Experimental study of heat transfer during pseudo-dropwise condensation of water-ethanol and water-isopropanol vapor mixtures on a vertical tube

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Abstract. In the present study experimental heat transfer data on condensation of almost immobile water-ethanol and water-isopropanol vapor mixtures on the vertical smooth copper tube 100 mm long with an outer diameter of 12.0 mm were obtained. Experiments for water-ethanol mixture were carried out at mass concentrations of ethanol from 0.4 to 16% in the vapor phase, and for a water-isopropanol mixture - from 0.6 to 8.4%. The pressure was 0.12…0.13 MPa, vapor-to-surface temperature difference varied from 2 to 40K. The experimental data are represented as dependency of heat transfer coefficient and heat flux on the vapor-to-surface temperature difference. The results of high-speed photography of the condensation process are discussed. It is noted that the transition from film mode to pseudo-dropwise condensation occurs when vapor-to-surface temperature difference is close to dew point - bubble point temperature difference for a given composition of the mixture. According to experimental data, the diffusion thermal resistance and thermal resistance of the liquid phase at different concentrations of the mixture were calculated.

1. Introduction

During condensation of vapor mixtures of miscible liquids with very different surface tension coefficients, the transition from film condensation to pseudo-dropwise mode occurs due to the Marangoni effect. Pseudo-dropwise condensation, unlike the dropwise condensation, takes place on the wettable surfaces. The greatest number of studies on heat transfer in the case of pseudo-dropwise condensation is performed for steam-ethanol vapor mixtures. It was shown in [1] that heat transfer coefficient during pseudo-dropwise condensation of a moving water-ethanol vapor mixture on a vertical plate for a very small (about 1%) mass concentration of ethanol in a mixture, was 8 times higher than for film condensation of pure steam. This result caused an increased interest in the study of pseudo-dropwise condensation in connection with the prospect of its practical application for the enhancement of heat transfer. The effects on heat transfer during pseudo-dropwise condensation of the composition, velocity and pressure of the mixture, vapor-to-surface temperature difference, presence of noncondensable gas in the mixture, and also the temperature gradient along the heat transfer surface were studied in [2-7]. However, all these studies were mainly carried out on a steam-ethanol mixture moving along the condensation surface at high velocity. A heat transfer during pseudo-dropwise condensation of almost immobile vapor mixtures is also necessary to investigate, especially at low
concentrations of the low-boiling component, when the negative effect of the diffusion thermal resistance on heat transfer is relatively small.

2. Condensation of a water-ethanol vapor mixture
In the present study we obtained experimental data on heat transfer during pseudo-dropwise condensation of almost immobile saturated steam-ethanol and steam-isopropanol mixtures on a vertical copper smooth tube with an external diameter of 12.0 mm and a length of 100 mm. The pressure was 0.12 ... 0.13 MPa, the vapor-to-surface temperature difference $\Delta T = T_s - T_w$ varied from 2 to 43 K. For the steam-ethanol mixture, the mass concentration of ethanol in the vapor phase $c_v = 0.4 \ldots 16\%$, and for the steam-isopropanol mixture $c_v = 0.6 \ldots 8.4\%$. The scheme of the installation and the method of investigation are detailed in [8].

Before carrying out the experiments on vapor mixtures, study of the heat transfer was made for the condensation of pure almost immobile saturated steam. These experimental data are in good agreement with the calculation using Nusselt theory (see figure 1a).

![Figure 1](image1.png)

**Figure 1.** Heat transfer coefficient depending on vapor-to-surface temperature difference during condensation of pure steam and steam-ethanol steam mixture on a vertical tube:
- a) 1 - $c_v = 0$; 2 - 0.4\%; 3 - 0.8\%; 4 - 1.9\%.
- Data [7]: 5 - $c_v = 1\%$; 6 - $c_v = 3\%$;
- b) 1 - $c_v = 5.5\%$; 2 - 7.1\%, 3 - 12\%;
- c) 1 - $c_v = 14.4\%$; 2 - $c_v = 16\%$.

Curves 3, 4, 7 - Nusselt equation for $c_v = 0$

The results of a study of heat transfer during the condensation of a steam-ethanol mixture are shown in figures 1, 2. In figures 1b and 1c, with $c_v = 5.5 \div 16\%$, there are three successive sections of the dependence of the heat transfer coefficient on the vapor-to-surface temperature difference:
- the first section, characterized by relatively low values of heat transfer coefficient, due to significant role of diffusion thermal resistance;
- the second section, in which, with a relatively small change in vapor-wall temperature difference there is a rapid increase in heat transfer coefficient due to a transition from the film condensation...
regime to a pseudo-dropwise regime;
- the third section, where the heat transfer coefficient is reduced to values practically corresponding to the film condensation of the steam mixture.

For small concentrations of ethanol \((c_v < 1\%)\), only a decrease in heat transfer coefficient with an increase in \(\Delta T\) is observed because the first and second sections of the condensation curve correspond to very small values of \(\Delta T\), which could not be realized in the experiments (figure 1a). At low concentrations of ethanol \((c_v = 0.4\ldots1.9\%)\) and \(\Delta T\) about 5 K, heat transfer coefficients reaching 90 kW/(m²K) were obtained, which is 4.5 times greater than with film condensation of pure steam. Experimental data [7] on the condensation of a steam-ethanol mixture on a vertical plate for ethanol concentration of 1% and 3% and a mixture velocity of 0.3 m/s, shown in figure 1a, are consistent with the results of our measurements.

Figure 2 shows the dependence of the heat flux \(q_w\) on \(\Delta T\). With an increase in the concentration of ethanol in the mixture, a maximum appears at this dependence even at \(c_v = 0.8\%\) (figure 2a).

![Figure 2](image)

**Figure 2.** Dependence of the heat flux on the vapor-to-surface temperature difference during condensation of pure steam and steam-ethanol mixture on a vertical tube:
a) 1 - \(c_v = 0\); 2 - 0.4%, 3 - 0.8%; 4 - 1.9%.
data [7] for condensation on a vertical plate: 5 - \(c_v = 1\%\); 6 - 3%; b) 1 - \(c_v = 5.5\%\);
2 - 7.1%; 3 - 12%;
c) 1 - \(c_v = 14.4\%\); 2 - \(c_v = 16\%\).
Curves 3, 4, 7 - Nusselt theory for \(c_v = 0\)

At \(c_v > 12\%\), the maximum of \(q_w\) disappears: immediately after the transition to the pseudo-dropwise condensation regime, the heat flux is practically constant; i.e. the heat transfer coefficient is inversely proportional to the \(\Delta T\) (figures 2b, 2c). The greatest value of the heat flux is about 700 kW/m² at \(c_v = 7.1\%\).

Through the viewing windows of the test section, a hydrodynamic pattern was observed on the surface of the tube and high-speed photography was performed. In photographs corresponding to the first section of the dependence of \(q_w\) on \(\Delta T\), small droplets of condensate were clearly visible. Drops grow relatively slowly; they can be distinguished without the use of high-speed photography. Having reached the separation diameter, the droplets roll off the surface of the tube. With an increase in \(\Delta T\) to values corresponding to the second section of the condensation curve (a sharp increase in \(q_w\)), the
droplets increase in size and have a hemispherical shape. With a further increase in ΔT, the average droplet size and the intensity of their removal from the surface increase; the rolling drops merge into irregular streamlets. At comparatively large ΔT, the rivulets merge and a strongly perturbed film is formed, which, with a further increase in ΔT, gradually transforms into a smooth film. At the same time, the heat transfer coefficients are close to the values calculated from the Nusselt theory for film condensation of the vapor mixture on a vertical tube.

From the experimental data presented in figure 3, it follows that the temperature difference at which the transition to the second section of the condensation curve begins (ΔT₁) changes markedly with increasing ethanol concentration in the mixture and is close to the difference between dew point and bubble point temperatures for a given composition of the mixture. It can be seen that these data obtained for an almost immobile water-ethanol vapor mixture are in satisfactory agreement with the results of [1] on the condensation of a mixture on a vertical plate at velocities V=0.4 m/s and 1.5 m/s. This allows to assume that the value of ΔT₁ is mainly determined by the composition of the mixture.

When the vapor mixture is condensed, the total thermal resistance \( R = \frac{(T_s - T_w)}{q_w} \) consists of two parts, one of which is \( R_d = \frac{(T_i - T_{c})}{q_w} \) is thermal resistance of the vapor diffusion layer, and the other \( R_c = \frac{(T_i - T_{c})}{q_w} \) is thermal resistance of liquid phase. Here, \( T_i \) is temperature of interfacial surface. Calculations show that for the descending parts of condensation curves the composition of condensate was practically equal to the composition of vapor, and \( T_i \) was equal to the bubble point temperature determined from the phase equilibrium diagram for a given composition of the mixture.

For the descending parts of condensation curves obtained in experiments at \( c_v = 0.8\% \) and \( c_v = 16\% \), figure 4 shows the variation of \( R_d \) and \( R_c \), and in figure 5 the ratios \( R_d/R \) and \( R_c/R \) as a function of the vapor-to-surface temperature difference are presented. For \( c_v = 0.8\% \) at ΔT ≈2.5K, thermal resistances \( R_d \) and \( R_c \) are close to each other. With increasing ΔT, thermal resistance of vapor diffusion layer first decreases slightly, and then remains practically unchanged. The thermal resistance of liquid phase increases with increasing ΔT, and the dependence of \( R_c \) on ΔT is close to linear. At a maximum ΔT≈38K, it was found that \( R_d/R = 0.02 \), and \( R_c/R = 0.98 \), i.e. the thermal resistance of the liquid phase is predominant. For \( c_v = 16\% \) with a minimum ΔT = 13K for the descending part of the condensation curve, the thermal resistance of the vapor diffusion layer is significantly higher than the thermal resistance of the liquid phase (\( R_d/R = 0.72 \), \( R_c/R = 0.28 \)). As with \( c_v = 0.8\% \), here, too, a
practically linear dependence of $R_c$ on $\Delta T$ is observed, and $R_c$ slightly changes with increasing $\Delta T$. At $\Delta T = 19K$, the contribution of the thermal resistances $R_d$ and $R_c$ to the total thermal resistance is the same. For a maximum $\Delta T = 41K$, the share of $R_c$ in the total thermal resistance is 76%.

Figure 4. Dependence of thermal resistances of the liquid phase and vapor diffusion layer on the vapor-to-surface temperature difference in experiments on the condensation of a steam-ethanol vapor mixture: a) $c_v = 0.8\%$; b) $16\%$. 1 - $R_c$; 2 - $R_d$

Figure 5. Contributions of thermal resistances of the liquid phase and the vapor diffusion layer to the total thermal resistance in experiments on the condensation of a steam-ethanol mixture: a) $c_v = 0.8\%$; b) $16\%$. 1 - $R_c / R$; 2 - $R_d / R$

3. Condensation of a water-isopropanol vapor mixture

Experimental data were obtained on the condensation of water-isopropanol vapor mixture with mass concentrations of isopropanol $c_v = 0.6 \ldots 8.4 \%$ on the same vertical tube. All experiments were carried out at a mixture pressure close to 0.12 MPa. Figure 6 presents the experimental data in the form of the dependence of the heat transfer coefficient on the vapor-to-surface temperature difference. It can be seen that the experimental data on the condensation of pure steam are in good agreement with the calculation using the Nusselt equation.

For all concentrations of isopropanol in the mixture, a qualitatively identical dependences of $h(\Delta T)$ are observed. First, the heat transfer coefficient sharply increases, and after reaching the maximum value, it gradually decreases. For $c_v = 3.2\%, 5.1\%$, and $8.4\%$ for low $\Delta T$, the heat transfer coefficient
Figure 6. Dependence of heat transfer coefficient during condensation of pure steam and water-isopropanol vapor mixture on the vapor-to-surface temperature difference:

a) 1 - \( c_v = 0 \); 2 - 0.6%; 3 - 1%;

b) 1 - \( c_v = 2.4\% \); 2 - 3.2%;

c) 1 - \( c_v = 5.1\% \); 2 - 8.4%.

Curves 3, 4 – Nusselt equation for \( c_v = 0 \)

Figure 7. Dependence of heat flux on vapor-to-surface temperature difference during condensation of pure steam and water-isopropanol vapor mixture:

a) 1 - \( c_v = 0 \); 2 - 0.6%; 3 - 1%;

b) 1 - \( c_v = 2.4\% \); 2 - 3.2%;

c) 1 - \( c_v = 5.1\% \); 2 - 8.4%.

Curves 3, 4 – Nusselt theory
is lower than for the film condensation of pure steam due to the influence of diffusion layer at the phase interface enriched with isopropanol vapor. The sharp growth of $h$ corresponds to the transition from the film condensation regime to the pseudo-dropwise, and a further decrease in $h$ indicates that the pseudo-dropwise regime with the increase of $\Delta T$ is gradually replaced by the film one. With increasing $c_v$, the maximum values of $h$ decrease, and they correspond to ever larger values of $\Delta T$. For $c_v = 0.6\%$, the region with a sharp increase in heat transfer coefficient was not obtained, since it corresponds to comparatively small values of $\Delta T$, which are difficult to realize in the experiment.

In figure 7 experimental data are presented in the form of $q_w(\Delta T)$ dependences. The maximum values of $q_w$ are about 0.5MW/m$^2$.

Figures 8 and 9 show the dependence of the thermal resistances on the vapor-to-surface temperature difference for isopropanol concentrations in the mixture $c_v = 0.6\%$ and 8.4\%.

![Figure 8](image1)

**Figure 8.** Dependence of thermal resistance of liquid phase and thermal resistance of vapor diffusion layer on vapor-to-surface temperature difference in the experiments on condensation of steam-isopropanol vapor mixture: a) $c_v = 0.6\%$; b) $c_v = 8.4\%$; 1 - $R_c$; 2 - $R_d$

![Figure 9](image2)

**Figure 9.** Contributions of thermal resistances of liquid phase and vapor diffusion layer to the total thermal resistance in the experiments on the condensation of a steam-isopropanol mixture: a) $c_v = 0.6\%$; b) $c_v = 8.4\%$; 1 - $R_c/R$; 2 - $R_d/R$

For $c_v = 0.6\%$ at a maximum $\Delta T \approx 38K$, it was found that $R_d / R = 0.02$ and $R_c / R = 0.98$, i.e. the thermal resistance of the liquid phase is predominant. For the concentration $c_v = 8.4\%$ at a maximum
value of $\Delta T \approx 36 K$, the fraction of $R_c$ in the total thermal resistance is 74%, and $R_d/R_c = 26\%$, i.e. at high concentrations of the low-boiling component in the mixture, an increasing influence of the resistance of the diffusion vapor layer is observed.

Experimental data for a water-ethanol vapor mixture can be compared with the data for a water-ethanol mixture at close concentrations of the low-boiling component.

Figure 10 shows that the experimental data for the mixture with ethanol at $c_v = 0.8\%$ and the data for the mixture with isopropanol at $c_v = 0.6\%$ for $\Delta T$ more than 10 K are close to each other. At $\Delta T = 5 K$ heat transfer coefficient for the mixture with ethanol is much higher.

In figure 11 an experimental heat transfer data for the mixture with ethanol ($c_v = 5.5\%$) and with isopropanol ($c_v = 5.1\%$) are given. The maximum value of the heat transfer coefficient for a mixture with ethanol is about 60 kW/(m$^2$K), and for a mixture with isopropanol it is 35 kW/(m$^2$K). Here, too, we see a faster decrease in heat transfer coefficient with an increase in $\Delta T$ for the mixture with ethanol. Such differences in the $h(\Delta T)$ dependences for these mixtures can be explained by the difference in their thermophysical properties, including the phase equilibrium diagram.

For a mixture with isopropanol, the difference in dew and bubble point temperatures at $c_v \approx 5\%$ is noticeably higher, which indicates a stronger effect of the diffusion resistance for heat transfer.
References

[1] Utaka Y and Wang S 2004 *Int. J. Heat Mass Transfer* **47** 4507
[2] Utaka Y and Wang S X 2001 *Trans. Japan Soc. Refr. Air Cond. Eng.* **18** 127
[3] Wang S and Utaka Y 2005 *Exp. Heat Transfer* **18** 61
[4] Utaka Y and Kobayashi H 2003 *Proc. 6th ASME-JSME Thermal Eng. Conf.*
  CD paper TED – AJ03-604.
[5] Li Y, Yan J J, Qiao L and Hu S H 2008 *Heat and Mass Transfer* **44** 607
[6] Ali H, Wang H S, Briggs A and Rose JW 2013 *J. of Heat Transfer* **135** 031502.
[7] He Y P, Yan J J and Yan Y S 2004 *Heat Transfer - Asian Res.* **33** 348
[8] Chindyakov A A and Smirnov Yu B 2013 *Vestnik MPEI* **1** 46-54