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HEAT TRANSFER CHARACTERISTICS OF AMMONIA-WATER FALLING FILM GENERATION OUTSIDE A VERTICAL TUBE

by

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A heat transfer experimental of vertical out-tube falling film was conducted with different inlet spray density of ammonia-water solution and inlet hot water temperature. The inlet liquid mass concentration was selected as 60% of ammonia. The experiments showed that the overall heat transfer coefficient increases with the increase of inlet spray density and a maximum overall heat transfer coefficient could be obtained in an optimum spray density of ammonia-water solution, Γ, between 0.26 and 0.29 kg/ms. The generation of ammonia vapor outside the vertical falling film had a similar trend with the overall heat transfer coefficient basing on different spray density. The effect of hot water temperature difference, ΔT, on overall heat transfer coefficient showed that ΔT between 10 and 13 K is the optimum temperature difference of the vertical falling film generation.

Key words: *heat transfer performance, vertical falling film, generation, ammonia-water solution*

Introduction

The use of binary and ternary mixtures as a working fluid was strongly recommended to improve the system performance not only in generation cycles but also in combined cycles. The internal heat exchange owing to the temperature glide of a binary mixture provides the fundamental basis for the generation cycle such as generator absorber heat exchange (GAX) cycle [1] and the combined cycle [2]. Ammonia-water (NH_3-H_2O) solution pair was widely used in generator-absorption cycles because of its excellent thermal characteristics. It is also an attractive to ozone-depleting chlorofluorocarbon (CFC) and CO_2 emitting hydrofluorocarbon (HFC) used in conventional vapor compression systems. In both GAX and Kalina cycles, the generator is one of the most critical components from the viewpoint of size and performance. It has a complicated heat and mass transfer mechanism which influences the system performance significantly. To increase the heat transfer performance and design a more compact generator, a vertical out-tube falling film heat transfer was experimentally investigated in this paper. The ammonia-water solution in the film falling on the outside of the vertical tube was heated by hot water from boiler.

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Falling film heat transfer has been widely utilized in the chemical engineering. Relevant research has been performed in this area. However, most research previously conducted was analytical. There were comparatively few experimental investigations performed on this type of heat transfer [3]. Chun and Seban [4] conducted falling film generation 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. Kang *et al.* [5] studied the combined heat and mass transfer for NH_3/H_2O falling film absorption. In Shi's [6] experiment with $LiBr/H_2O$ solution, for falling film evaporation inside vertical tube, the relations of local heat transfer coefficient, heat flux, and inlet concentration were correlated. The heat transfer test of water falling film inside a vertical tube carried out by Fujita and Ueda [7] showed that increasing Reynolds number of laminar falling film flow results in an insignificant decreasing of the heat transfer coefficient. Xia *et al.* [8, 9] mathematically and experimentally investigated the capillary-assisted evaporation inside circumferential rectangular groove. In the capillary-assisted evaporation, the liquid film outside the tube was heated by the hot fluid inside the tube evaporates. Compared with the horizontal falling film for ammonia-water solution, this research demonstrates that the vertical falling film have a higher heat transfer coefficient in lower hot water temperature.

The performance of ammonia-water solution falling film generation heat transfer is seldom found in literature. In order to have an in-depth understanding of the process of the falling film evaporation, a set of experiments of vertical falling film for ammonia-water solution was carried out under the conditions of spray density, Γ, between 0.15 and 0.35 kg/ms and the inlet hot water temperature, T, between 343.15 K and 358.15 K.

Experimental methods and procedures

Experimental set-up

In the vertical 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 distributor is not perpendicular to the horizontal level or the annular gap is partially blocked, the wall of the test tube would locally dry out because of uneven film spreading, the temperature around the dry area on the wall will be higher than the temperature around the wet area. In the experimental test the recorded parameters include the inlet and outlet volume flow rate, the inlet and outlet temperature of ammonia-water solution, the generation pressure of the ammonia-water solution in test cell, the inlet and outlet temperature of hot water and the volume flow rate of hot water.

Schematics and picture of the experimental set-up are shown in figs. 1 and 2, respectively. Main components and all connections and valves are made of stainless steel. Teflon is used as a seal material. The test cell of falling film generation has a total height of 5 m, and is equipped internally with heating tube. Figure 1 gives schematic diagram of the experimental set-up. The test section is composed of two basic flow loops: the generation of high concentration ammonia-water solution outside the vertical falling film tube surface loop and hot water from boiler inside the vertical falling film tube loop. The generated ammonia steam is absorbed by the low concentration ammonia-water solution in the vertical falling film absorber. The heat loss of hot water transferring through the juncture of the shell to the ground and through the shell surface to the ambient may account for a considerably high percentage of the input heat. As a result, the thermal loss significantly influences the boiling heat transfer inside the generator. The shell of adiabatic material instead of metal material effectively impedes the heat loss to the ground. The polypropylene shell is thermally insulated with polytetrafluoro-
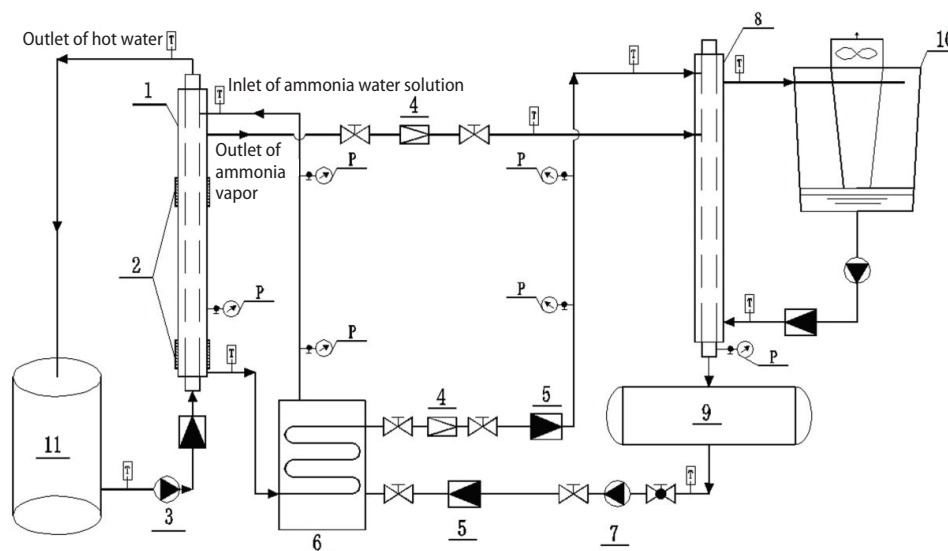
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Figure 1. Schematic diagram of the experimental set-up;
*1 – test section of vertical falling film generator, 2 – Pyrex sight glass, 3 – feed hot water pump,
4 – reduce pressure valve, 5 – flow meter, 6 – heat exchanger, 7 – feed ammonia-water solution
pump, 8 – vertical falling film absorber, 9 – feed ammonia-water solution tank, 10 – cooling tower,
11 – boiler. The points T and P represent thermocouple and pressure transducer, respectively*

ethylene to reduce the heat loss to the ambient. The volume of the vapor-liquid separator has to be sufficiently large to ensure that the liquid droplet in the mixture of the liquid and vapor can be separated by gravity. In this experiment the outside tube and inside tube of the test cell has an outside diameter of $\varnothing 57$ mm with 3.5 mm wall thickness and $\varnothing 25$ mm with 2.0 mm wall thickness respectively. For observing the state of falling film and adjusting the designed bottom position of the interface, the test cell is equipped with two Pyrex sight glass with 80 mm sight diameter.

Figure 2 gives the picture of the experiment, we have to observe the state of the inlet liquid for helping the ladder because the height of the actual experiment platform is 7.5 m. All of the tubes for hot water, cooling water and ammonia-water solution were insulated. Deviation of measurement data could not be avoided as the precision of measuring instruments.

Figure 3 shows the schematic of the film distributor. The working liquid through the tangential inlet and annular gap flows down along the outside vertical tube surface. The annular

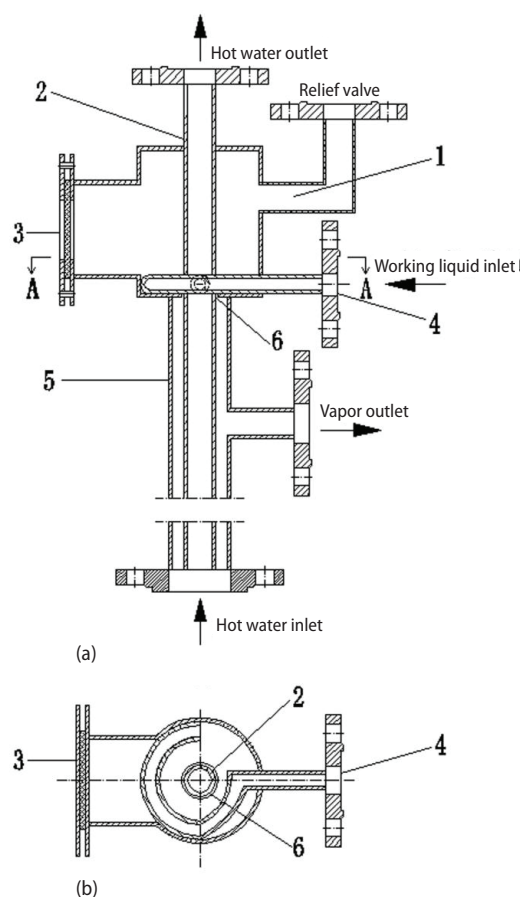**Figure 2. Picture of the experimental set-up**

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Figure 3. (a) Schematic of film distributor, (b) Schematic of A-A cross-section in the film distributor;
1 – distributor of vertical falling film, 2 – inside tube of the test cell, 3 – Pyrex sight glass, 4 – inlet of ammonia-water solution, 5 – outside tube of the test cell, 6 – annular gap

Figure 4. Phenomenon and values of the stationary system on a fixed point

gap is formed by the falling film test tube and the hole at the bottom of the falling film tank. Single-tube rotated 270° along the falling film tank wall was used in order to make the liquid flows into the falling-film tank tangentially, show in fig. 3(b), the perpendicularity of test tube is calibrated to ensure uniform film spreading along the circumference. The steam and liquid solution is sealed hermetically by two matching flanges. The film steady-state is judged by the phenomenon that the working liquid level is constant in the falling film tank, while the spray density is the same as the pumped working liquid amount in the falling film tank. The inlet working liquid volume flow rate is measured by electromagnetic flow-meter and adjusted by the control valve.

Figure 4 gives the experimental values on a fixed point, the interface of the ammonia-water solution is stationary by the Pyrex sight glass on the bottom of the test cell. There are generation pressure and outlet flow rate of ammonia-water solution. Value of generation pressure (236 kPa) for falling film and flow rate (1.03%) for outlet ammonia-water solution from the test cell fluctuates slightly.

Experimental conditions

The experimental conditions are listed in tab. 1.

Table 1. Experimental conditions

Item	Symbol	Value
Inlet concentration of ammonia water solution	ξ [%]	60
Inlet temperature of hot water	T [K]	343.15-358.15
Volume flow rate of ammonia water solution	Γ^* [kgm^{-1}s^{-1}]	0.15-0.35

$^*\Gamma = m_{in}/(\pi \cdot 0.025 \cdot 3600)$

Data analysis

The equations governing the processes occurring at each generator are the mass and energy balances, referring to the test cell in fig. 1. They can be stated as follows.
– mass balances, steady-state:

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$$m_{in} = W + m_{out} \tag{1}$$

– energy balances, steady-state:

$$Q + \frac{m_{in} h_{in}}{3.6} = \frac{m_{out} h_{out}}{3.6} + \frac{Wh'}{3.6} \tag{2}$$

– transfer equation:

$$h_\alpha A \Delta T_m = \frac{m_{out} h_{out} + Wh' + m_{in} h_{in}}{3.6} \tag{3}$$

So the overall heat transfer coefficient, h_α, is given by means of the following equation:

$$h_\alpha = \frac{m_{out} h_{out} + Wh' + m_{in} h_{in}}{3.6 \Delta T_m A} \tag{4}$$

Results and discussion

Figure 5 shows the influence of the inlet spray densities on the overall heat transfer coefficient, h_α, when the hot water flow velocity is 0.95 m/s. It can be concluded from the figure that when increasing inlet spray density of ammonia-water solution, the heat transfer coefficient, h_α, of falling film generation increases former and decreases later gently for different hot water inlet temperature from 343.15 to 358.15 K. A maximum overall heat transfer coefficient can be obtained in an optimum spray density between 0.26 and 0.29 kg/ms of ammonia-water solution. It is worthy to note that value of the overall heat transfer coefficient is about 2000 W/m²K when inlet spray density reached optimum value.

Figure 5. The h_α-Γ relation with different hot water inlet temperature

Under the condition of same hot water inlet temperature and less than optimum spray density, the higher the inlet spray density, the larger the conductivity and diffusivity of ammonia-water solution. On one hand, increasing the inlet spray density, there will be stronger waves and higher velocity of film flow. On the other hand, the wet effective area will increase when the inlet spray density increases, which increases the overall heat transfer coefficient. As a result, the overall heat transfer coefficient of falling film generation increases as the inlet spray density of ammonia-water solution increases. The trend agrees with Parizhskiy *et al.* [10] and Zeng *et al.* [11] for ammonia, Yang and Shen [12] for water.

On the contrary, under the condition of same hot water inlet temperature and more than optimum spray density, the higher the inlet spray density the smaller the overall heat transfer coefficients of ammonia-water solution. This can be explained: As spray density increases, leading to a thicker falling film, which determines the overall heat-transfer coefficient of the generation compared with the velocity of solution. As spray density increases, the falling film
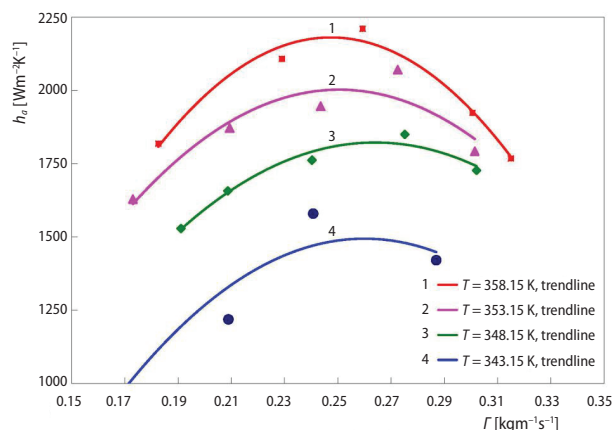
Figure 6. The *W-Γ* relation with different hot water inlet temperature
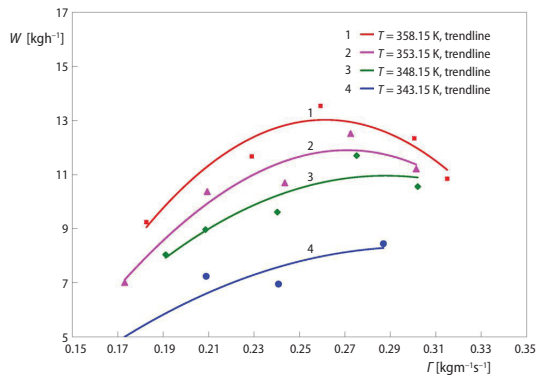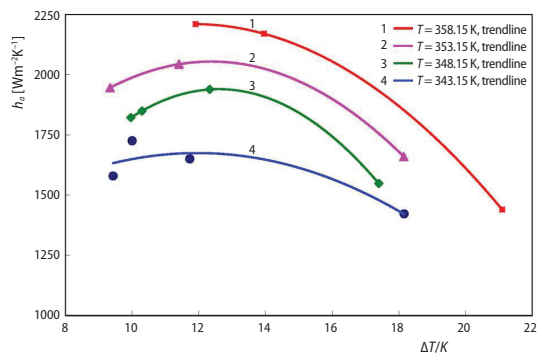
solution becomes a drip liquid, which results in a smaller effective wet area leading to lower overall heat transfer coefficients. Xu *et al.* [13] indicated the heat transfer coefficient on evaporation surface is determined by the thickness aspect when spray density exceeded optimum spray density, especially when the pipe diameter was relatively high.

It is shown in fig. 6 that the effect of the inlet spray densities to the ammonia vapor amount, W, with different hot water inlet temperature. It can be seen that a maximum account of ammonia vapor can be obtained in an optimum spray density of ammonia-water solution between 0.26-0.29 kg/ms. It is important to highlight that optimum spray density for ammonia vapor in fig. 6 corresponds to the value for maximum overall heat transfer coefficient in fig. 5. In the process of ammonia-water solution in the film falling on the outside of the vertical tube, the larger spray density the smaller ammonia-water solution concentration difference between inlet and outlet, which will lead to less ammonia vapor. Correspondingly, when reducing the spray density the concentration difference increases, but the amount of ammonia vapor will decrease because of less inlet spray density [14]. Therefore, the spray density has an optimum value for maximum ammonia vapor amount, W.

Figure 7 shows the relationship between the overall heat transfer coefficient, h_α, of falling film generation and the hot water temperature difference, ΔT, with different hot water inlet temperature, where the inlet concentrations and spray density of ammonia-water solution is fixed. As shown in fig. 7, h_α increases first and then decreases between $\Delta T = 10$ K and $\Delta T = 13$ K. It was explained in [15] that heat transfer coefficient decreases with the increase of ΔT in low number and then increases with high number which is presented in fig. 8, this is consistent with our experimental result. Figure 8 presented the variation of heat transfer coefficient with temperature difference the curve in fig. 8 was divided into three segments. The first was the low ΔT segment of AB, in which local heat transfer coefficient increased with an increase in ΔT as the function of $h_\alpha \propto \Delta T^{0.53}$. The BC segment for medium ΔT was in nucleate boiling state. Lo-

Figure 7. The *h*$_\alpha$-*ΔT* relation with different hot water inlet temperature

cal heat transfer coefficient in this segment was higher than that in the segment of AB because the bubbles generated around the surface of the tube stirred the feed water inside the vertical tube and intensify the heat transfer. The CD segment stands for high ΔT, which stayed in annular flow region. In this segment, the fluid absorbed the heat to evaporate through the liquid film around the tube inner surface by entire conduction. As the conductive resistance increased with an increase in ΔT, heat transfer coefficient reduced with an increase in ΔT.

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In this experiment, $\Delta T = 10\text{-}13$ K is considered as the optimum temperature difference of the vertical falling film generation. Due to low heat transfer temperature difference, the drag force of upstream is not able to impel the film to reach the top of the tube, therefore, only a part of the vertical tube surface involves in the heat transfer. Correspondingly, when increasing the temperature difference, the superheat degree increases and thermal efficiency decreases, which slightly reduces the overall heat transfer coefficient on generation outside surface.

Figure 8. Local heat transfer coefficient as a function of tube-inside temperature difference ($A_1B_1C_1D_1$ – high feed rate, $A_2B_2C_2D_2$ – medium feed rate, and $A_3B_3C_3D_3$ – low feed rate)

Error estimation

The estimation of errors is calculated for the experiment. Temperature and flow rate are the main measurement parameters. Overall heat transfer coefficient, h_α and ammonia vapor flow rate, W, are calculated by the measurement parameters indirectly. The relative error, δ, can be calculated based on the error transfer principle:

$$\delta_1 = \frac{h_R}{h_\alpha} = \frac{\sqrt{\left(\dfrac{\partial h_R}{\partial \Gamma} \mathrm{d}\Gamma\right)^2 + \left(\dfrac{\partial h_R}{\partial \Delta T} \mathrm{d}\Delta T\right)^2}}{h_\alpha} \times 100\%$$ (5)

$$\delta_2 = \frac{W_R}{W} = \frac{\dfrac{\partial W_R}{\partial \Gamma} \mathrm{d}\Gamma}{W} \times 100\%$$ (6)

The maximum relative error of h_α and W are 7.67% and 6.5% from the eqs. (5) and (6), which are permitted in actual project in China.

Conclusions

A vertical falling film generator was designed and installed to conduct experiments, which evaluates the influence of the inlet spray density and temperature difference on heat transfer performance. From the experimental observation and heat transfer data comparison, the following conclusions can be drawn.

Based falling film of vertical out-tube, the overall heat transfer coefficient of ammonia-water solution increases first and then decreases with the small spray density. A maximum overall heat transfer coefficient can be obtained in an optimum spray density between 0.26 and 0.29 kg/ms of ammonia-water solution. The value of overall heat transfer coefficient is about 2000 W/m^{2}K when inlet spray density reached optimum value. The generation of ammonia vapor in the vertical falling film has a similar trend with the overall heat transfer coefficient basing on the spray density. As a result, it is crucial to select a suitable spray density in the practical design.
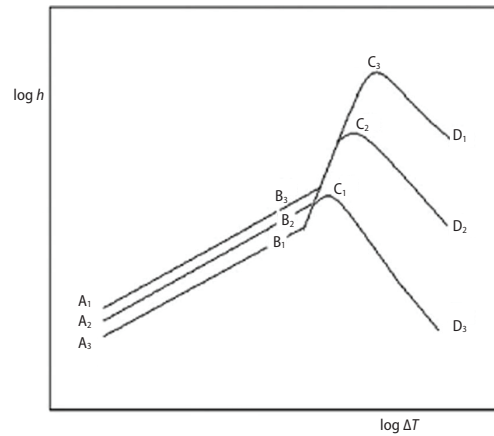
The overall heat transfer coefficient outside a vertical tube increases first and then decreases with ΔT. The ΔT between 10 K and 13 K is considered as the optimum temperature difference of the vertical falling film generation. Therefore, the vertical falling film generation is suitable for a wide range of driving temperature difference, which proves its superiority in utilizing low-grade surplus heating source.

Using this type of generator driven by a low grade heat source is an improvement on refrigeration technology and power cycle, which will bring great energy efficacy benefits. The falling film generator can be tried to apply in ammonia-water solution absorption chiller.

Acknowledgement

Nomenclature

A – heat transfer area, [m^2]
h – enthalpy of ammonia-water liquid per mass, [kJkg^{-1}]
h' – enthalpy of ammonia vapor per mass, [kJkg^{-1}]
h_R – overall heat transfer coefficient of trend line, [Wm^{-2}K^{-1}]
h_α – overall heat transfer coefficient of measurement, [Wm^{-2}K^{-1}]
m – liquid mass flow rate, [kgh^{-1}]
Q – heat flux of hot water, [W]
T – inlet temperature of hot water, [K]
ΔT – hot water temperature difference between inlet and outlet, [K]
ΔT_m – logarithmic temperature difference of the test cell, [K]
W – ammonia vapor flow rate of measurement, [kgh^{-1}]

W_R – ammonia vapor flow rate of trend line, [kgh^{-1}]

Greek symbols

Γ – inlet spray density of ammonia-water solution, [kgm^{-1}s^{-1}]
δ_1 – relative error for overall heat transfer coefficient, [%]
δ_2 – relative error for ammonia vapor flow rate, [%]
ξ – inlet concentration of ammonia water solution, [%]
$\Delta\xi$ – ammonia-water solution concentration difference between inlet and outlet, [%]

Subscripts

in   – inlet
out – outlet

Reference

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