Condensation of water vapor in the presence of fluocarbons in the turbulent stream of liquid

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Abstract. The paper presents an experimental study of condensation of pure water vapor and water vapor in the presence of octafluoropropane (C₃F₈) in a vapor-gas mixture (VGM) in a turbulent jet of liquid.

1. Introduction

The process of condensation of water vapor in the presence of a surfactant is still little studied, this applies to experimental work and theoretical justification. This work is dedicated to:

- Carrying out a series of experiments on the condensation of water vapor on a jet of water in the presence and without fluorocarbon vapors.
- The theoretical justification of the obtained experimental results.

2. Presentation of experimental results and methods of their processing

Figure 1. Dependence of water vapor condensation in the turbulent liquid jet on the flow rate of C₃F₈

\( d_0=0.4 \text{ mm}; \ P_{\text{mix}}=10^5 \text{ Pa}; \ G_p=9.12 \times 10^{-4} \text{ g/s}; \ G_g=0-16 \text{ g/s} \)

\( 1-t_0=24^\circ \text{C}; \ G_0=0.0021 \text{ kg/s}; \ U_0=16.94 \text{ m/s}; \ Re=6700 \)

\( 2-t_0=24^\circ \text{C}; \ G^2=0.00305 \text{ kg/s}; \ U_0=24.3 \text{ m/s}; \ Re=9730. \)
From figure 1 it is clear that the ratio of the mass flow rate of $G_{\text{cond}}$ (condensed water vapor from VGM), to the flow rate of liquid from the nozzle $G_0$ is higher than that of pure water vapor condensation in the water jet (curve 1 in figure 1). This dependence of condensation on the flow rate of non-condensable gas $C_3F_8$ is observed at the volume concentration of gas in VGM equal to $0 \leq \beta \leq 0.3$.

There is a decrease in the intensity of condensation of water vapor from the VGM compared with pure steam (curve 2 in figure 1) at a liquid flow rate of 23.3 m/s from the nozzle. A similar pattern is observed for the 0.6 mm nozzle at a speed of ~12 m/s.

The experimentally obtained results allow us to conclude about the existence of the region of regime parameters of the liquid jet and VGM, in which non-condensable surfactants (surfactants), for example $C_3F_8$, can serve as "catalysts" of the jet condensation process.

Calculations using the simplified method of jet condensation allow explaining and predicting the desired region of regime parameters.

The method of jet condensation [1] is based on the turbulence model k-l, which takes into account the effect of irregular perturbations $h$ on the portable properties of the jet (figure 2). Within the framework of the model, the mean square amplitude of irregular perturbations of the interfacial surface $h$ is found for energy reasons [2]:

$$h = C_h \frac{\rho_l l_T^2 k}{\sigma_{A-AB}}$$  \hspace{1cm} (1)

Here $\rho_l$ is the density of the liquid (kg/m$^3$); $k$ is the energy of turbulent fluctuations (m$^2$/s$^2$); $\sigma_{A-AB}$ is the surface tension at the interface "liquid ("A") -gas-vapor mixture ("AB")" (the Dj/m$^2$); and $C_h$ is the constant turbulence for the jet streams [2].

![Figure 2. Irregular perturbations of the interfacial surface.](image)

Depending on the scale of turbulence $l_T$, the energy of turbulent fluctuations $k$ and the surface tension $\sigma_{A-AB}$, the value $h$ (see figure 2) varies in the range of $[0, l_T]$.

At values of $h > l_T$, turbulent spray of the jet occurs and the calculation, in this case, should be carried out according to the method for dispersed jets.

In accordance with the Kolmogorov-Prandtl turbulence model, the total thermal diffusivity $a_\Sigma$ on the interfacial surface is calculated as:

$$a_\Sigma = \frac{V_l}{Pr_l} + \frac{C_k h k^{0.5}}{Pr_l}$$  \hspace{1cm} (2)

Here $V_l$ is the kinematic viscosity of the liquid (m$^2$/s); $Pr_l$ is the Prandtl number of the liquid; and $C_k$ is the turbulence constant for jet flows [2].

The coefficient of turbulent thermal conductivity $a_\Sigma$ at $h/l_T \rightarrow 1$ reaches its maximum.
The calculations show (figure 3) that for nozzles with a diameter of 0.4 and 0.6 mm, the level of irregular perturbations of the interfacial surface $h$ reaches a maximum value equal to the size of the turbulent praying $l_T$ for condensation of pure vapor on the turbulent jet of water at the flow rates of water leakage from the nozzle of 15 and 12 m/s.

\[ \frac{h}{l_T} = \begin{cases} 1 & U_l = 10 \text{ m/s} \\ 1.5 & U_l = 12 \text{ m/s} \\ 2 & U_l = 14 \text{ m/s} \\ 3 & U_l = 16 \text{ m/s} \\ 4 & \frac{h}{l_T} = 1 \end{cases} \]

Figure 3. Dependence of irregular perturbations of the interfacial surface of the jet on the nozzle diameter (mm) and fluid velocity (m/s)

1- $U_l = 10$ m/s; 2- $U_l = 12$ m/s; 3- $U_l = 14$ m/s; 4- $U_l = 16$ m/s; 5- $\frac{h}{l_T} = 1$.

In this case, the addition of surfactants ($G_g > 0$) to the vapor phase, resulting in a decrease in the surface tension $\sigma_{A,AB}$ compared to $\sigma_{A,A}$, the surface tension coefficient at the interface "liquid ("A") - vapor phase("AA")", will not lead to an increase in $\frac{h}{l_T}$, and hence in $\Delta \Sigma$ (see formula (2)).

Thus, when octafluoropropane ($C_3F_8$) is added to water vapor, the effect of increasing the condensation of water vapor on the water jet associated with the surface tension of the mixture $\sigma_{A,AB}$ ceases to work. The condensation process is similar to the condensation of water vapor from the steam-air mixture, when the effect of lowering the saturation temperature on the interfacial surface will be predominant.

Condensation is expected to worsen in this case, the addition of surfactants ($G_g > 0$) to the vapor phase, resulting in a decrease in the surface tension $\sigma_{A,AB}$ compared to $\sigma_{A,A}$, the surface tension coefficient at the interface "liquid ("A") -vapor phase("AA"), will not lead to an increase in $\frac{h}{l_T}$, and hence in $\Delta \Sigma$ (see formula (2)).

Condensation is expected to worsen.

The observed effect of increasing the intensity of water vapor condensation (in the presence of surfactants in VGM) can be implemented in NPP safety systems. In these systems, the coolant flows out of the holes with a diameter of 0.01 m at speeds of about 1 m/s.

The results of the calculations in figure 4 show that the parameters of the nozzle and the vapor-gas mixture lie in the area where the use of surfactants is justified.

The calculation method, in the form in which it was used, cannot claim sufficient accuracy of the calculation due to ignoring the factors affecting the condensation: the evolution of turbulence along and across the jet section; the dynamic interaction of the phases, and the dependence of the thermophysical properties of water, steam, VGM on temperature. There was no optimization of constants used in the method. However, this technique [1] takes into account and qualitatively correctly describes the degree of influence on condensation of two opposite effects. The latter are associated with the surface tension of the mixture [1] and the local saturation temperature on the interfacial surface in the presence of surfactants in VGM.
Figure 4. Dependence of irregular perturbations of the interfacial surface of the jet on the nozzle diameter (mm) and the fluid velocity (m/s): 1 - $U_l=2$ m/s; 2 - $U_l=4$ m/s; 3 - $U_l=6$ m/s; 4 - $U_l=8$ m/s; 5 - $h/l_T =1$.

Figure 4 shows that at the flow rate of 2 m/s from the nozzle (hole) with a diameter of 0.01 m, the turbulent flow of the water jet is realized and the critical value $h/L_T =1$ is not achieved.

3. Conclusions

It has been experimentally obtained and numerically substantiated that the intensity of condensation of water vapor from the mix gas (water vapor + fluorocarbon gas) increases with an increase in the concentration of C3F8 in the VGM at a set of operating parameters of the fluid flowing from the nozzle and parameters of VGM. When selecting parameters, it is necessary for the flow of the liquid jet to be turbulent. In addition, the amplitude of irregular perturbations of the interfacial surface should be less than the turbulence scale $l_T$. Thus, when adding surfactants to the steam flow, the ratio $h/l_T$ did not reach the value equal to unity.

References

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