The influence of surface-active agents in gas mixture on the intensity of jet condensation

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Abstract. The report presents: the methodology of calculation of contact condensation of steam from the steam-gas mixture into the stream of water, taking into account: the mass flow of steam through the boundary phase, particularly the change in turbulent transport properties near the interface and their connection to the interface perturbations due to the surface tension of the mixture; the method of calculation of the surface tension at the interface water - a mixture of fluorocarbon vapor and water, based on the previously established analytical methods we calculate the surface tension for simple one-component liquid-vapor systems. The obtained analytical relation to calculate the surface tension of the mixture is a function of temperature and volume concentration of the fluorocarbon gas in the mixture and is true for all sizes of gas molecules. On the newly created experimental stand is made verification of experimental studies to determine the surface tension of pure substances: water, steam, C₃F₈ pair C₃F₈, produced the first experimental data on surface tension at the water - a mixture of water vapor and fluorocarbon C₃F₈. The obtained experimental data allow us to refine the values of the two constants used in the calculated model of the surface tension of the mixture. Experimental study of jet condensation was carried out with the flow in the zone of condensation of different gases. The condensation process was monitored by measurement of consumption of water flowing from the nozzle, and the formed condensate. When submitting C₃F₈, there was a noticeable, intensification condensation process compared with the condensation of pure water vapor. The calculation results are in satisfactory agreement with the experimental data on surface tension of the mixture and steam condensation from steam-gas mixture. Analysis of calculation results shows that the presence of surfactants in the condensation zone affects the partial vapor pressure on the interfacial surface, and the thermal conductivity of the liquid jet. The first circumstance leads to deterioration of the condensation process, the second to the intensification of this process. There is obviously an optimum value of concentration of the additive surfactants to the vapour when the condensation process is maximum. According to the developed design methodology contact condensation can evaluate these optimum conditions, their practical effect in the field study.

1. Introduction
Method of calculating contact condensation of water vapor from the gas mixture in the jet of water takes into account the turbulent changes of the transport properties near the surface section of phases and their connection to the interface perturbations due to lead-the reason for surface tension σ.
As the results of the analysis of experimental data and calculation by the model of jet condensation [1, 2], surface tension is one of the determining process of contact heat transfer parameters. Analysis of the condition of the surface shows that when $\sigma \rightarrow 0$ has an irregular disturbance on the surface section of phases, as is the case $\sigma \rightarrow \infty$ corresponds to a smooth undisturbed surface.

With the growth of $\sigma$ the intensity of heat exchange decreases. When you create of model of contact heat exchange took into account the influence of turbulence energy on the condition surface (the presence of irregular perturbation). In this case the surface tension at the interface liquid-gas- vapor mixture $\sigma_{A-AB}$, has a critical influence on the presence of irregular disturbances.

In the present work the subscript "A" corresponds to the $H_2O$, the index "In" corresponds $C_3F_8$, index "A-AB" means that the value refers to the interface between water and vapor mixture (water vapor + gas $C_3F_8$).

### 2. Numerical studies of jet condensation

We consider the problem of steam condensation from steam-gas-vapour mixture "A" and on desiremale gas "B" on the surface of an axisymmetric turbulent jet "A".

The jet diameter $d_0$, the temperature of the liquid at the nozzle is $t_0$, the rate of liquid outflow from the nozzle $U_0$ and turbulent energy $k_0$. Gas "B" is surface-active, insoluble in the liquid "A". In the considered range of parameters the gas is not condensers at the surface of a liquid jet "A". The temperature gas is equal the temperature mixture $t_{mix}$. The pressure of the mixture is equal to $P_{mix}$. Steam-gas mixture moves at the same speed and in the same direction as the jet of liquid $U_{mix} = U_0$. In this case there is no friction on the interface.

When the considered values of velocity $U_0$ gravitational forces are not taken into account. The increase of mass of fluid "A" due to the condensation of steam "A" on the surface of the jet is neglected.

Given the above assumptions, the solution reduces to the unsteady heating of an infinite axisymmetric cylinder, the value of the $Bi \rightarrow \infty$. The last condition corresponds to the condition of constant temperature the interfacial surface and, consequently, the concentration of impurities along the surface. In the case of pure steam, this temperature is equal to the temperature of saturation at the saturation pressure $p_S$. In the presence of gas "B" paired "A" surface temperature $t_{suf}$ is equal to the saturation temperature at the partial vapor pressure of the "A" on the surface.

The amount of energy of turbulence in the jet is almost a constant because of the low dissipation and diffusion, lack of offspring and equal to energy of turbulence at the nozzle $k_0$:

$$ k_0 = 0.036 \gamma \left( \frac{K_S}{d_0} + \frac{68}{Re_0} \right) U_0^2, \quad \gamma = 1 - \exp \left( - \frac{Re_0 - Re_{cr}}{Re_{cr}} \right) $$

(1)

Here the Reynolds number is calculated on a water output from the nozzle; $Re_{cr}=2300$, the value of the critical Reynolds number, $K_S/d_0 = 0.01$ and the relative roughness of the nozzle, $\gamma$ is the coefficient of intermittency.

The desired value is $Q_{mix_con} / Q_{0_con}$ -the ratio of the amount of heat transferred to the fluid jet in the condensation on a pair of "A" from the vapor mixture "A" and "B" and condensation of dry saturated steam:

$$ \tilde{Q}_{mix} = \frac{Q_{mix_con}}{Q_{0_con}} = \frac{(\tilde{t}_l - t_0)}{(\tilde{t}^*_l - t_0)}. $$

(2)

Here $\tilde{t}_l$ , $\tilde{t}^*_l$ are the average temperatures of the liquid jets "A" (along the coordinate $x$), respectively, for the cases of pure steam condensation and steam condensation from steam-gas mixture.

The average temperature of the heating jet for both cases is calculated as [1]:
\[ \theta = \frac{t_s - t_0}{t_s - t_0} = \sum_{i=0}^{\infty} \frac{4}{\varepsilon_i} \exp(-\varepsilon_i^2Fo), \quad \theta^* = \frac{t_{suf} - t_0}{t_{suf} - t_0} = \sum_{i=0}^{\infty} \frac{4}{\varepsilon_i} \exp(-\varepsilon_i^2Fo^*), \] 
\[ \varepsilon_i \mid_{Bi \to \infty} \approx \frac{\pi}{4} \left( i - \frac{1}{4} \right) \]

The number of Fourier coefficients and effective thermal diffusivity equal to, respectively:
\[ Fo = \frac{\alpha_C}{\rho} \left( \frac{d_v}{2} \right)^2, \quad Fo^* = \frac{\alpha_C^*}{\rho} \left( \frac{d_v}{2} \right)^2, \quad \alpha_C = \frac{v}{\Pr_t} + \frac{C_k}{\Pr_{l,m}} k_0^{0.5}, \quad \alpha_C^* = \frac{v}{\Pr_t} + \frac{C_k^*}{\Pr_{l,m}} k_0^{0.5}. \]

The amplitude of the irregular perturbations of the interface \( h \) is determined from energy considerations [1]:
\[ h = C_h \frac{\rho_{l,t}^2 k_0}{\sigma}, \quad h^* = C_h \frac{\rho_{l,t}^2 k_0}{\sigma_{A,AB}}. \]

Here \( l = C_d_0 \), where the constants of the turbulence will be equal to \( C_k = 0.56, C_M = 0.5, C_l = 0.07 \). The value of surface tension \( \sigma_{A,AB} \) is by the following formula (9).
Expressing the average temperature of (3) and substituting them in (2) find the ratio of the heat flows:
\[ Q_{C_4,F_i} = \frac{t_{suf} - \theta^* (t_{suf} - t_0) - t_0}{t_s - \theta^* (t_s - t_0) - t_0}. \]

Analyses of methods of calculation of contact condensation and the results of the calculation show that with increasing the concentration of surfactants in water vapor decreases vapor pressure on the interfacial surface.
As a consequence, the reduced saturation temperature of water vapor and as a consequence reduces the intensity of condensation. At the same time when the concentration of surfactants in water vapor will reduce surface tension \( \sigma_{A,AB} \). This leads to an increase in the intensity of condensation.
Thus, increasing the concentration of surfactants in water vapor leads to the appearance of two effects, the opposite of which influence the intensity of condensation densely. Therefore, there must exist an optimum value of the concentration of surfactants in water vapor when the condensation intensity is maximum.
In Fig.1 shows calculation results showing the possibility of the settings area \( t_{suf} \), where the presence of gas "B" In pair "A" provides condensation, greater in magnitude than in the pure pair.

3. The method of calculation of the surface tension at the interface water - a mixture of fluorocarbon vapor and water
The method of calculation of the surface tension at the interface water - a mixture of fluorocarbon vapor and water, based on previously established analytical method we calculate the surface tension for simple one - component liquid-vapor systems:
\[ \sigma_{A,i} = \sigma_{0,i} - \rho_{A,i} \left( 1 - \frac{\rho_{A,i}}{\rho_{v,i}} \right) \exp \left( -A_1 \sqrt{\frac{3kT}{2}} \right). \]

The obtained analytical relation to calculate the surface tension of the mixture is a function of temperature and volume concentration of the fluorocarbon gas in the mixture and is true for all sizes of gas molecules:
\[ \sigma_{A,i} = \rho_{A}^{st} \sigma_{A,i} + \phi_{A}^{st} \left[ \sigma_{0,A}^{st} - \left( \sigma_{0,A}^{st} \sigma_{0,B}^{st} \right)^{0.5} \right]. \]

Value \( \sigma_{0,A} \) in the formula (7), taken from [3-4, 6]. The values of \( \sigma_{0,A}^{st}, \sigma_{0,B}^{st} \) in (8) are adjusted with consideration of the peculiarities of the interaction of molecules "A" molecules "B" [5]. Values \( \phi_{A}^{st}, \phi_{B}^{st}, \phi_{0}^{st} \) shares interfacial surface occupied by the molecules "A", "B", the empty cells in the monomolecular layer:

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\[
\varphi_A^{\text{eff}} = \frac{\rho_A}{\rho_A^*} \left(1 - \frac{\rho_A}{\rho_A^*} - \frac{\rho_B}{\rho_B^*} \right) \exp \left( \frac{-A_A}{3kT} \right), \quad \varphi_B^{\text{eff}} = \frac{\rho_B}{\rho_B^*} \left(1 - \frac{\rho_A}{\rho_A^*} - \frac{\rho_B}{\rho_B^*} \right) \exp \left( \frac{-A_B^{0.5} - A_B^{0.5}}{3kT} \right)
\]

Here

\[
\varphi_0^{\text{eff}} = 1 - \varphi_A^{\text{eff}} - \varphi_B^{\text{eff}}
\]

\[
A_A = \frac{u_A m_{0A}}{6k_A^2}, \quad A_B = \frac{u_B m_{0B}}{6k_B^2}, \quad A_{AB} = \frac{k_B V_B^{2/3}}{V_A^{2/3}} \sigma_{0A}^*, \quad \sigma_{0A}^* = \frac{1}{6k_A^2 k_B} \frac{u_A m_{0A}}{V_A^{2/3}}, \quad \sigma_{0B}^* = \frac{1}{6k_A^2 k_B} \frac{u_B m_{0B}}{V_B^{2/3}}
\]

where \(m_{0A}, V_A, u_A, m_{0B}, V_B, u_B\) - mass, volume, internal energy of the molecules "A" and "B"; \(k_A, k_B, k_B^{F}\) - constants model the surface tension of the mixture.

The developed model of surface tension is included in the calculation methodology for jet condensation (5) used for the calculation of water vapor condensation from vapor-gas mixture on the water.

4. Experimental study on determination of surface tension

On the newly created experimental stand-oriented weighting technique drops, made experimental verification studies to determine over-personal tension for pure substances: water, steam, \(\text{C}_3\text{F}_8\) pair \(\text{C}_3\text{F}_8\).

In the lower part of the working volume of the stand filled with water. Throughout the experience, the tension is maintained equal to the temperature of saturation. In the upper part of the volume is dry saturated steam. The measuring pipette is in the same volume.

Using a pipette is extruded a drop of water having the same temperature as the water at the bottom of the installation. Is the expense of the drops, and after filling the measuring Cup is determined by the size of the drops. In the method based on the Tait equation is calculated surface tension at the interface liquid-vapor of the same physical nature, liquid-vapor-gas mixture:

\[
\sigma = \frac{Mg}{2\pi rm} - K_\sigma.
\]

In equation (11) \(M\) is the total mass of the \(n\) droplets detached under the action of gravity from the outlet of a capillary tube of radius \(r\). To improve the accuracy of the right part is multiplied by the basis of exhibition \(K_\sigma\) coefficient depending on the radius \(r\) and the volume drops. The value of the correction factor for that particular dropper was verified by the known values of surface tension for pure substances: \(\text{H}_2\text{O}\) - \(\text{H}_2\text{O}\) pair, \(\text{C}_3\text{F}_8\) pair \(\text{C}_3\text{F}_8\).

Obtained the first experimental data on surface tension at the water - a mixture of water vapor and gas \(\text{C}_3\text{F}_8\).

The calculation of the first experimental data on surface tension for the above-mentioned substances was carried out according to the formula (7) and the calculation results were compared with the tabular experimental data, with values of \(m_i\) reported in this work.
In the gas of the volume of the stand was applied fluorocarbon $\text{C}_3\text{F}_8$ gas of fixed mass (the density of the fluorocarbon gas in the experiment is equal to the mass of gas/volume in the setting occupied by the gas-vapor mixture). After the establishment of thermodynamic equilibrium in a volume, starts-fell to the expense of liquid droplets. Was conducted trial experiments with small volumetric concentration of $\text{C}_3\text{F}_8$ in mixture of water vapor and gas. In the area studied parameters and the initial data consistent with the calculations by the developed technique (formula 8).

To change the density of the gas, and therefore its concentration in the gas-vapor mixture to sufficient to install to change the volume occupied by the gas-vapor mixture. In a reduced capacity of the work area the installation of steam-gas mixture is in thermodynamic equilibrium. Part of the water vapor will condense. Undissolved gas will have a higher concentration in gas mixtures than in previous experience.

Thus, by varying the volume of the mixture in the installation and saturation temperature of water in the installation we get the experimental values of the surface tension of the mixture in a wide ohms range of temperatures and concentrations of insoluble non-condensable gas.

5. Experimental study of jet condensation

Experimental study of jet condensation was carried out on the installation schematic diagram of which is shown in Fig.3. The water pump 15 through the nozzle 10 was supplied to the condensation zone 8. Gas out of the cylinder 1 are mixed with steam "And" 18. Gas-vapor mixture through the separator 11 was fed into the condensation zone 8.
In the experiment were measured: water flow emanating from the nozzle, the total costs during the liquid phase, the cost of steam and gas, the temperature of the liquid at the entrance and the exit of the zone condensely, the temperature of the gas mixture, the walls, the air temperature in the laboratory.

In Fig. 4 shows the data for jet condensation: a clean pair and a pair that contains fluoride-uglerodnye gas C₃F₈. If you increase the flow C₃F₈ in water vapor, there is a marked inteficacia process of water vapour condensing on the water jet in comparison with the condensation of pure water vapor.

On the y-axis (Fig. 4) shows the values of K₀ and K_C₃F₈, representing the attitude of condensate flow G-cond to the water flow from the nozzle G₀. K₀ corresponds to condensation of pure water vapor on the jet water. K_C₃F₈ corresponds to condensation water vapor from gas-vapor mixture (water vapor + gas C₃F₈) on the jet water. On the x-axis (Fig. 4) values of the gas flow rate Gg. The gas flow ranged from zero to 40 cm³/min.

The theoretical basis of the experimentally obtained effect can be seen in an analysis of the calculation results. From the calculations it follows that the presence of surfactants in the condensation zone affects the partial vapor pressure on the interfacial surface, and the thermal conductivity of the liquid jet.
The first circumstance leads to deterioration of the condensation process, the second to the intensification of this process. Apparently there is an optimum value of surface concentration of active gas in water vapor, when the process of condensation max. According to the developed design methodology contact condensation can evaluate these optimum conditions (Fig.1), their practical effect in the field study.

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