculate the relative errors based on the instrument precision. The results are as follows, $\varepsilon_r(Q_o) = 0.62\%,\ \varepsilon_r(A) = 0.01\%,\ \varepsilon_r(\Delta T) = 0.02\%$.

It shows that the relative discrepancy of experimental data resulting from measuring errors of instruments is acceptable, and the results from experiments are dependable.

$$\text{Outside wall temperature of test tube}: \ T_o = \frac{\sum_{n=1}^{12} T_n}{12} \quad (3)$$

$$\text{Inside wall temperature of test tube}: \ T_i = T_o - \frac{q_w \ln\frac{R_o}{R_i}}{2\pi\lambda_w L} \quad (4)$$

$$\text{Heat transfer coefficient}: \ h_m = \frac{Q_w}{A_i \Delta T} = \frac{Q_o - Q_l}{A_i(T_i - T_m)} \quad (5)$$

where T_n (n = 1, 2, 3, ..., 11, 12) is the measured temperature of individual thermal couple on the outside wall of the test tube and T_m is mean temperature of the in-tube solution.

Fig. 3 shows the effect of the inlet concentration W_{in} of lithium bromide solution to the heat transfer coefficient h_m of falling film evaporation as the volume flow rate q = 7 ml/s. It can be concluded from the figure that when increasing inlet concentration W_{in} of lithium bromide solution, the heat transfer coefficient h_m of falling film evaporation decreases for different condition of heat flux. Under the condition of same falling film flow rate and same heat flux

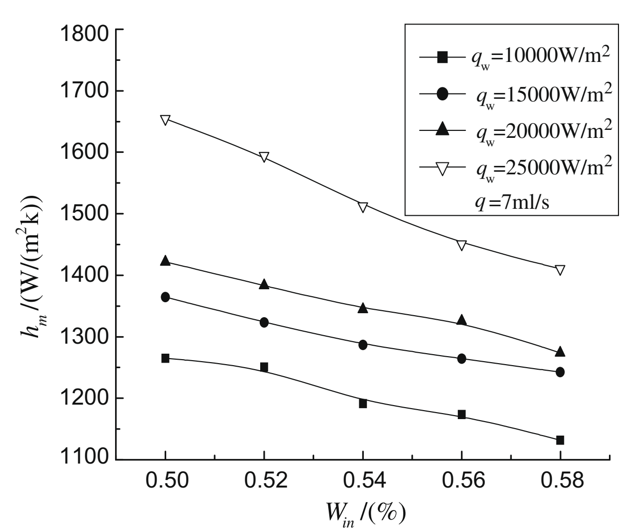

Fig. 3. h_m–W_{in} relation with different heat flux.

the higher the inlet concentration the lower the conductivity and mass diffusivity of lithium bromide solution, the viscosity and surface tension of lithium bromide solution will also become larger, while the fluidity of lithium bromide solution will become weaker. As a result, the heat transfer coefficient of falling film evaporation decreases as the inlet concentration of lithium bromide solution increases.

Fig. 4 shows the relationship between the heat transfer coefficient h_m of falling film evaporation and the heat flux q_w with different inlet concentrations W_{in} of lithium bromide solution. It can be seen in the figure that the changing trend of the heat transfer coefficient h_m of falling film evaporation with heat flux q_w for different inlet concentration is the same, i.e. the heat transfer coefficient h_m of falling film evaporation rises when the heat flux q_w increases. As the heat flux increases, the increase of the heat transfer coefficient becomes more significant. It is because increasing the heat flux results in more solution evaporation, thinner film thickness, larger superheat temperature of solution on the wall, smaller solution viscosity, higher velocity of film flow and larger mass diffusivity. It is worthy to note that the increase of the heat transfer coefficient is nearly constant when heat flux is between 10,000 W/m^2 and 20,000 W/m^2.The increase of heat transfer coefficient between 20,000 W/m^2 and 25,000 W/m^2 is more significant than that between 15,000 W/m^2 and 20,000 W/m^2, especially, for lower solution concentration. The phenomenon described above could be caused by altering the heat transfer mechanism. In the test tube, the heat transfer could undergo the transition from surface evaporation to nucleate boiling. There probably exists a heat flux at which the surface heat transfer of falling film in the tube starts the change from evaporation to nucleate boiling. However, this needs to be investigated further.

Fig. 5 shows h_m–q correlation with different heat flux curves in the condition of W_{in} = 49.5%. As shown in Fig. 5, h_m decreases and then increases at the point about q = 9.5 ml/s. It was explained in Ref. [5] that heat transfer coefficient decreases with the increase of Re number in low Re number; this is consistent with our experimental result. Defining $Re = \frac{4\Gamma}{\mu}$ in this experiment, the range of Reynolds number is from 287 to 770 (Re < 1600), which is in the laminar flow region [3]. Because the density and viscosity of LiBr solution are relatively high, the experimental Re is limited in deviation. For the purpose of generator design, the experimental data are correlated to a formula for the convenience of utilization. Since

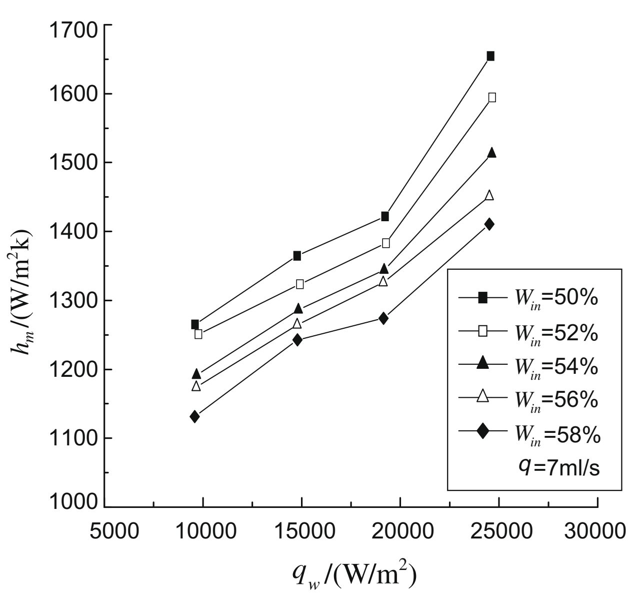

Fig. 4. h_m–q_w relation with different inlet concentration W_{in}.

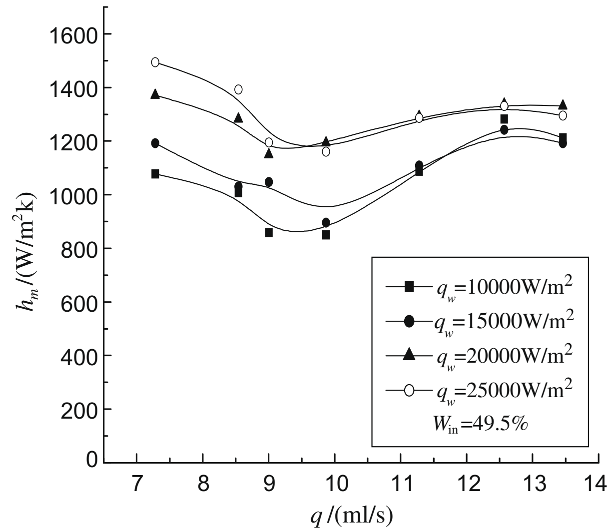

Fig. 5. h_m–q relation with different heat flux.

heat flux and inlet concentration of solution are the dominant effects in the heat transfer coefficient in this region [4,6], it is reasonable to correlate the effects mentioned above by including Reynolds Number Re into following equation:

$$h_m = aW_{in}^b q_w^c Re^d \tag{6}$$

By using the method of multivariate linear regression analysis, the regression coefficients in the equation obtained from the experiment are: a=129.7712, b=–0.8058, c = 0.2422 and d = –0.0856. Therefore, under the experiment condition in this investigation the correlation for the heat transfer coefficient of falling film evaporation in vertical tube can be written as:

$$h_m = 129.7712 W_{in}^{-0.8058} q_w^{0.2422} Re^{-0.0856} \tag{7}$$

In the significance testing of above correlation, the F value is 102.6069 and multiple correlation coefficient R value is 0.9524. These values show that the experimental correlation Eq. (7) is dependable, and it can be used for the design of generator of falling film evaporation in tubes.

4. The performance comparison of in-tube falling film generator and immersed tube generator

For comparison the design calculations are conducted for in-tube falling film generator and immersed tube generator, respectively. Flue gas is used as the heat source in both generators. The design parameters are: the flow rate of flue gas is 49,800 Nm^3/h; the inlet and outlet temperatures of flue gas are 170 °C and 150 °C; the outside diameter d_o and thickness δ_t of the tubes for falling film generator are 0.025 m and 0.002 m and the fin spacing S_f and fin thickness δ_f on the outside surface of tubes for falling film generator are 0.01 m and 0.0015 m; the outside diameter and thickness of the tube for immersed tube generator are 0.038 m and 0.003 m. The heat transfer coefficient of falling film evaporation in vertical tubes is calculated from the correlation Eq. (7) since the Reynolds number of the falling film flow in this design is 552 which is in the laminar region of the experiment. And the heat transfer coefficient outside the immersed tubes is calculated by using the recommended correlation in Ref. [8]. The design calculation results of both generators are compared in Table. 2.

From Table. 2, it can be seen that the heat flux of immersed tube generator is much lower due to the low heat transfer coefficients on both sides of flue gas convection on the inside surface of the

Table 2
Performance comparison.

Item	Symbol	Unit	Falling film	Immersed tube
Heat transfer	Q	W	388,880.73	
Inlet temperature of solution	T_{in}'	°C	81.15	
Outlet temperature of solution	T_{out}''	°C	87.60	
Inlet concentration of solution	W_{in}	%	56	
Outlet concentration of solution	W_{out}	%	59	
Logarithmic mean temperature difference	ΔT_m	°C	75.42	
Heat flux	q_w	W/m^2	19610	3900
Heat transfer coefficient of solution side	h_m	$W/(m^2 K)$	1323	608
Heat transfer coefficient of flue gas side	h_g	$W/(m^2 K)$	381.39	66.72
Overall heat transfer coefficient	K	$W/(m^2 K)$	262.07	59.58
Heat transfer area	A_o	m^2	19.826	86.542
Length of heat transfer tube	L	m	2.3	0.98
Number of heat transfer tubes	N		130	878
Weight of heat transfer tubes	m	kg	726.31	2274.5
Volume of generator	V	m^3	1012	1.9404

tubes and evaporation on the outside surface of the tubes. The heat transfer coefficients on both sides of flue gas convection on the outside finned surface of the vertical tubes and falling film evaporation on inside surface of the vertical tubes for in-tube falling film generator are much higher than the corresponding ones of immersed tube generator. The overall heat transfer coefficient of in-tube falling film generator is 4.37 times higher than that of immersed tube generator. The weight of heat transfer tubes in in-tube falling film generator is 31.93% of that in immersed tube generator and the volume of in-tube falling film generator is 52.1% of that of immersed tube generator. This comparison exhibits the excellent performance of in-tube falling film generator. It will benefit from energy saving when utilizing in-tube falling film generator in lithium bromide absorption chiller for waste heat recovery of flue gas.

5. Conclusion remarks

The experimental correlation Eq. (7) of in-tube falling film heat transfer coefficient for laminar flow of $Re < 600$ is obtained. The performance comparison of in-tube falling film generator and immersed tube generator exhibits the excellent performance of in-tube falling film generator. Using this type of generator driven by a low grade heat source is an improvement on refrigeration technology, which will bring great economic benefits. The in-tube falling film generator in lithium bromide absorption chiller can be widely applied to recover waste heat from flue gas.

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