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

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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 \( \Gamma \) between 0.26 and 0.29 \( \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \). 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 \( \Delta T \) on overall heat transfer coefficient showed that \( \Delta T \) between 10 and 13 K is the optimum temperature difference of the vertical falling film generation.

Keywords: heat transfer performance, vertical falling film, generation, ammonia water solution

1 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 solution pair was widely used in generator-absorption cycles because of its excellent thermal characteristics. It is also an attractive to ozone-depleting CFCs and CO\(_2\)-emitting HFCs 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.

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.

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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. Y.T. Kang et al. [5] studied the combined heat and mass transfer for NH\textsubscript{3}-H\textsubscript{2}O falling film absorption. In Shi’s [6] experiment of LiBr/H\textsubscript{2}O solution, falling film evaporation inside vertical tube, the relations of local heat transfer coefficient and heat flux and inlet concentration of falling film were correlated. The heat transfer test of water falling film inside a vertical tube carried out by Fujita and Ueda [7] showed that increasing Re number of laminar falling film flow results in an insignificant decreasing of the heat transfer coefficient. Xia [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 \( \Gamma \) between 0.15 and 0.35 kg·m\(^{-1}\)·s\(^{-1}\) and the inlet hot water temperature \( T \) between 343.15K and 358.15K.

### 2 Experimental methods and procedures

#### 2.1 Experimental setup

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.
Figure 1 Schematic diagram of the experimental setup: (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. T and P represent thermocouple and pressure transducer respectively.

Schematics and picture of the experimental setup are shown in figure 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 5m, and is equipped internally with heating tube. Figure 1 gives schematic diagram of the experimental setup. 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 PTFE (Polytetrafluoroethylene) 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 $\Phi 57$mm with 3.5mm wall thickness and $\Phi 25$mm with 2.0mm 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 80mm 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 7.5m. 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 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 figure 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 Phenomenon and values of the stationary system on a fixed point

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 percentage) for outlet ammonia water solution from the test cell fluctuates slightly.

2.2 Experimental conditions

The experimental conditions are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<tbody>
<tr>
<td>Item</td>
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<tr>
<td>Inlet concentration of ammonia water solution</td>
</tr>
<tr>
<td>Inlet temperature of hot water</td>
</tr>
<tr>
<td>Volume flow rate of ammonia water solution</td>
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</tbody>
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Where $\Gamma = \frac{m_{in}}{\pi0.025·3600}$

2.3 Data analysis

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

Mass balances, steady state:

$$m_{in} = W + m_{out} \quad (1)$$

Energy balances, steady state:

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

Transfer equation:

$$h_{ia}A\Delta T_m = \frac{m_{out}h_{out}+Wh'+m_{in}h_{in}}{3.6} \quad (3)$$

So the overall heat transfer coefficient $h_{ia}$ is given by means of the following equation:

$$h_{ia} = \frac{m_{out}h_{out}+Wh'+m_{in}h_{in}}{3.6A\Delta T_m} \quad (4)$$

3 Results and discussion
Fig. 5 shows the influence of the inlet spray densities $\Gamma$ on the overall heat transfer coefficient $h_\alpha$, when the hot water flow velocity is 0.95 m/s. It can be concluded from the figure that when increasing inlet spray density $\Gamma$ of ammonia water solution, the heat transfer coefficient $h_\alpha$ of falling film generation increases former and decreases later gently for different hot water inlet temperature $T$ from 343.15 to 358.15 K. A maximum overall heat transfer coefficient can be obtained in an optimum spray density $\Gamma$ between 0.26 and 0.29 kg·m$^{-1}$·s$^{-1}$ of ammonia water solution. It is worthy to note that value of the overall heat transfer coefficient is about 2000 w·m$^{-2}$·k$^{-1}$ when inlet spray density reached optimum value.

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 $\Gamma$ 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 increases. The trend agrees with Parizhskiy et al. [10] and Zeng et al. [11] for ammonia, Du et al. [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 follow: As spray density $\Gamma$ 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 $\Gamma$ increases, the falling film solution becomes a drip liquid, which results in a smaller effective wet area leading to lower overall heat transfer coefficients. Xu Li [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 figure 6 that the effect of the inlet spray densities $\Gamma$ 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 $\Gamma$ between 0.26-0.29 kg·m$^{-1}$·s$^{-1}$. It is important to highlight that optimum spray density $\Gamma$ for ammonia vapor in figure 6 corresponds to the value for maximum overall heat transfer coefficient in figure 5. In the process of ammonia water solution in the film falling on the outside of the vertical tube, the larger spray density $\Gamma$, the smaller ammonia water solution concentration difference $\Delta \xi$ between inlet and outlet, which will lead to less ammonia vapor. Correspondingly, when reducing the spray density $\Gamma$, the concentration difference $\Delta \xi$ increases, but the amount of ammonia vapor will decrease because of less inlet spray density $\Gamma$ [14]. Therefore the spray density $\Gamma$ has an optimum value for maximum ammonia vapor amount $W$. 

Figure 6 $W-\Gamma$ relation with different hot water inlet temperature $T$
Figure 7 $h_\alpha$-$\Delta T$ relation with different hot water inlet temperature $T$

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

Figure 8
In this experiment, $\Delta T = (10-13)$ 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.

4. Error estimation

The estimation of errors is calculated for the experiment. Temperature and flow rate are the main measurement parameters. Overall heat transfer coefficient $h_\alpha$ and ammonia vapor flow rate $W$ are calculated by the measurement parameters indirectly. The relative error $\delta$ can be calculated based on the error transfer principle.

$$\delta_1 = \frac{\frac{\partial h_\alpha}{\partial T} \Delta T^2 + \frac{\partial h_\alpha}{\partial \Delta T} \Delta \Delta T^2}{h_\alpha} \times 100\% \quad (5)$$

$$\delta_2 = \frac{\frac{\partial W}{\partial T} \Delta T}{W} \times 100\% \quad (6)$$

The maximum relative error of $h_\alpha$ and $W$ are 7.67% and 6.5% from the formula (5) and (6), which are permitted in actual project in China.

5. Conclusions remarks

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 $\Gamma$ between 0.26 and 0.29 kg·m$^{-1}$·s$^{-1}$ of ammonia water solution. The value of overall heat transfer coefficient is about 2000 W·m$^{-2}$·k$^{-1}$ 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 $\Delta T$. $\Delta T$ between 10K and 13K 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

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Nomenclature

- $A$ - Heat transfer area, [m$^2$]
- $Q$ - Heat flux of hot water, [W]
- $T$ - Inlet temperature of hot water, [K]
- $V$ - Hot water flow velocity, [m·s$^{-1}$]
- $W$ - Ammonia vapor flow rate of measurement, [kg·h$^{-1}$]
- $W_R$ - Ammonia vapor flow rate of trend line, [kg·h$^{-1}$]
- $h$ - Enthalpy of ammonia water liquid per mass, [kJ·kg$^{-1}$]
- $h'$ - Enthalpy of ammonia vapor per mass, [kJ·kg$^{-1}$]
- $h_R$ - Overall heat transfer coefficient of trend line, [W·m$^{-2}$·k$^{-1}$]
- $h_o$ - Overall heat transfer coefficient of measurement, [W·m$^{-2}$·k$^{-1}$]
- $m$ - Liquid mass flow rate, [kg·h$^{-1}$]
- $\Gamma$ - Inlet spray density of ammonia water solution, [kg·m$^{-1}$·s$^{-1}$]
- $\Delta T$ - Hot water temperature difference between inlet and outlet, [K]
- $\Delta T_m$ - Logarithmic temperature difference of the test cell, [K]
- $\Delta \xi$ - Ammonia water solution concentration difference between inlet and outlet, [%]
- $\delta_1$ - Relative error for overall heat transfer coefficient, [%]
- $\delta_2$ - Relative error for ammonia vapor flow rate, [%]
- $\mu$ - Dynamic viscosity, [kg·m$^{-1}$·s$^{-1}$]
- $\xi$ - Inlet concentration of ammonia water solution, [%]
Subscripts

in - inlet
out - outlet

Reference