Heat transfer during condensation of steam from steam-gas mixtures in the passive safety systems of nuclear power plants

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Abstract. A theoretical model for calculation of heat transfer during condensation of multicomponent vapor-gas mixtures on vertical surfaces, based on film theory and heat and mass transfer analogy is proposed. Calculations were performed for the conditions implemented in experimental studies of heat transfer during condensation of steam-gas mixtures in the passive safety systems of PWR-type reactors of different designs. Calculated values of heat transfer coefficients for condensation of steam-air, steam-air-helium and steam-air-hydrogen mixtures at pressures of 0.2 to 0.6 MPa and of steam-nitrogen mixture at the pressures of 0.4 to 2.6 MPa were obtained. The composition of mixtures and vapor-to-surface temperature difference were varied within wide limits. Tube length ranged from 0.65 to 9.79m. The condensation of all steam-gas mixtures took place in a laminar-wave flow mode of condensate film and turbulent free convection in the diffusion boundary layer. The heat transfer coefficients obtained by calculation using the proposed model are in good agreement with the considered experimental data for both the binary and ternary mixtures.

1. Introduction.

In case of emergency operation of the power unit of nuclear power plants associated with the depressurization of the primary circuit, the condensation of steam from the steam-gas mixture (SGM) occurs both on the cooled inner surface of the nuclear reactor containment and on the elements of the passive safety system located inside it. The noncondensable component of the SGM can be not only air, but also a mixture of air with hydrogen and other gases. According to the available calculations, when the primary circuit is depressurized, the pressure in the nuclear reactor containment with the PWR type reactor increases to 0.5…0.6 MPa, and the mass fraction of non-condensable gases in the mixture can be from 10 to 80% [1]. In the new projects of low-power nuclear reactors (REX-10 - an integrated version of the PWR type reactor developed in South Korea, fuel - thorium, power 10 MW), the passive safety system uses nitrogen gas at a pressure of 20 bar [2]. This caused interest in the study of heat transfer during the condensation of steam from the SGM at high pressures. Thus, a very urgent task is to calculate and experimentally study the process of condensation of steam-gas mixtures of various compositions on plates and tubes in a wide range of pressures. This is necessary to create accurate methods for calculating the passive safety systems of nuclear power plants.
During condensation of steam from the SGM a diffusion boundary layer forms near the condensation surface, which leads to the appearance of an additional thermal resistance. In this connection, the heat transfer coefficient (HTC) at condensation of steam from the SGM is noticeably lower than with the condensation of pure steam.

Since the 1960s, a large number of experimental studies on the condensation of steam in the presence of non-condensable gases have been carried out under conditions typical for the operation of the nuclear safety systems [2-7]. These studies were carried out with the condensation of SGM on vertical plates, and also on vertical tubes from 0.65 m to 9.79 m in height. In the majority of investigations binary mixtures of steam-air and steam-nitrogen were studied. The pressure was varied from 0.1 MPa to 2.6 MPa, the vapor-to-wall temperature difference - from 10 to 140 K, the mass fraction of steam in the mixture - from 0.09 to 0.93. The condensation occurred under turbulent free convection in the diffusion boundary layer. Only in [6] heat transfer studies were carried out for ternary (steam-air-helium) mixtures.

Uchida [3] first obtained a simple empirical formula for calculating HTC during condensation of steam from a mixture with air in the regime of free convection on the wall of a containment of a nuclear reactor. HTC depends only on the composition of the mixture in this formula. In a number of later papers empirical formulas for calculating HTC were obtained, which differ from formula proposed in [3] only by coefficients and limits of applicability. Some authors, when creating empirical formulas for calculating HTC, took into account the fact that HTC also depends on the pressure of the SGM and on vapor-to-wall temperature difference, as well as on the geometric dimensions and shape of the heat exchange surface. The data presented in [7] show that the HTC for the condensation of a steam-air mixture calculated by different empirical formulas may differ up to 4 times. Dehbi [8] obtained recently a formula that generalizes only the data on heat transfer during condensation of steam-air and steam-nitrogen mixtures.

The purpose of the present study is to calculate heat transfer coefficients during condensation of binary and ternary mixtures on vertical surfaces for operating conditions of passive safety systems of nuclear power plants.

2. Fundamentals of the model, results of calculations and discussion

The condensation heat transfer model is based on the film theory and the analogy between heat and mass transfer. The heat transfer coefficient during condensation of steam from the SGM is determined by:

\[ h = \frac{q_w}{(T_b - T_w)}. \] (1)

Bulk mixture temperature \( T_b \) is determined by the partial steam pressure in the mixture; wall temperature \( T_w \) is calculated from the experimental data presented in the publications. The heat flux on the wall \( q_w \) and the interface temperature \( T_i \) can be obtained by the following equations:

\[ q_w = h_f (T_i - T_w) \] (2)

\[ q_w = h_{conv}(T_b - T_i) + m_{cond}h_{fg}. \] (3)

Here \( h_f \) is the transfer coefficient corresponding to the thermal resistance of condensate film, determined by the Nusselt formula with a correction for the dependence of physical properties of condensate on temperature and a correction accounting for film waviness [9]; \( h_{conv} \) is heat transfer coefficient for turbulent natural convection in the diffusion layer calculated with the correction for the suction effect on heat transfer according to film theory; \( h_{fg} \) is latent heat of vaporization. The mass flux \( m_{cond} \) is calculated by:
\[ m_{\text{cond}} = \rho_{\text{mix,b}} h_m \ln \left( \frac{1 - \omega_{b,i}}{1 - \omega_{b,b}} \right), \]  \hspace{1cm} (4)

where \( \rho_{\text{mix,b}} \) is mixture density in the bulk, \( h_m \) is mass transfer coefficient, \( \omega_{b,i} \) and \( \omega_{b,b} \) - mass fraction of steam at the interface and at bulk conditions.

For vertical wall:

\[ Sh = 0.15 \left( Gr_d Sc \right)^{1/3} \quad \text{for} \quad Gr_d Sc > 10^9, \]  \hspace{1cm} (5)

where \( Sh \) is Sherwood number, \( Gr_d \) - Grashof number for mass transfer, \( Sc \) – Schmidt number for mixture. Mass transfer coefficient \( h_m = Sh D/L \), where \( D \) is the diffusion coefficient, \( L \) – condensing length. Density of steam and noncondensable gas and the diffusion coefficient were calculated with account of deviation of the ideal gas properties at high pressures (p>1 MPa). To calculate heat transfer during condensation of ternary mixtures of steam-air-helium and steam-air-hydrogen, the effective diffusion coefficient was used [10].

Kim [2] presented experimental data on heat transfer during condensation of steam-nitrogen mixture at pressures from 0.4 to 2.0 MPa. Some of these data and results of our study are presented at figure 1 (\( \omega_{N2} \) – mass fraction of nitrogen in the SGM). At relatively low pressures (0.4 and 1.2 MPa), the difference between calculated and experimental data on heat transfer is not more than 20%. When pressure increased to 2 MPa, the largest deviation of the experimental points from the calculated curve was equal to 30%.

![Figure 1](image-url)

**Figure 1.** Heat transfer during condensation of steam – nitrogen mixture: a) \( p = 1.2 \) MPa; b) 2.0 MPa. 1 – experimental data [2], 2 – calculated results

In an emergency situation of the nuclear power plant, the condensing steam-gas mixture in the containment consists mainly of steam, air and hydrogen. Hydrogen is an explosive substance, so experimental laboratory studies are usually conducted with the replacement of hydrogen with helium. In this connection, only the experimental data on the steam-air-helium and the corresponding empirical generalizing formulas are available in the literature [6].

According to the method described above, we calculated the heat transfer coefficients for the condensation of a steam-air-helium mixture and compared them with the experimental data from [6]. The wall temperature in the publication [6] was not indicated for any regime, and therefore it was determined (with some error) by the generalizing formulas given in [6].

In figures 2, 3 the following notation is used: \( \omega_{nc} \), \( x_{nc} \) - mass and mole fractions of noncondensable components in the mixture bulk, \( x_{He} \) and \( x_{H2} \) - mole fractions of helium and hydrogen, respectively.
It can be seen from figure 2 that the maximum discrepancy between the calculated results and the data [6] is about 26% at a pressure of 0.2 MPa. At a pressure of 0.5 MPa, the discrepancy between the experimental data and the results of our calculations is about 9%. Thus, with increasing pressure, the calculated values are located closer to the experimental data [6].

Figure 2. Heat transfer during condensation of steam-air-helium mixture 
\( p = 0.5 \) MPa: a) \( x_{He}/x_{nc} = 0.06 \); b) 0.22. 1 - data [6], 2 – calculated results

Figure 3 shows that the replacement of hydrogen by helium for the conditions realized in [6] (with the same mass fraction of non-condensable gases in the mixture bulk) increases the HTC. This can be explained by the fact that when adding helium to the mixture, instead of hydrogen, the volume fraction of the noncondensable gases of the mixture decreases, and the effect of this factor on HTC is stronger than the decrease in the effective diffusion coefficient and other physical properties of the mixture.

It can be noted, however, that heat transfer coefficients for ternary SGM with helium and for ternary SGM with hydrogen do not differ very much. For example, their difference at pressure of 0.5 MPa and \( x_{He}/x_{nc} = x_{H2}/x_{nc} = 0.06 \) is about 17% (see figure 3). This indicates the possibility of using in the laboratory experiments on the condensation of such SGM helium instead of hydrogen.

Generally, the heat transfer coefficients obtained by calculation using the proposed model are in good agreement with the considered experimental data for both the binary and ternary mixtures.
References
[1] Yan W 2013 Energy Procedia 39 240 – 47
[2] Kim J-W, Lee Y-G, Ahn H-K and Park G-C 2009 Nucl. Eng. Des. 239 688 – 98
[3] Uchida H, Oyama A and Togo Y 1965 Proc. Int. Conf. on Peaceful Uses of Atomic Energy 13 93-102
[4] Liu H-Y, Todreas N E and Driscoll M J 2000 Nucl. Eng. 199 243-55
[5] Anderson M H, Herranz L H and Corradini M L 1998 Nucl. Eng. 185 153-72
[6] Su J, Sun Z, Fan G and Ding M 2013 Nucl. Eng. 262 201-08
[7] Sharma P K, Gera B, Singh R K and Vaze K K 2012 Sci. Techn. Nucl. Install. 2012 Article ID 106759 doi: 10.1155/2012/106759
[8] Dehbi A 2015 Int. J. Heat Mass Transfer 86 1-15
[9] Yagov VV 2014 Heat transfer in single-phase media and in phase transformations (Moscow: MPEI Publishing House) p 372
[10] Reid R, Prausnitz J and Sherwood T 1982 Properties of gases and liquids (Leningrad: Chemistry Publishing House) p 592