Experimental study on overall heat transfer coefficient of sea water and fresh water for horizontal-tube falling film evaporator

Xingsen Mu, Gangtao Liang, Tianyu Zhang, Shengqiang Shen

Key Laboratory of Liaoning Province for Desalination, School of Energy and Power Engineering Dalian University of Technology, Dalian 116024, Liaoning, China

*Corresponding author: Shengqiang Shen, Corresponding email: muxingsen@dlut.edu.cn

Contact information
Xingsen Mu: email: muxingsen@dlut.edu.cn; Tel: +8613591366001
Shengqiang Shen: email: zzbshen@dlut.edu.cn; Tel: +8613050505853

ABSTRACT
In this paper, two sets of experimental devices has been established for studying the falling film evaporation outside a horizontal tube and condensation inside a horizontal tube, with freshwater and seawater as the experimental fluid. The rules of overall heat transfer coefficient (K) are elucidated by changing saturation temperature (T), Reynolds number (Re), total temperature difference (ΔT), inlet steam velocity (v_s) and vapor quality (x). Experimental results indicate that the overall heat transfer coefficient (K) increase first and then decrease with the increase of Re, the difference of K for fresh water and seawater goes smaller gradually. With the increase of T, K of fresh water increases but K of sea water decreases. The increase of ΔT leads to the decrease of K, while v_s has little effect on K. The growth of x contributes a lot to the increase of K. In the evaporator, x along the tube direction has main effect on K, and Re on tube row direction play main effect on K. in this experiment, the heat transfer coefficient in evaporator of fresh water distributes more equally.

KEYWORDS: horizontal-tube falling film; overall heat transfer coefficient; desalination; seawater; fresh water

1 INTRODUCTION
The desalination is efficient method to explore new fresh water sources, which has been considered as effective way to solve the shortage of fresh water. Low temperature multi-effect evaporation desalinaion has become one of primary methods in desalination technologies, with the advantages on stable operation, high desalinated water quality, utilizing low temperature heat sources and low cost. Horizontal tube falling film evaporation is the main technology of LT-MED with small temperature difference and high heat transfer coefficient, which has been widely used in refrigeration engineering, food processing, petrochemical engineering, etc.

The researchers have developed the researched on horizontal tube falling film evaporation for decades years, and many areas are fairly mature. But in the process of horizontal tube falling film evaporation it is quite difficult to measure the total heat transfer coefficient by experiments, when condensation inside tube and evaporation outside tube occur at the same time. The papers mentioned on total heat transfer coefficient are quite few, and the researchers selected different working liquids and parametric change interval make the results with large different.

Hu and Jacob[1], Yang[2], Zeng[3], have got the same results about the effect of spray Re on heat transfer, which the heat transfer coefficient outside tube (h_o) increases with the increase of Re. Fujita and Tsutsui[4,5] consider that h_o decrease first and then increase with the increase of Re. In the study of Mu[6], h_o increase first and then decrease with the increase of Re, on the effects of increasing the velocity and thickness of liquid film.

In the researches on effect of saturation temperature (T) on heat transfer, different experimental fluids make the results with large differences. Chang[7] selected refrigerating fluid of R141b as experimental fluid and Mu[8] ’s experimental fluid is sea water. They got the same result of h_o decrease with the increase of T. Armbruster[9], Parken[10], Mu[6] got the result is h_o increasing with the increase of T working with fresh water.

In the research on effect of total temperature difference (ΔT) on heat transfer, Fujita and Tsutsui[4], Hu and Jacob[1], Shen[11] consider that ΔT has no effect on h_o. Cavallini[12]’s research states that the increase of ΔT causes the thickness of condensation film increasing to make local h_i decreasing.

In the research on effect of inlet steam velocity (v_s) on heat transfer, Dobson[13] considered that the increase of v_s can enhance heat convection inside tubes, thereby local h_i and average h_i increase a bit little.
Studying on the effect of vapor quality ($x$) on heat transfer process, Hossaina[14] presents that $h_i$ decrease with the decrease of $x$ gradually. Grauso[15], Quiben[16], Jung[17] state that when $x>0.8$ $h_i$ increases a bit with the decrease of $x$.

About the liquid concentration effect: Fan [16] reported that the heat transfer coefficient did not depend on liquid concentration. His experiment used copper tube with diameter of 14mm, fresh water and seawater as experimental liquid, and the range of spray density is 0–0.13 kg/m s. Slesarenko [17,18] 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[19], Parken et al.[10], have significant discrepancies.

The researchers have developed many studies on inside and outside tubes heat transfer characters of horizontal tube falling film process. However it is necessary to combine the inside and outside tube experiments with same conditions, to discuss different factors influencing on total heat transfer coefficient, in order to understand the mechanism of horizontal tube falling film process.

2 Experimental process

2.1 Experimental devices

The overall heat transfer coefficient is calculated based on the results of the heat transfer coefficient of inside and outside tubes in two sets of experimental devices. Fig.1 shows the schematic diagram of experimental device for evaporation outside the horizontal tubes. It consists of a heating tank, a high position liquid feeder, a testing cell (evaporator), a metering pot and two double-pipe condensers.

Seawater is pumped into the high position liquid feeder when it is heated up to the index temperature for the experiment. The partitions and overflow zone are set in high position liquid feeder to keep the working fluids stable (Fig.1(2)). Then the fluid is directed toward the evaporator, passing by a rotor flow meter. Uniform spray has benefits to integrated liquid film outside the heat transfer tube surface, where the vaporization occurs. The vapor will subsequently turn into the condenser to be measured while the unevaporated brine will be discharged out of the system after passing through the measuring pot.

The test tube is made of HAL77-2A aluminum brass with outer diameter of 25.4 mm, inside diameter of 24 mm and length of 2000 mm. Heat flux is provided by an electric heater whose power ranges from 0 kW to 3 kW embedded inside the tube. The saturation temperature ($T$) and the spray Reynolds number ($Re$) in this experiment vary from 50°C to 70°C and 100 to 600, respectively. More details about this experimental device have been present in the paper of References [6].

![Fig.1 The schematic diagram of evaporation outside a horizontal-tube experimental device](image)

Fig.1 The schematic diagram of evaporation outside a horizontal-tube experimental device
1 heating tank 2 high position liquid feeder 3 evaporator 4 measuring pot 5 condenser

Fig.2 shows the schematic diagram of experimental device for condensation inside a horizontal tube. It is composed of a boiler, five test tubes in a horizontal line, vapor-liquid separator, two double-pipe condensers, a condensate tank and a cooling water tank.

The boiler serves to provide the steam for the whole experimental system. The steam exchanges heat with the cooling water flowing outside the tube, which is pumped from the cooling water tank. The utilized cooling water flows back to the cooling water tank after circulating. Subsequently, the steam-water mixture flows into the moisture separator to remove the condensation water and entrained water.
from the steam. The separated water is gathered in the reservoir, and flows back to the boiler for
recirculation through the pump ultimately.

The material is still HAL77-2A aluminum brass for the five test tubes, with outer diameter of 25.4
mm, the inner diameter of 24 mm and the length of 1800 mm same as above. The double pipe condenser
is used to replace falling film outside tube. These five test tubes compose five heat transfer test parts
while a 300 mm quartz glass tube is designed to observe the two-phase flow between every two test
tubes. The heat transfer performance of single test part was analyzed by comparing the ratio of steam
and fluid. The steam temperature, as conditions selected in this experiment, ranges from 45°C to 70°C,
and the velocity of inlet steam varies from 20m/s to 45m/s, as well as the inlet temperature difference
changes between 0.5°C and 2°C. More details about the experimental device have been stated in the
paper of References [20].

![Fig.2 The schematic diagram of condensation inside a horizontal tube experimental device](image)

The heat transfer coefficient of outside tube \( (h_o) \) and inside tube \( (h_i) \) are measured individually in
both experimental systems. The total heat transfer coefficient \( (K) \) is calculated by equation (1). The
parameters including spray density, inlet steam velocity, inlet steam pressure and vapor quality etc. are
changed to simulate the heat transfer process of bundles in experiments.

\[
K = \frac{1}{h_i \ln \frac{d_o}{d_i} + \frac{1}{2\lambda i} + \frac{1}{h_o}}
\]

1.2 Other details

The tube spacing with triangular pitch arrangement is about 2.25 times of the tube diameter.
The fresh water for the experiment is distilled water, while the seawater from the Yellow Sea in
China is adopted as the working fluid with a salinity of 3.4%. Tab.1 presents the main ion concentration
of the experimental seawater.

<table>
<thead>
<tr>
<th>Cation</th>
<th>Concentration (g/L)</th>
<th>Anion</th>
<th>Concentration (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N^+ )</td>
<td>13.99</td>
<td>( SO_4^- )</td>
<td>3.04</td>
</tr>
<tr>
<td>( K^+ )</td>
<td>0.21</td>
<td>( HCO_3^- )</td>
<td>0.14</td>
</tr>
<tr>
<td>( C^+ )</td>
<td>0.38</td>
<td>( B^- )</td>
<td>0.08</td>
</tr>
<tr>
<td>( M^+ )</td>
<td>3.46</td>
<td>( Cl^- )</td>
<td>21.6</td>
</tr>
</tbody>
</table>

The Reynolds number can be calculated by formula (2)

\[
Re = \frac{4\Gamma}{\eta}
\]

The uncertainty analysis is showed in Table 2.

<table>
<thead>
<tr>
<th>Position</th>
<th>Instrument</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation outside horizontal</td>
<td>Thermocouple</td>
<td>±0.05 °C</td>
</tr>
<tr>
<td></td>
<td>Rotameter</td>
<td>±1.5%</td>
</tr>
<tr>
<td>tubes</td>
<td>Testo 240 Conductivity measuring instrument</td>
<td>±1mg/L</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>Power governor</td>
<td>±0.5%</td>
</tr>
<tr>
<td></td>
<td>Pressure sensors</td>
<td>±0.2KPa</td>
</tr>
<tr>
<td>Condensation inside a horizontal tube</td>
<td>Thermocouples</td>
<td>±0.05℃</td>
</tr>
<tr>
<td></td>
<td>Pressure sensors</td>
<td>±28Pa</td>
</tr>
<tr>
<td></td>
<td>Differential pressure gauge</td>
<td>±1Pa</td>
</tr>
<tr>
<td></td>
<td>Gas flowmeter</td>
<td>±1%</td>
</tr>
<tr>
<td></td>
<td>Liquid flowmeter</td>
<td>±0.5%R</td>
</tr>
</tbody>
</table>

3 Experimental results and discussions

Considering different experimental parameters, such as \( Re, T, \Delta T, \nu_s \) and \( x \), the change of the overall heat transfer coefficient has been analyzed in the experiment. Specific parameters are shown in Tab.3. The dry-out area will occur in this experimental system with \( Re < 60 \) showing in our previous researches. Whereas, the heat tube is fully wetted visually because the minimum \( Re \) is significantly larger than 60 in this paper.

| Figure 3 | 166-544 | 60 | 1.25 | 30 | 0.8 |
| Figure 4 | 333     | 50-70 | 1.25 | 30 | 0.8 |
| Figure 6 | 333     | 60 | 1.25 | 20-45 | 0.8 |
| Figure 7 | 333     | 60 | 0.5-2 | 30 | 0.8 |
| Figure 8 | 333     | 60 | 1.25 | 30 | 0-1 |

3.1 Effect of Reynolds number on the overall heat transfer coefficient

Take saturation temperature is 60℃, inlet steam velocity is 30m/s, total temperature difference is 1.25℃ and dryness is 0.8 were chosen as the example, and figure 4 shows the curve of overall heat transfer coefficient varies with the \( Re \). The figure has shown that the overall heat transfer coefficients for fresh water and seawater increase with \( Re \) at the beginning, go smoothly and then get small decrement.

![Fig.3 The influence of Reynolds number (Re) on the overall heat transfer coefficient (K) with two experimental fluids](image)

The drop-let which has liquid drop impacting film with low frequency is mainly flow pattern when \( Re \) is small. The liquid film with weak fluctuation inside it is mainly affected by viscous force. With the increasing of \( Re \), the fluctuation of liquid film get stronger and effect of heat convection increases
gradually, therefore $K$ increases with the increment of $Re$ has occurred. However when $Re$ reaches to the critical value, the effect of the thickness of liquid film on heat diffusion resistance will counteract the effect of fluctuation of liquid film on enhancing convection heat transfer, and in this moment $K$ does not increase with the increment of $Re$. The value of $Re$ corresponding to the maximum value of $K$ is defined as the critical value ($Re_{cr}$). The effect of liquid film thickness on heat convection balances with the fluctuation of liquid film enhancing on convection. When the spray $Re$ is more than $Re_{cr}$, the thickness of liquid film increases further and heat diffusion resistance takes the leading role in heat transfer process, thus $K$ begins to decrease.

From the Fig. 3 it also shows that, the fresh water and seawater have similar $Re_{cr}$ around 450, but the difference between the $Re_{cr}$ of seawater and $Re$ of prior mark point is much higher than that of fresh water. It is found that in the previous experiment outside the tubes the $Re_{cr}$ of fresh water is a little higher than that of seawater. The similar $Re_{cr}$ for both fresh water and seawater is because that the interval of two mark points is a little larger, so that the $Re_{cr}$ cannot be defined accurately, only proximate mark point to $Re_{cr}$ can be got.

The $Re_{cr}$ of fresh water is higher than seawater is because that the heat transfer coefficient of seawater is smaller than fresh water, it means the thermal resistance has significant effect on heat transfer process, and the viscosity of seawater is higher than fresh water with same condition which states that the sea water has bigger thickness of liquid film and smaller wave. Therefore the $Re_{cr}$ of fresh water is higher than that of seawater.

Moreover, the figure shows that the total heat transfer coefficient of fresh water is higher than what of seawater which is combined impacted by the thickness of liquid film, amplitude of liquid film fluctuation, velocity of thermal diffusion and others. Because of the higher viscosity of fresh water than seawater with the same $Re$, the fluctuation of liquid film for fresh water is stronger which is advantaged to convection heat transfer. Furthermore the viscosity is smaller the thickness of liquid film for fresh water is thicker with the same $Re$. In additionally, when the evaporating temperature is 60°C, the thermal diffusion coefficient of fresh water is 1.59*10^{-7} m^2/s and seawater is 1.42*10^{-7} m^2/s. The thermal diffusion coefficient of fresh water is much higher than seawater which has significant benefits for the convection heat transfer process. On the whole with combined influence the overall heat transfer coefficient of fresh water is higher what of sea water.

### 3.2 Effect of saturation temperature on the overall heat transfer coefficient

The effect of saturation temperature on the overall heat transfer coefficient has been discussed under the conditions of Reynolds number 333, inlet steam velocity 30 m/s, total temperature difference 1.25 °C and vapor quality 0.8.
### Table 4 Thermal conductivity of seawater and fresh water [21]

<table>
<thead>
<tr>
<th>$T_{sat}$ (°C)</th>
<th>$\lambda$ of seawater (W/m°C)</th>
<th>$\lambda$ of freshwater (W/m°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.576</td>
<td>0.644</td>
</tr>
<tr>
<td>55</td>
<td>0.573</td>
<td>0.649</td>
</tr>
<tr>
<td>60</td>
<td>0.569</td>
<td>0.654</td>
</tr>
<tr>
<td>65</td>
<td>0.566</td>
<td>0.659</td>
</tr>
<tr>
<td>70</td>
<td>0.562</td>
<td>0.663</td>
</tr>
</tbody>
</table>

The figure 4 shows the distribution curve of heat transfer coefficient of fresh water and seawater varying with saturation temperature. The heat transfer coefficient of fresh water is proportional to saturation temperature. But an interesting phenomenon occurred when the seawater is selected as the experimental fluid, that the heat transfer coefficient is inversely proportional to saturation temperature. This is because the changing of heat transfer coefficient outside the tube. The heat conduction $\lambda$ of seawater decreases with $T$ (Table 4)[21]. Meanwhile, we can see from Fig. 5[22] that the surface tension increases with $T$ in this experimental conditions (the saturation temperature is 50-70 °C). There may be more than two reasons for this strange phenomenon.

### 3.3 Effect of inlet steam velocity on the overall heat transfer coefficient

The effect of inlet steam velocity on the overall heat transfer coefficient has been discussed under the conditions of Reynolds number 333, total temperature difference 1.25 °C and vapor quality 0.8.

![Fig.6 The influence of inlet steam velocity ($v_s$) on the overall heat transfer coefficient ($K$) with two experimental fluids](image)
Fig. 6 shows the influence of inlet steam velocity on the overall heat transfer coefficient ($K$) with two experimental fluids. In the outside tube, the increase of $v_s$ is caused the increment of heat flux, but in the previous study we have found that heat flux has little impact on $h_d[6]$. In the inside tube, the increase of $v_s$ contributes to the fluctuation of condensation water surface, which slightly enhances the heat transfer coefficient. With this situation, we can hardly use $K$ to represent the influence on heat transfer. Therefore, the effect of $v_s$ on $K$ can be ignored in this experiment. Also figure 6 has present that heat transfer coefficient of fresh water is bigger than that of seawater in this condition with same reason as pervious statement.

### 3.4 Effect of total temperature difference on the overall heat transfer coefficient

The effect of total temperature difference on the overall heat transfer coefficient has been discussed under the conditions of Reynolds number 333, inlet steam velocity 30 m/s and vapor quality 0.8.

![Fig.7 The influence of total temperature difference ($\Delta T$) on the overall heat transfer coefficient ($K$) with two experimental fluids](image)

Fig. 7 gives the relationship between total temperature difference ($\Delta T$) and the $K$ at 333 spray Re, 60 °C saturation temperature, 30 m·s⁻¹ inlet steam velocity and 0.8 dryness. As shown in Fig. 7, $K$ decrease with the increasing of $K$. $h_i$ for heat transfer inside tube is consisted of local heat transfer coefficient for steam region and local heat transfer coefficient for condensed liquid region.

With the increasing of $\Delta T$, the condensed water increases in steam region, and the thickness of liquid film covering on inside tube surface increases, also the thermal resistance will increase, so the local heat transfer coefficient of steam decreases. The temperature difference has a little impact on local heat transfer for condensed liquid region. In conclusion, $h_i$ decreases with the increase of $\Delta T$.

The increase of $\Delta T$ causes the increase of heat transfer amount for outside tube which causes the spray $Re$ for bottom row decrease in large scale evaporator with multi-row, that lead to the decrease of heat transfer coefficient. But the increase of heat transfer amount has little effect on $h_o$ in this experiment, which make the similar curves of heat transfer coefficient for fresh water and seawater in Fig.7. Overall, the increase of $\Delta T$ makes the decrease of $K$.

### 3.5 Effect of local vapor quality on the overall heat transfer coefficient

Figure 8 gives the distribution of heat transfer coefficient varying with local vapor quality($x$) with $Re$ is 333, steam inlet velocity is 30 m·s⁻¹, $\Delta T$ is 1.25°C and $T$ is 60°C.

It shows that $K$ increase with the increase of $x$. 
For the process of heat transfer inside the tube, ratio of steam region to condensate region is relative to \(x\), and it rises when \(x\) increases. In the previous study it is noticed that the local heat transfer coefficient of steam is obviously bigger than that of condensation. In this case \(h_i\) increases with the ratio increment, and \(K\) increase finally.

Additionally, the increase of condensation zone causes the increment of flow resistance for steam obviously, which restrains the processes of heat transfer and causes the increase of \(x\) with \(K\) increasing.

![Graph showing the influence of local vapor quality \(x\) on the overall heat transfer coefficient \(K\) with two experimental fluids](image)

**Fig. 8** The influence of local vapor quality \(x\) on the overall heat transfer coefficient \(K\) with two experimental fluids

4 Space distribution of the \(K\) in the evaporator

![Graph showing the comparison between calculated results and test results of \(h_o\)](image)

**Fig. 9** The Comparison between calculated results and test results of \(h_o\)
Fig. 10 The Comparison between calculated results and test results of $h_i$.

Fig. 11 Space distribution of the overall heat transfer coefficient ($K$) in the evaporator with freshwater.
According to the data from two experiment systems, different space distributions of the overall heat transfer coefficient ($K$) in the evaporator with three tube arrangements are calculated, respectively. The calculated results are matching well with experimental data, and the maximum error was 7% (Fig. 9, Fig. 10). The heat transfer tube bundle in the evaporator is composed of 50 columns and 100 rows. Each tube is made of aluminum brass with an outer diameter of 25.4 mm, inside diameter of 24 mm and length of 10000 mm. Three different tube arrangements are considered in the calculation respectively, with the other conditions, for instance, spray $Re$ of the tubes at the top of 333, saturation temperature of 60 °C, saturated steam inlet velocity of 30 m/s, temperature difference of 1.25 °C as well as inlet vapor quality of 1. The minimum $Re$ of bottom tubes in this evaporator is around 230, to make sure fully wetted of tubes.

Figure 11 and 12 has shown the distribution curve of $K$ in the evaporator for fresh water and seawater individually. The figures present that $K$ decrease along the tube direction continuously. The changes of $K$ for top row tube are determined by $x$ along tube direction, and the condensation occurs inside the tube continually. $x$ continues to decrease so $K$ decreases gradually.

$K$ for tubes except top one is influenced by amount of spray $Re$ and $x$ which continues to decrease along tube direction. But due to different amounts of evaporation along tube direction of top row tube, the farther distance is away from steam inlet the lower $K$ is and the less amount of evaporation became, which makes the amount of spray $Re$ increasing for lower row tubes.

When $Re$ is between 100 and 333, $K$ increases with the increase of $Re$ according to the previous studies. The combined effects on $K$ make it showing as decreasing trend along the tube direction.

It can be considered that, under conditions of this experiment, the effect of $x$ is greater than $Re$ on $K$.

Furthermore, $K$ also decreases along with the direction of growing tube rows. In the steam inlet region, $x$ remains the same with the increasing tube rows while $Re$ decreases because of the different evaporation outside the tube at the top row, which leads to the decline of $K$. For the other regions, the growing tube rows result in the rise of $x$ and the reduction of $Re$. In a word, it shows that under conditions of this experiment, $K$ is affected more by $Re$ than $x$ along with the direction of growing tube rows.

<table>
<thead>
<tr>
<th>Tab.5 Ratio of heat transfer coefficient of bottom row with top row in different positions for two experimental liquids.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region</strong></td>
</tr>
<tr>
<td>Inlet region</td>
</tr>
<tr>
<td>Middle region</td>
</tr>
<tr>
<td>Outlet region</td>
</tr>
</tbody>
</table>

Table 5 has given the ratio of heat transfer coefficient of bottom row with top row in different positions for two liquids in experimental condition. It presents that the percentage of decrement for heat transfer coefficient of fresh water along tube direction appears decreasing trend gradually and the amplitude of decrease becomes smaller.

The percentage of decrement for heat transfer coefficient of seawater also shows decreasing trend gradually but the amplitude of decrease becomes bigger. Figure 4 has given the reason of different amplitudes which is because the changing of heat transfer coefficient of fresh water is smaller than that
of seawater with the increase of spray density and the effect of \( Re \) on heat transfer coefficient for fresh water is smaller than sea water.

The table also gives that the decrease of heat transfer coefficient of fresh water at inlet is lower than seawater, and higher at medium and outlet. This is because the effect of \( Re \) on heat transfer coefficient for fresh water is smaller than sea water and the changing percentage of heat transfer coefficient for fresh water varying with \( x \) is small.

5 CONCLUSIONS

In this paper the fresh water and sea water have been selected as experimental liquids. The total heat transfer coefficient varying with different factors for two liquids have been compared according to the results of two experiments. Discussing the distribution of total heat transfer coefficient in evaporator for two liquids some main points can be drawn as following:

1. With the increase of \( Re \), \( K \) increase first and then decrease. And with the increase of \( Re \), the difference of \( K \) for fresh water and seawater goes smaller gradually.
2. With the increase of \( T \), \( K \) of fresh water increases but \( K \) of sea water decreases.
3. \( K \) becomes smaller gradually with the increase of \( \Delta T \).
4. Under conditions of this experiment, \( v_s \) has less effect on \( K \).
5. The \( x \) has significant effect on \( K \) and \( K \) increase with \( x \) increasing.
6. In the evaporator, \( x \) along the tube direction has main effect on \( K \), and \( Re \) on tube row direction play main effect on \( K \). In this experiment, the heat transfer coefficient in evaporator of fresh water distributes more equally.

6 NOMENCLATURE

<table>
<thead>
<tr>
<th>( K )</th>
<th>Total heat transfer coefficient (kW/ m(^2)℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h )</td>
<td>Heat transfer coefficient (kW/ m(^2)℃)</td>
</tr>
<tr>
<td>( Re )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( T )</td>
<td>Saturation temperature (℃)</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Temperature difference (℃)</td>
</tr>
<tr>
<td>( v_s )</td>
<td>Inlet steam velocity (m/s)</td>
</tr>
<tr>
<td>( x )</td>
<td>Vapor quality</td>
</tr>
<tr>
<td>( d )</td>
<td>Tube diameter</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Thermal conductivity</td>
</tr>
</tbody>
</table>

subscripts

| \( o \) | Outside tube |
| \( i \) | Inside tube |
| \( cr \) | Critical |

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