

# Studying The Influence Of Concentration On Heat Exchange Intensity And Critical Density Of Heat Flow During Boiling Mixtures And Solutions

Gaffar Avalbaev, Mahzuna Baimuratova, Khozhiakbar Khidirov

**Abstract:** A qualitative analysis of the influence of the concentration boundary layer formed at the surface of steam bubbles on the heat transfer rate and critical heat flux density during boiling of mixtures of mutually soluble liquids and solutions of non-volatile substances is presented. The effect of the coefficient of surface tension on the process of occurrence of a heat transfer crisis during the boiling of mixtures and solutions is shown.

**Index Terms:** boiling, concentration heat exchange, intensity, liquids, solutions, soluble.

## 1. INTRODUCTION

It is known that the heat transfer coefficient  $\alpha$  and critical heat flux density  $q_{kp}$  when boiling mixtures of mutually soluble liquids and solutions of non-volatile substances are a function of the concentration of the components  $c_0$ . Dependencies  $\alpha$  and  $q_{kp}$  on  $c_0$  are very complex. The presence of extrema on the curves  $\alpha = f(c_0)$  in [1, 2], they are explained on the basis of the obtained equations, which determine the probability of the emergence of vapor phase nuclei upon boiling of mixtures and solutions. It follows from these equations, for example, that when boiling binary mixtures, the form of the curve  $\alpha = f(c_0)$  determined by the difference in concentrations of low-boiling (NK) components in the vapor phase  $c_0''$  and in liquid  $c_0 (\Delta c_0'' = c_0'' - c_0)$ , as well as the derivative of concentration by temperature  $dc/dT$ . Given that  $dc/dT < 0$  with increasing value  $\Delta c_0''$  heat transfer rate decreases, and with a decrease  $\Delta c_0''$  -increases. This is in qualitative agreement with the experimental data [3] (Fig. 1). When boiling solutions of non-volatile substances from these equations it follows that with increasing concentration of the solution  $c_0$  the heat transfer coefficient is continuously decreasing. as seen in fig. 2a [4–7], this conclusion is consistent with experiment only in individual sections of the curves  $\alpha = f(c_0)$ . With the exception of KCl and urea solutions, for all other solutions shown in Fig. 2, a, the curves  $\alpha = f(c_0)$  have an extreme minimum. However, it should be noted that experiments with KcL and urea were completed in [4,5] at concentrations substantially lower than the saturation concentration  $c_{0,нас}$ . In these experiments for KCl  $c_{0,нас} = 38\%$ , and for urea -97%. Thus, the absence of an extremum (minimum) in these curves does not exclude the possibility of its occurrence at high concentrations of these solutions

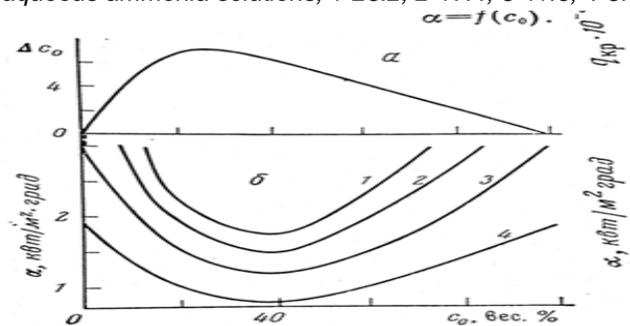
## 2 METHODOLOGY AND CONCLUSIONS

Experience shows that when boiling mixtures of mutually

soluble liquids, the dependence  $\alpha_{kp} = f_1(c_0)$  it turns out to be inverse relationship  $\alpha = f(c_0)$ . In fig. 3 shows the progress of the change  $\alpha$  and  $q_{kp}$  with an increase in the concentration of benzene (NK component) upon boiling of the diphenylbenzene mixture [8]. In [8], an increase  $q_{kp}$  with growth in the initial portion of the curve  $\alpha_{kp} = f_1(c_0)$  It is explained by the fact that an increase in the temperature of the mixture due to its higher concentration in the near-wall region as compared with the saturation temperature in the main volume requires additional heat for heating the fluid flowing to the wall on the main volume. Moreover, the larger the value  $\Delta c_0''$  and the stronger the saturation temperature of the mixture decreases with increasing concentration of the NK components, the greater the difference between the enthalpies of the liquid at the wall and in the volume, and the greater the value  $q_{kp}$ . From the same positions, the second extremum (weaker) on the curve is explained in [8]  $\alpha_{kp} = f_1(c_0)$ .

Thus, by fitting the equations proposed in [1,2], it turned out to be possible to predict the qualitative picture of the change  $\alpha$  and  $q_{kp}$  from the concentration of mixtures. However, we note that these equations do not fully reflect the complexity of the phenomenon under consideration. Noteworthy, for example, is the mismatch of the concentration values at which the maximum on the curve  $\Delta c_0'' = f_2(c_0)$  and minimum on the curve  $\alpha = f(c_0)$ .

**Fig. 1.** Dependence of and (a) on the boiling of solutions of aqueous ammonia solutions; 1-23.2; 2-17.4; 3-11.6; 4-5.8

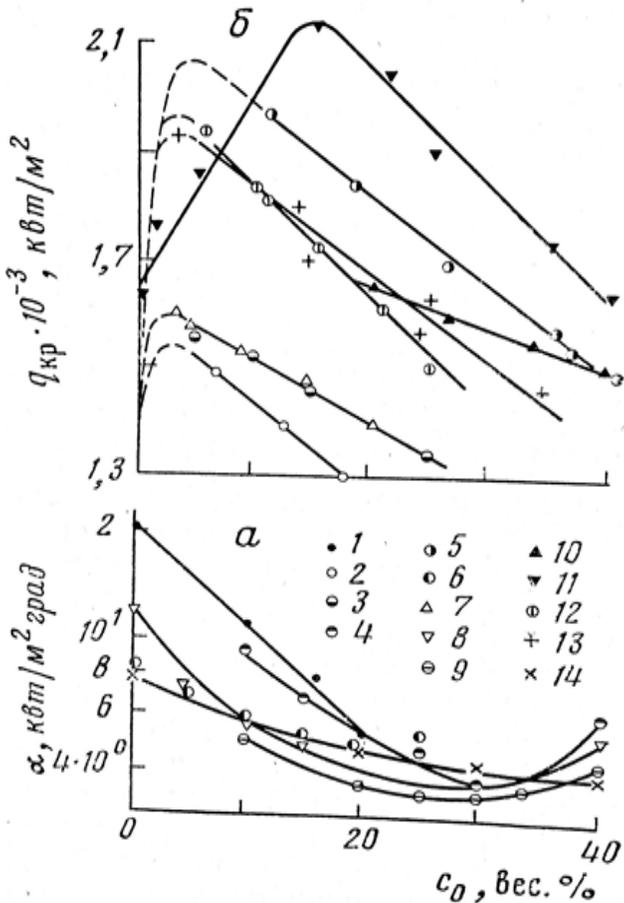


So, when boiling water-ammonia solution, the maximum value  $\Delta c_0''$  set when  $c \approx 25\%$  (Fig. 1, a), and the minimum value for  $c_0 \approx 38\%$  (Fig. 1, b). The same discrepancy is observed during the boiling of the -propyl alcohol - water mixture [9] (Fig. 4) and for the ethyl alcohol - benzene mixture [9] \*. It can be seen from Fig. 4 that on the left side of the graph (up to the

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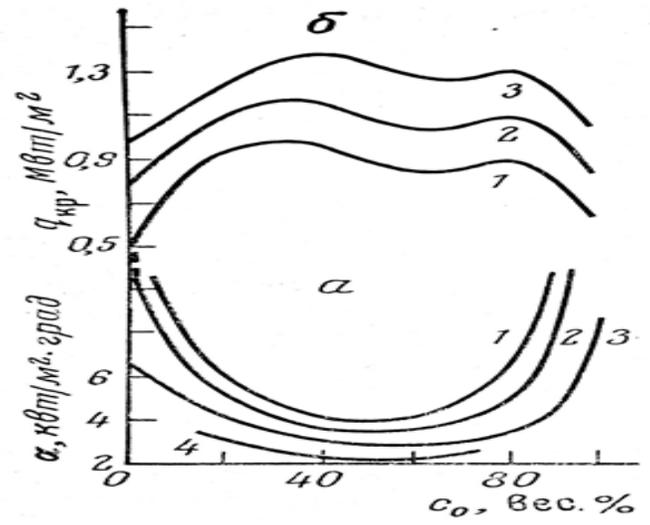
concentration of the azeotropic composition  $c_{az}$  with a decrease in the specific heat flux, the extremum (minimum) shifts toward higher concentrations. So, the course of the curve  $\alpha = f(c_0)$  depends on the value of  $q$ , which is not reflected by the equations proposed in [1,2].

**Fig 2.** Dependence  $\alpha =$  (a) and  $q_{kp}$  (b) from  $c_0$  when boiling solutions of non-volatile substances: 1-KCl,  $q = 245 \text{ kw/M}^2$  [4]; 2- KCl [16]; 3- KCl [7]; 4-KOH,  $q = 108,5 \text{ kw/M}^2$ , circulation rate  $\omega_0 = 0,89 \text{ m/sec}$  [5]; 5-KOH [7]; 6-NaCl,  $q = 100 \text{ kw/M}^2$  [6]; 7-NaCl [7]; 8 - NaOH,  $q = 116 \text{ kw/M}^2$  [7]; 9 - NaOH,  $q = 100 \text{ kw/M}^2$  [6]; 10 - NaOH, [7]; 11- NaOH [16]; 12-boric acid [7]; 14-urea  $q = 6,25 \text{ kw/M}^2, \omega = 0,80 \text{ m/sec}$  [5];

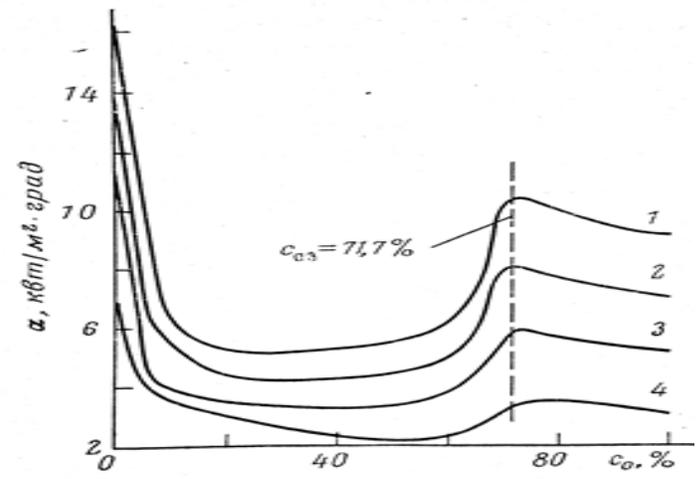


The qualitative analysis of the dependence performed in [8] (essentially based on the same equations)  $\alpha_{kp} = f_1(c_0)$  also does not fully disclose the occurrence of a heat transfer crisis during boiling mixtures of mutually soluble liquids. When explaining the dependency  $\alpha_{kp} = f_1(c_0)$ . First of all, it is necessary to proceed from the fact that in this case the heat transfer crisis is directly related to the hydrodynamics of the two-phase wall layer [10].

**Fig 3.** Addition  $\alpha =$  (a) (at  $q_{kp} = 290 \text{ kw/M}^2, p = 7,8 \text{ bar}$ ) and  $q_{kp}$  (b) (at  $p = 7,8 \text{ bar}$ ) from  $c_0$  benzene at boiling of diphenylbenzene mixtures not heated to saturation temperature [8];  $\Delta T_{нел.} \text{ } ^\circ\text{C}$ ; 1-0; 2-10; 3-30; 4-80



**Fig 4.** Addition  $\alpha$  from  $c_0$  alcohol while boiling a mixture of n-propyl alcohol-water [9];  $q, \text{ kw/M}^2$ ; 1-232; 2-174; 3-116,3; 4-58



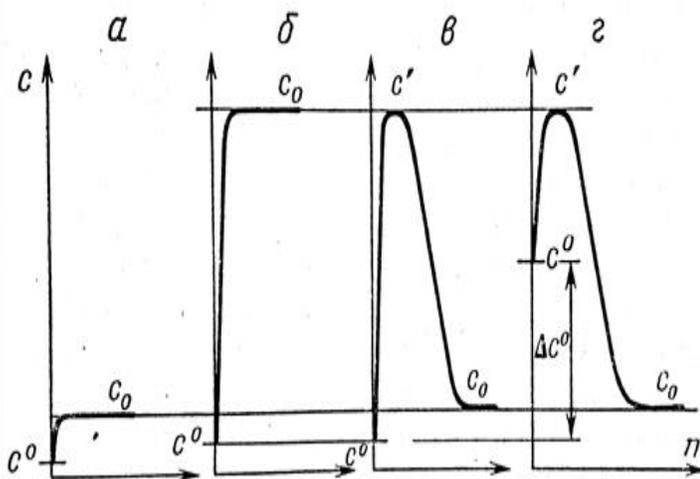
Identity of dependencies  $\alpha = f(c_0)$  for solutions of non-volatile substances and mixtures of mutually soluble liquids, it indicates that when one liquid is dissolved in another or a solid in any solvent, qualitatively new effects of the same physical nature appear that have a significant effect on the heat transfer rate. Therefore, the reason for such a complex dependence  $\alpha$  from  $c_0$  and  $q_{kp}$  when boiling mixtures and solutions, one should look for the features of the heat transfer mechanism due to the presence of a dissolved substance in the liquid. These features consist in the fact that a concentration boundary layer (CPS) with a higher concentration of non-volatile or high boiling (VC) component near the bubble surface is formed around the vapor bubbles growing on the heat-transfer surface of the vapor bubbles  $c'$  compared to its concentration  $c_0$  in the bulk of the liquid [4,8,11-13]. Within this layer, along with the temperature gradient, a concentration gradient always arises. If during the boiling of a solution and a pure solvent the temperature of the

heat-transfer surface is maintained the same, then the appearance of excess temperature depression in the solution around the bubbles  $\delta(\Delta T) > 0$  leads to a decrease in the bubble growth rate  $w_n = dR/d\tau$  and their separation frequencies  $f$  [11,12] \*. The decrease in the magnitude of the indicated internal characteristics of the boiling process is confirmed by the data of the movie shooting [14,15]. So, in [15], it was noted that during the boiling of water – butyl alcohol and water – methyl ethyl ketone mixtures, the values  $w_n$  4-5 times, and  $f$  1.5-3 times less than when boiling pure NK components. The formation of CPS around the bubbles causes a certain increase in the concentration and, correspondingly, the saturation temperature in general in the attached layer — the zone of vapor phase nucleation. As a result, the number of active centers of vaporization decreases  $z$ . With decreasing  $z, w_n$  and  $f$  the intensity of turbulization of the near-wall layer by steam bubbles decreases, and the proportion of heat removed from the wall in the form of heat of evaporation also decreases. Consequently  $\alpha$  when boiling, the solution is lower than when boiling a pure solvent, for which  $\delta(\Delta T) = 0$ . When boiling mutually soluble liquids do not form azeotropic compositions, the value  $\delta(\Delta T_D)$  as the value concentrates, then decreases to zero (for the pure second component) [11]. Value  $\alpha$  in this case, respectively, first decreases to a minimum value, and then with growth  $c_0$  increasing. The effect of KPS on the heat transfer rate during the boiling of mixtures and solutions is manifested not only in a change in the saturation temperature of the solution around the bubble. The fact is that the internal characteristics of the boiling process also depend on the value of the surface tension coefficient of the liquid  $\sigma$  and from the corner  $\theta$ . When boiling solutions of non-volatiles, increasing the concentration of the solution by  $\Delta c = c' - c_0$  entails a special increase  $\sigma$  on  $\Delta\sigma = \sigma' - \sigma_0$ . Here  $\sigma_0$  and  $\sigma'$  - respectively, the surface tension coefficients of the solution at its concentrations  $c'$  and  $c_0$ . An increase in the surface tension coefficient at the phase boundary in terms of external manifestation is equivalent to an additional decrease in the liquid overheating. This is due to the effects of Laplace and Thomson. Thus, when boiling solutions  $\alpha$  decreases not only as a result of exposure to  $\delta(\Delta T_D)$ , but also influenced by  $\Delta\sigma$ . For mixtures of mutually soluble liquids  $\sigma'$  may be more or less  $\sigma_0$  depending on which pure component of the mixture has a greater surface tension coefficient  $\sigma_{0,n}$ . Then, if  $\sigma_{0,n}$  VK components are smaller  $\sigma_{0,n}$  NK components, then in the concentration layer enriched with a high boiling component,  $\sigma'$  will be less than the original mixture ( $\sigma' > \sigma_0, \Delta\sigma > 0$ ). If  $\sigma_{0,n}$  VK components more  $\sigma_{0,n}$  NK components then ( $\sigma' < \sigma_0, \Delta\sigma < 0$ ). Excess depression  $\delta(\Delta T_D)$  causes a decrease  $\alpha$  both when boiling solutions, and when boiling mixtures. Impact  $\Delta\sigma$  on  $\alpha$  is more complex and depending on the sign  $\Delta\sigma$  can lead not only to a decrease, but also to an increase  $\alpha$  (at  $\Delta\sigma > 0$ ). Impact  $\delta(\Delta T_D)$  on  $\alpha$  is usually stronger than  $\Delta\sigma$ , however, when analyzing the heat transfer process during the boiling of mixtures and solutions, it is necessary to take into account the influence of both factors. It follows directly from the foregoing that when boiling mixtures of mutually soluble liquids, the dependences  $\alpha = f(c_0)$  and  $q_{kp} = f_1(c_0)$  must be inverse. Indeed, on the ascending branch of the curve  $\delta(\Delta T_D) = f_2(c_0)$  due to a decrease in the values and the heat transfer intensity decreases, and the critical density of the heat flux increases, since the lower the value  $z, w_n$  and  $f$ ., however, with greater heat flux, the steam bubbles

begin to merge with each other, making it difficult for the liquid to reach the wall. Increase  $q_{kp}$  due to the need to increase the wall temperature to compensate for the effects caused by the decrease in the values  $z, w_n$  and  $f$ . second reason for growth  $q_{kp}$  It is associated with an increase in the amount of heat removed from the wall in the form of excess enthalpy of the liquid [8]. Since with developed boiling, the bulk of the heat is removed from the near-wall region in the form of evaporation heat, the influence of the second factor is weaker than the first. The effects on  $\alpha$  and  $q_{kp}$  heating the bulk of the liquid to saturation temperature  $\Delta T_{\text{нед}}$ . With growth  $\Delta T_{\text{нед}}$  an increasingly colder liquid enters the heat-transfer surface, as a result of which the conditions for the formation and growth of vapor bubbles worsen and, therefore, the likelihood of a heat transfer crisis decreases. Hence, in this case, the main reason for lowering  $\alpha$  and increase  $q_{kp}$  with an increase in underheating (Fig. 3), there is a change in the hydrodynamic situation within the two-phase layer. Marked link between  $\alpha$  and  $q_{kp}$  makes it possible in some cases to predict qualitative dependence  $q_{kp}$  from  $c_0$  by known dependency  $\alpha$  from  $c_0$  for a mixture of mutually soluble liquids, including azeotropically forming, especially when the dependencies  $\alpha$  from  $c_0$  obtained at close to critical heat fluxes. Nature of dependence of  $q_{kp}$  from  $c_0$  for solutions of non-volatiles other than for the mixtures considered above. It can be seen from Fig. 2, b that upon the boiling of solutions over almost the entire studied range of concentration changes ( $c_0 > 3 \div 5\%$ ) critical heat flux decreases with increasing  $c_0$  [7,16]. Similar relationship  $q_{kp}$  from  $c_0$  observed for a number of other non-volatile liquids [7]. An exception is only the experimental data [16] obtained by boiling solutions  $NaOH$  [16]. According to [16], for  $NaOH$  (as with boiling mixtures) curves  $\alpha = f(c_0)$  and  $q_{kp} = f_1(c_0)$  are mutually inverse. However, this is not confirmed by the works [6,7], from which it follows (Fig. 2) that when boiling  $NaOH$  the laws characteristic of solutions of non-volatile substances remain. For highly diluted solutions ( $c_0 > 3 \div 5\%$ ) There are no experimental data on critical heat fluxes; therefore, experimental curves in this concentration range  $q_{kp} = f_1(c_0)$  extrapolated to  $c_0 = 0$  dashed lines in Fig. 2, b). Extrapolation is based on the fact that when boiling clean water at atmospheric pressure ( $q_{kp} = (1,2 \div 1,4) * 10^6 \text{ W/m}^2$ ) and therefore, all the curves in Fig. 2b should go from one point. Thus, at very low concentrations  $q_{kp}$  with growth  $c_0$  increases. Slight increase  $q_{kp}$  with growth  $c_0$  It was also observed at concentrations close to the saturation concentration [7]. The peculiar nature of addition  $q_{kp}$  from  $c_0$  for solutions of non-volatile substances can be explained as follows: the value of the surface tension coefficient at the phase boundary for mixtures is limited from above to below by  $\sigma_{0,n}$  pure components and as a result of enrichment of KPS  $\sigma_{0,n}$  high boiling component tends to  $\sigma_{0,n}$  this component. Very often the components of the mixture have close values  $\sigma_{0,n}$ . In such cases, as  $c_0$  size  $\sigma'$  changes slightly, and accordingly the influence  $\Delta\sigma$  the heat transfer coefficient and critical heat flux density are also weakly manifested. In contrast to mixtures, the surface tension coefficient at the interface  $\sigma'$  when boiling solutions of non-volatile substances increases sharply with increasing concentration  $c_0$  and significantly exceeds  $\sigma_{0,n}$  solvent. In addition, for example, the property of negative surface adsorption is inherent in an aqueous solution of inorganic salts, which qualitatively consists in the fact that as a result of the action of internal interparticle (adsorption) forces,

the concentration of the solute on the interphase surface (in contrast to the previously introduced concept of the interphase surface) is significantly less than in the main volume, as well as in the KPS, and is equal to  $c^0 > c_0 > c'$ . with growth  $c_0$  increases and  $c'$ , lead to a sharp increase  $\sigma^0$ . It is the composition of the solution on the interphase surface that determines the value of the surface tension coefficient [17, 18]. With the intensive formation of interphase surfaces in the development during boiling, the adsorption forces do not have time to rebuild the surface layer [18]. This leads to an increase in  $c'$ , and in the limit.

**Fig. 5.** Concentration fields in the surface and concentration boundary layers of solutions of non-volatile substances with negative surface adsorbent substances with negative surface adsorption.



$c^0$  may become equal to  $c'$ . In fig. Figures 5a and 5b show the concentration fields in a solution of a non-volatile substance in the absence of solvent transfer to the vapor phase (planar interface  $n = 0$ ; to the left of the axis of concentration is the vapor phase, to the right is the solution). From these figures it is seen that in the surface layer of the solution several molecular (ionic) layers thick, a sharp drop in the concentration of the dissolved substance occurs. However, a significant increase in solution concentration  $c_0$  does not lead to a noticeable change in value  $c^0$ . In fig. Figures 5c and 5d show the concentration fields in the solution during an intensive transition of the solvent to the vapor phase with the formation of a CPS, when the adsorption forces have time (Fig. 5, c) and do not have time (Fig. 5, d) to reconstruct the surface layer. Comparing Fig. 5, a, b, with Fig. 5c, d, it can be noted that in the case when the adsorption forces have time to rearrange the surface layer, then with an intensive transition of the solvent to the vapor phase, a significant increase in the concentration of the solution near the surface of the bubble to  $c'$  does not lead to a noticeable increase in  $c^0$ . When the adsorption forces do not have time to rebuild the surface layer, then the concentration of the solution on the interfacial surface  $c^0$  increases markedly (by  $\Delta c^0$ ) and accordingly, the surface tension coefficient increases by  $\Delta \sigma^0$ . Therefore, in relation to processes with a nonequilibrium state of the interphase surface during an intensive transition of the solvent to the vapor phase, the quantity  $\sigma$  not compound solution  $c_0$  (or in the presence of KPS value  $c'$ ), and the composition of the

interface  $c^0$ . Sharp increase of  $\sigma^0$  with growth  $c_0$  when boiling solutions  $c_0$  non-volatile substances leads to a significant increase in the detachable size of the bubbles and to an increase in their residence time on the heat-transfer surface (compared to boiling mixtures). The effect of this effect is not offset by a decrease in the number of active centers of vaporization  $z$ , therefore, when boiling solutions of non-volatiles, the value  $q_{\text{кр}}$  with growth  $c_0$  continuously decreases in the entire interval of change of the latter.

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