Heat transfer during pseudo-dropwise condensation of water-ethanol vapor mixture on horizontal finned tubes

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Heat transfer during pseudo-dropwise condensation of water-ethanol vapor mixture on horizontal finned tubes

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Abstract. In the present work experimental data on heat transfer are obtained for the condensation of almost immobile pure steam and water-ethanol vapor mixture on three copper horizontal finned tubes with a cooled length of 100 mm. The fins are rectangular in shape, their height and thickness are 1 mm, and the spacing between fins 1.3, 2.0 and 3.0 mm. The experiments were carried out at pressures of 0.12...0.15 MPa, the vapor-to-surface temperature difference varied from 5 to 35 K. The mass concentration of ethanol in the vapor phase varied from 8.7 to 14.5%. The experimental data are presented in the form of the dependences of heat transfer coefficient on the vapor-to-wall temperature difference. The heat transfer coefficients for the condensation of pure steam are in good agreement with the calculations by the method of Srinivasan et al. According to experimental data for the condensation of the vapor mixture, diffusion thermal resistance and thermal resistance of the liquid phase at various ethanol concentrations and the spacing between fins were calculated.

1. Introduction

Condensation of binary vapors of infinitely mixing liquids with very different surface tension coefficients due to Marangoni effect leads to a transition from film condensation to pseudo-dropwise, which, unlike the dropwise regime, occurs on the wettable heat transfer surface. With pseudo-dropwise condensation of vapor mixtures on smooth tubes and plates, the same order of heat transfer coefficients were obtained, as for dropwise condensation [1-5]. In most of studies, a water-ethanol vapor mixture was used, for which, with a small concentration of ethanol (about 1% in vapor phase), heat transfer coefficient in the pseudo-dropwise regime increases several times compared to the condensation of pure steam. The effect on heat transfer of the composition of vapor mixture, vapor-to-surface temperature difference, presence of non-condensable gas in the mixture, the velocity of the mixture, pressure and other factors were studied. However, only Ali et al. [6] studied heat transfer during pseudo-dropwise condensation of a water-ethanol vapor mixture on low-finned horizontal tube. Mass fractions of ethanol in vapor phase were 0.25 to 10%, range of vapor velocity at approach to the finned tube was 0.78 to 7.5 m/s. As a result of pseudo-dropwise condensation, a maximum heat transfer enhancement up to 3 times to that of pure steam was obtained.

All these studies were conducted for the pseudo-dropwise condensation of moving mixtures. From the point of view of practical applications and for the development of theory, it is necessary to study heat transfer during pseudo-dropwise condensation of immobile vapor mixtures on finned surfaces. In this paper we present the results of an experimental study of heat transfer in the case of pseudo-dropwise condensation of almost immobile water-ethanol vapor mixture on horizontal finned tubes.
2. Experimental setup

The experimental setup scheme of which is described in figure 1 allowed in the automated mode to collect and process primary data, and to obtain the dependence of the heat transfer coefficient on the vapor-to-wall temperature difference \( \Delta T = T_s - T_w \).

The setup consists of two closed circuits, the main and auxiliary ones. The main circuit includes a steam generator, a superheater and a test unit. By turning the test unit, it is possible to carry out experiments on both horizontal and vertical tubes. The auxiliary circuit consists of a thermostat with distilled water, a circulation pump, electromagnetic flowmeter and control valves. It is designed to remove heat from the test unit and is also associated with the automation system of the experimental setup. The pressure was maintained with high accuracy by means of a PID controller by changing the power of the steam generator. The thermostat was also controlled by a PID controller, with the wall temperature selected as the control parameter. This allowed us to obtain the dependence of the heat transfer coefficient on the \( \Delta T \) with a predetermined steps in the \( \Delta T \) during the experiment.

![Diagram of experimental setup](image)

**Figure 1.** Scheme of experimental setup: 1 - steam generator; 2 - superheater; 3 – test unit; 4 - thermostat; 5 - blowdown valve; 6 - circulating pump; 7 - flow valve; 8 - manometer; 9 - pressure sensor; 10 - thermocouple \( T_{\text{vapor}} \); 11 - platinum resistance thermometer \( T_{\text{outlet}} \); 12 - thermocouple \( T_w \), 13 - platinum resistance thermometer \( T_{\text{inlet}} \); 14 - electromagnetic flowmeter; 15 - power regulator; 16 - module for inputting thermocouple the signals of thermocouples; 17 - module for inputting the signals of resistance thermometers; 18 - output module 0-10V; 19 - converter of interfaces RS485 / USB; 20 – ethanol feed sluice chamber

The experimental setup allowed in an automated mode to collect and process primary data, and also to control the experimental parameters of the experiment with high accuracy.

Particular attention was paid to the removal of non-condensable gases from the circuit of the setup, which was carried out by multiple purges from the test unit to the atmosphere during operation with distilled water for 10-12 hours. Then the setup was carried out for a further 3-5 hours at the given initial stationary mode. First, we measured the heat transfer coefficients for the film condensation of pure practically immobile steam. In the experiments on condensation of a water-ethanol vapor...
mixture, liquid ethanol was added to the water in the steam generator through the sluice chamber in an amount necessary to obtain the value of the composition of the mixture close to that required, after which a steady-state regime was established and automated measurements of the heat transfer coefficients were carried out.

The heat transfer coefficient \( h \) was found as the ratio of the heat flux on the wall \( q_w \) to the \( \Delta T \). The heat flux was determined from the mass flux of cooling water measured by the flowmeter and its heating \( (T_{\text{outlet}} - T_{\text{inlet}}) \), which was found from the results of measuring the temperature of cooling water by platinum resistance thermometers installed in the flow of cooling water at the inlet and outlet of the test tube.

The wall temperature was measured by thermocouples embedded in the wall of the test tube. The hot junctions of thermocouples were located under the fin in the middle of the condensation section. When calculating \( \Delta T \), the mean value of the wall temperature \( T_w \) along the perimeter of the tube was used. The saturation temperature \( T_s \) was determined from the temperature-composition diagram for the water-ethanol mixture, taking into account the pressure in the working section, measured by the high-precision manometer, and the composition of the mixture, which was found with a prismatic refractometer (see details in [7]).

3. An experimental results for condensation of pure steam

The experiments were carried out on three copper tubes with rectangular fins on the outer surface. The height and thickness of the fins for all tubes were 1.0 mm, the tube diameter at the root of the fins was 10.0 mm, and the spacing between fins was \( s = 1.3, 2.0 \) and \( 3.0 \) mm. The degree of development of the tube surface due to finning was 2.05, 1.8 and 1.6, respectively. The length of the condensation section was 100 mm. The experiments were carried out at pressures of \( 0.12 \ldots 0.15 \) MPa. When calculating heat transfer coefficient from the primary experimental data, the heat flux was referred to the surface of a smooth tube with a diameter equal to the diameter of the finned tube measured by the roots of

![Figure 2](image.png)

**Figure 2.** Dependence of heat transfer coefficient on vapor-to-wall temperature difference during condensation of pure steam on finned tubes:

- a) \( s = 1.3 \) mm
- b) \( 2.0 \) mm
- c) \( 3.0 \) mm

1 - experimental data;
2 – Srinivasan et al. model [8],
3 – Rose model [9]
fins. Previously, a series of experiments on the condensation of pure steam was carried out on the same tubes. The highest values of heat transfer coefficients were obtained at \( s = 2 \text{ mm} \). The results of experiments on pure steam for all values of spacing between the fins agree well with the calculation of heat transfer by the method of Srinivasan et al. [8]. Calculation by the Rose method [9] predicts lower values of heat transfer coefficients compared with experimental data (figure 2).

4. **An experimental results for condensation of a water-ethanol vapor mixture**

Experiments on the condensation of a water-ethanol vapor mixture were carried out at mass concentration of ethanol in a vapor phase \( c_v = 8.7, 12.0 \) and \( 14.5\% \). Figure 3 shows the condensation curves, i.e. dependences \( h(\Delta T) \) obtained for each ethanol concentration in the vapor phase at different spacing between fins. The condensation curve can be conditionally divided into three sections: 1) a region with a low heat transfer coefficients due to the predominance of the diffusion resistance in the vapor phase; 2) a sharp increase in heat transfer (a transition to a pseudo-dropwise condensation regime); 3) the descending section of the condensation curve (gradual transition to film mode).

The greatest value of the heat transfer coefficient (for \( c_v = 8.7\% \) and \( s = 2 \text{ mm} \), see figure 3, b) was about 65 kW/(m\(^2\)K), i.e. approximately 4 times higher than for film condensation of pure steam on a horizontal smooth tube, which is associated not only with surface finning but also with the augmentation of heat transfer due to the transition to a pseudo-dropwise condensation regime. With increasing \( c_v \), the maximum of the heat transfer coefficient decreases, and larger values of \( \Delta T \) correspond to it.

![Figure 3](image3.png)

*Figure 3. Dependence of heat transfer coefficient on vapor-to-surface temperature difference during condensation of water-ethanol vapor mixture on finned tubes: a) - \( s = 1.3 \text{ mm} \); b) - \( 2.0 \text{ mm} \); c) - \( 3.0 \text{ mm} \). Experimental data: \( 1 - c_v = 8.7\% \); \( 2 - 12\% \), \( 3 - 14.5\% \). 4 - Nusselt theory for smooth tube, \( c_v = 0 \).*
According to the experimental data, the onset of a sharp increase in heat transfer corresponds to the vapor-to-surface temperature difference $\Delta T_r$, which is close to the difference in the condensation and bubble points temperature determined for a given value of $c_v$ in the phase equilibrium diagram. The same result was obtained in [7] for pseudo-dropwise condensation of water-ethanol vapor mixture on vertical smooth tube (figure 4).

![Figure 4](image_url)

**Figure 4.** Dependence of the vapor-to-surface temperature difference corresponding to the onset of a sharp increase in heat transfer, on the composition of the mixture. Data for finned tubes: 1 - $s = 1.3$ mm; 2 - $s = 2.0$ mm; 3 - $s = 3.0$ mm; 4 - data [7] for a vertical smooth tube; 5 - the difference between dew and bubble temperature points

It can be seen from figure 5 that in the $\Delta T$ range from 8 to 20 K the heat transfer coefficient during pseudo-dropwise condensation of a mixture with $c_v = 8.7\%$ on a finned tube with $s = 2$ mm is higher.

![Figure 5](image_url)

**Figure 5.** Dependence of the heat transfer coefficient on vapor-to-surface difference during condensation of the water-ethanol vapor mixture and pure steam on the finned tube with $s = 2.0$ mm. Experimental data: 1 - $c_v = 8.7\%$; 2 - $c_v = 0$. 3 - Nusselt theory for smooth tube, $c_v = 0$
than in film condensation of pure steam on the same finned tube. For $\Delta T > 20K$ heat transfer coefficients for condensation of the mixture and pure steam are approximately equal, and they are almost two times higher than for the film condensation of pure steam on a smooth tube.

When the vapor mixture is condensed, the total thermal resistance $R = (T_s - T_w)/q_w$ consists of two parts, one of which is $R_d = (T_s - T_i)/q_w$ is the thermal resistance of the vapor diffusion layer, and the other $R_c=(T_i - T_w)/q_w$ is the thermal resistance of the liquid phase. Here, $T_i$ is the temperature of the interfacial surface. Calculations show that with increasing $\Delta T$, the interface temperature initially decreases linearly and for the descending parts of the condensation curves $T_i$ is equal to the bubble point temperature determined from the phase equilibrium diagram for a given composition of the mixture (figure 6). It means that the concentration of the mixture in the liquid phase is equal to the concentration in the vapor for the descending parts of the condensation curves.

![Figure 6. Interfacial surface temperature (p=0.12 MPa for $c_v=8.7\%$ and $12\%$, p=0.15 MPa for $c_v=14.5\%$)](image)

![Figure 7. Dependences of thermal resistances on vapor-to-wall temperature difference for tube with $s = 2.0$ mm; $c_v = 12\%$)](image)

Figure 7 shows $R$, $R_d$ and $R_c$ during condensation of a water-ethanol vapor mixture on a finned tube with $s = 2$ mm and $c_v = 12\%$. Similar dependencies of the thermal resistances on $\Delta T$ were obtained for all values of $s$ and $c_v$. Analysis of these graphs allows us to draw the following conclusions:
1) total thermal resistance decreases rapidly with increasing $\Delta T$ (transition from film condensation to pseudo-dropwise mode), and then gradually increases (the reverse transition to film condensation);
2) diffusion thermal resistance decreases rapidly with increasing $\Delta T$, and then remains practically constant;
3) thermal resistance of the liquid phase is initially relatively small, and then it increases. At some $\Delta T$ it is compared with $R_d$, and then with an increase of $\Delta T$ it becomes much higher than $R_d$;
4) $\Delta T$ at which the equality $R_d$ and $R_c$ takes place increases with growth of ethanol concentration in the mixture.

Thus, the finning of horizontal tubes makes it possible to significantly intensify the heat transfer during pseudo-dropwise condensation of a water-ethanol vapor mixture.

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