

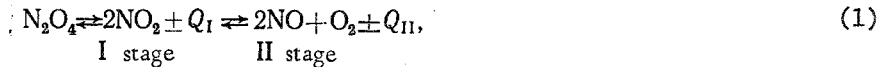
HEAT EXCHANGE DURING THE MOVEMENT OF A VAPOR-LIQUID STREAM
OF DISSOCIATING NITROGEN TETROXIDE

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UDC 536.423.1

The results of studies of heat exchange during the flow of a vapor-liquid stream of a dissociating N_2O_4 system in vertical pipes are analyzed and functions are given for calculating the heat-exchange intensity under different flow conditions.

Of the large class of dissociating substances with reversible reactions one of the greatest practical interest is nitrogen tetroxide, in which two reaction stages of the form



proceed in the temperature range of 300-1000°K during heating and cooling, where Q_I and Q_{II} are the calorific effects of the reactions, equal to 54.6 and 113 kJ/mole, respectively.

The physical properties of the N_2O_4 system permit the use of nitrogen tetroxide as the coolant and working substance of an atomic power plant with a gas-cooled reactor and the obtaining of efficient condensation cycles [1].

The results of studies of heat exchange during the rising movement of a vapor-liquid stream of N_2O_4 in heated vertical pipes under the conditions of natural and forced circulation are reported in the present article. The tests were performed in the pressure range of 0.01-0.8 of p_{cr} (1-80 bars), at heat flux densities of up to 230 kW/m², at mass velocities of up to $3.3 \cdot 10^3$ kg/m²·sec, and with variation in the heat content of the stream from unheated liquid to slightly superheated vapor. The content of process admixtures in the test coolant was 0.4% in conversion to nitric acid. On the basis of the results of the studies the heat-exchange properties of the given coolant are determined from the controlling parameters p , q , w , and x . The experimental conditions and the principal results are presented in [2-4].

In tests with natural circulation at stream velocities of $\rho w \leq 600$ kg/m²·sec and a vapor content of $0.01 \leq x \leq 0.08$ (the mode of bubble boiling) the pressure has a complicated effect on the heat exchange — the heat-exchange coefficients have intermediate extrema ($p = \text{var}$, $q = \text{const}$). A heat-exchange maximum is observed in the region of $p = 12-18$ bars and a minimum in the region of $p = 35-50$ bars (Fig. 1a), with an analysis of the experimental data on $\alpha = f(T_{wa})$ showing that the extremal values correspond to roughly the same wall temperature regardless of the heat flux density. The effect of the heat flux on the heat exchange also varies depending on the pressure (Fig. 1b).

Experiments with the forced movement of the vapor-liquid stream brought out the presence of a large region of vapor contents in which a considerable increase (by two to three times) in the heat-exchange intensity is observed in comparison with the heat exchange during bubble boiling (Fig. 2). With an increase in the pressure and mass velocity and a decrease in the heat flux density this region of vapor contents narrows. Modes of decline in the heat-exchange intensity to values of $\alpha = (8-10)$ kW/m²·deg, called modes with deteriorated heat exchange, are noted with an increase in the vapor content and with a heat flux density $q \geq 100$

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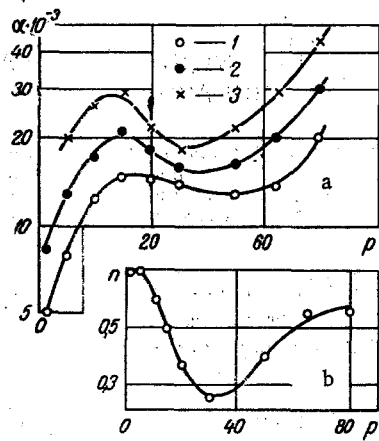


Fig. 1

Fig. 1. Effect of pressure on heat exchange during N_2O_4 boiling [a: dependence $\alpha_q \sim p$, where $q = 0.58 \cdot 10^5$ (1), $1.16 \cdot 10^5$ (2), and $2.30 \cdot 10^5$ W/m^2 (3); b: dependence $n \sim p$ in analysis of experimental data $\alpha_p \sim q^n(p)$]; $\alpha \cdot 10^{-3}$, $W/m^2 \cdot \text{deg}$; p , bars.

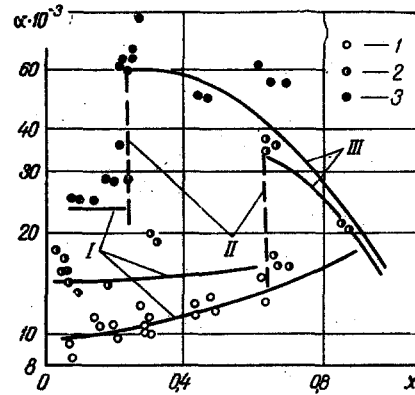


Fig. 2

Fig. 2. Dependence of heat-exchange coefficient on vapor content by weight: $p = 14.7$ bars; $\rho w = 750$ $kg/m^2 \cdot \text{sec}$; 1, 2, 3) $q = 0.58 \cdot 10^5$, $1.16 \cdot 10^5$, and $2.3 \cdot 10^5$ W/m^2 , respectively; I, II, III) calculation from (11), (12), and (13), respectively.

kW/m^2 at a mass velocity of 750 $kg/m^2 \cdot \text{sec}$ and a pressure $p \geq 50$ bars. The latter are distinguished from crises of the second kind in traditional coolants by more intense heat exchange and relatively lower superheating of the wall ($\Delta T = 30-50^\circ K$).

I. Only stage I of the reaction (1), which is characterized by a high rate of establishment of chemical equilibrium in the system upon an external disturbance [5], occurs in the phases during bubble boiling. According to the Gibbs phase rule the presence of a reaction between the components decreases the degree of variation of the N_2O_4 system in phase equilibrium; it becomes monovariant, i.e., has all the features of a simple (individual) substance. The conditions of phase and chemical equilibrium determine the phase composition (or the degree of dissociation of the N_2O_4 molecules), which is different for the vapor and the liquid, which to outward appearances brings the N_2O_4 system closer to binary mixtures.

An analysis of the data obtained in models of N_2O_4 as a simple substance and as a binary mixture of the components N_2O_4 and NO_2 showed that the existing functions unsatisfactorily describe the experimentally observed effect of the pressure and heat flux density on the heat exchange [2, 3], and therefore the usual calculating functions must be supplemented with a parameter which takes into account the specifics of the boiling of dissociating N_2O_4 liquid. However, from the results of a cinematographic study of the heat-exchange mechanism during the boiling of N_2O_4 in the region of $p \leq 20$ bars [6] one can conclude that such characteristics as the separation diameter d_0 of a bubble and the rate of bubble growth dR/dt are close to the calculated values when N_2O_4 is approached as a simple substance. A considerable difference in the bubble separation frequency f from the calculated values is noted (a maximum is observed in the region of $p \approx 5$ bars). When $p < 10$ bars the holding time is almost absent, the holding time increases with a further increase in pressure, and the vapor-generating centers begin to work less regularly. To a certain extent this confirms the hypothesis of a connection between the heat-exchange properties during the boiling of N_2O_4 and the characteristics of nucleation in a dissociating liquid [7].

The authors of [7] analyzed the stability of the superheated liquid phase of N_2O_4 in the form of the characteristics $r_{cr} = f(p, \Delta T)$ on the basis of the variation in the ratio between the conservative force — the surface tension — and the driving force — the difference in the thermodynamic Gibbs potentials of the liquid and vapor phases — with the parameters of the superheated liquid and the conditions of the equilibrium (instantaneous) occurrence of the reaction (1):

$$r_{cr} = \frac{2\sigma}{[g'(p, T) - g''(p, T)]\rho''} \quad (2)$$

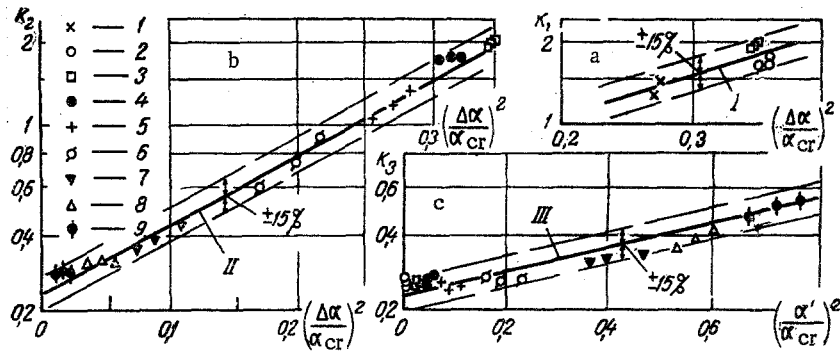


Fig. 3. Effect of the dissociation reaction on the heat exchange during N_2O_4 boiling [1) $p = 1$ bar; 2) 5; 3) 10; 4) 15; 5) 20; 6) 30; 7) 50; 8) 65; 9) 80 bars]: a) dependence of $\ln K_1 \sim (\Delta\alpha/\alpha_{cr})^2$ with $p \leq 10$ bars [I: $\ln K_1 = \ln 0.74 + 2.5 (\Delta\alpha/\alpha_{cr})^2$; $K_1 = Nu_{*1} / [0.125 Re_*^{0.65} Pr^{1/3} \exp (\alpha'/\alpha_{cr})^2]$ [II] $\ln K_2 = \ln 0.235 + (\Delta\alpha/\alpha_{cr})^2$]; b) dependence of $\ln K_2 \sim (\Delta\alpha/\alpha_{cr})^2$ with $p \leq 10$ bars; $K_2 = Nu_{*1} / [0.625 Re_*^{0.5} Pr^{1/3} \exp (\Delta\alpha/\alpha_{cr})^2]$; c) dependence of $\ln K_3 \sim (\alpha'/\alpha_{cr})^2$; $K_3 = Nu_{*1} / [Nu_{*2} \exp \beta (\Delta\alpha/\alpha_{cr})^2]$. [III] $\ln K_3 = \ln 0.235 + 1.05 (\alpha'/\alpha_{cr})^2$.

where $T = T_S(p) + \Delta T$. The difference $\Delta g = g' - g''$ in the specific thermodynamic Gibbs potentials of the liquid and vapor can be represented in the form $\Delta g = \delta g \cdot \Delta T$, where δg is the difference in specific Gibbs potentials which pertains to superheating of the liquid by $1^\circ K$. The two-parameter function $\delta g(p, T)$ can be replaced by the one-parameter function $\delta g(T)$ if one takes $\Delta T = \text{const}$ for the entire range of parameters and allows for the dependence $p = f(T_S)$. The assumptions which allow one to express the value δg through only the entropy $\Delta H/T_S$ of the phase transition are completely valid for simple substances. For the N_2O_4 system the value δg differs somewhat from the entropy of the phase transition, which is seen from an examination of the results of a Taylor series expansion of the function δg (when $\Delta T \ll T$),

$$\delta g \approx \frac{1}{T_s} \left[\Delta H + \frac{(c_p'' - c_p')}{2!} \Delta T \left(1 - \frac{\Delta T}{3T} \right) + \frac{(\partial c_p''/\partial T - \partial c_p'/\partial T)}{3!} \cdot \frac{\Delta T^2}{T} + \dots \right]. \quad (3)$$

In the N_2O_4 system the latent heat of vaporization ΔH increases smoothly with an increase in pressure and reaches a maximum at $p \approx 7$ bars, and the differences $(\alpha'' - \alpha')$ and $(c_p'' - c_p')$ have similar characteristics [5]. In the region of low pressures the specific heat capacity of the vapor exceeds the specific heat capacity of the liquid by several times, and while the degree of dissociation in the liquid phase is insignificant ($\alpha' \approx 0$), in the vapor phase $\alpha'' \approx 0.15-0.25$. The dissociation reactions during the phase transition and in the homogeneous phases affect the properties of the system. If one neglects a certain difference in the calorific effects of stage I of the reaction (1) in the liquid and the gas and assumes the equality $Q_I' \approx Q_I'' = Q_I$, then the variation in the thermodynamic properties of the N_2O_4 system caused by the development of the chemical reaction is conveniently analyzed as a function of the phase composition.

The deviation of the value δg for real N_2O_4 from the $\delta g^*(T)$ for N_2O_4 considered as a simple substance (without a chemical reaction) can be represented in the form of the relation

$$\frac{\delta g(T)}{\delta g^*(T)} \sim \left(\frac{\Delta\alpha}{\alpha_{cr}}, \frac{\alpha'}{\alpha_{cr}} \right), \quad (4)$$

where $\Delta\alpha = \alpha'' - \alpha'$ and α' were determined at the temperature $T = T_S(p) + \Delta T$ from the data of [5], and the degree of dissociation of N_2O_4 at the critical point $\alpha_{cr} = 0.32$ was taken as the scale of variation of the degree of dissociation.

The high wettability of Kh18N10T steel and other structural materials by liquid N_2O_4 (the wetting angle is close to zero) [8] hinders the conditions of nucleation at the solid surface of the heater, making them close to the conditions of boiling up in the superheated homogeneous phase. The reversible operation of nucleation in the form of the equation [9]

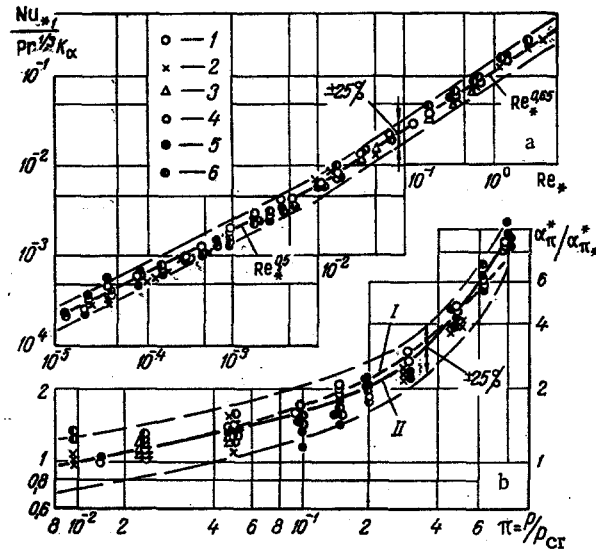


Fig. 4. Analysis of experimental data on N_2O_4 boiling: a) in the coordinates of Eq. (6); results of studies: 1) based on [12]; 2) [13]; 3) [2]; 4) [3], Ser. A; 5) [3], Ser. B; 6) [14]; b) in the coordinates of Eq. (7); I) dependence $\alpha_{\pi}^* / \alpha_{\pi_*}^* = F(\pi) / F(\pi_*)$ based on data of [11]; II) Eq. (8); $\pi_* = 0.01$.

$$J \sim \exp \left[- \frac{\Delta\Phi}{kT} \right], \text{ where } \Delta\Phi \sim r_{cr}^2$$

serves as the determining factor in the variation of the rate of nucleation during homogeneous boiling up. A calculation of r_{cr} by Eq. (2) gives the value $r_{cr} \approx 10^{-6} - 10^{-8}$ m, which is considerably less than the average size of the thermal boundary layer of the liquid, in which the drop in the thermal head $\Delta T = T_{wa} - T_s(p)$ mainly occurs. This allows one to take the temperature of the liquid layer where the boiling up occurs as equal to the temperature of the heating surface ($T = T_{wa}$). This assumption is the more valid, since under the actual conditions the boiling up occurs in recesses of the heating surface in which the temperature of the liquid is practically equal to T_{wa} .

The effect of the influence of the nucleation rate on the heat exchange can be represented in a first approximation by the dependence $\alpha \sim J^C(p)$. The deviation of the experimental data on heat exchange Nu_{*1} from the calculated values Nu_{*2} , which were determined from the critical equation of [10], in the phase composition coordinates

$$\ln [Nu_{*1} / Nu_{*2}] \sim \left(\frac{\Delta\alpha}{\alpha_{cr}} \right)^2, \left(\frac{\alpha'}{\alpha_{cr}} \right)^2,$$

where

$$Nu_* \equiv \frac{\alpha}{\lambda} \left(\frac{r_{cr}}{2} \cdot \rho' \frac{c_p \Delta T}{\Delta H \rho''} \right).$$

is shown in Fig. 3.

According to [10] there are two regions of Re_* with different effects of the heat flux density on the heat exchange. The possibility of analyzing the two regions in the presence of boiling with different effects of the heat flux density has been mentioned in the literature. This assumption has not been justified with respect to ordinary liquids [11]. For dissociating systems, however, in connection with the peculiarities of vapor formation this assumption has a definite advantage in comparison with the interpretation according to which the exponent in the heat flux density is taken as constant. For the N_2O_4 system the boundary between the indicated regions lies at $p \approx 10$ bars. On the basis of an analysis of experi-

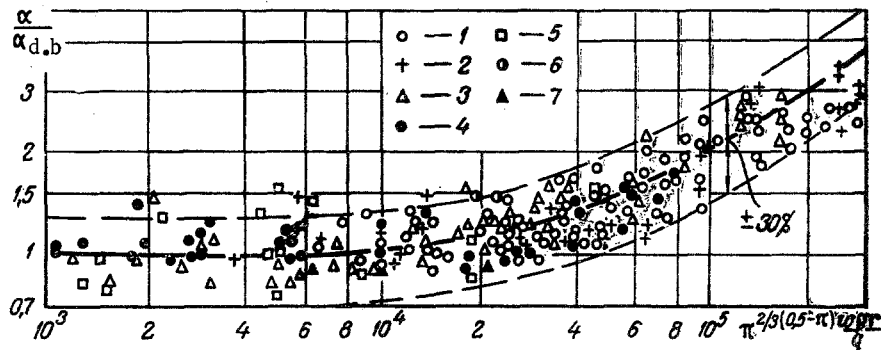


Fig. 5. Heat exchange during the forced movement of a vapor-liquid stream: 1, 2, 3, 4, 5) $p = 14.7, 29.4, 49, 63.7,$ and 78.5 bars, respectively; $d_1 = 4.13$ mm; 6, 7) $p = 14.7$ and 49 bars, respectively, $d_1 = 3.6$ mm.

mental data on the heat exchange and boiling of N_2O_4 under conditions of natural circulation in a pipe [3] an expression for the determination of the adjusting parameter K_α is obtained in the following form:

$$K_{\alpha_1} = 0.74 \exp \left\{ 2.50 \left(\frac{\Delta\alpha}{\alpha_{cr}} \right)^2 + 1.05 \left(\frac{\alpha'}{\alpha_{cr}} \right)^2 \right\}, \quad (5)$$

$$K_{\alpha_2} = 0.235 \exp \left\{ 6.15 \left(\frac{\Delta\alpha}{\alpha_{cr}} \right)^2 + 1.05 \left(\frac{\alpha'}{\alpha_{cr}} \right)^2 \right\}.$$

Accordingly, the adjusting parameter $K_\alpha(T_{wa})$ also takes into account the properties of the heat exchange during N_2O_4 boiling which are connected with the condition of nucleation through the mechanism of the effect of the phase composition on the equilibrium properties of the dissociating system. The criterial equation of [10] for the N_2O_4 system is transformed through the introduction of the parameter K_α :

$$Nu_* = A \cdot Re_*^n Pr^{1/3} K_\alpha,$$

where

$$\begin{aligned} A = 0.125, \quad n = 0.65, \quad K_\alpha = K_{\alpha_1}, \quad \text{when } 5 \geq Re_* \geq 10^{-2}; \\ A = 0.0625, \quad n = 0.5, \quad K_\alpha = K_{\alpha_2}, \quad \text{when } 10^{-2} \geq Re_* \geq 10^{-5}. \end{aligned} \quad (6)$$

The analysis of the results of a study of heat exchange during the boiling of N_2O_4 under the conditions of natural circulation [2, 3] and of free convection [12-14] in the coordinates of Eq. (6) is shown in Fig. 4a; the experimental data are generalized by Eq. (6) with a deviation of $\pm 25\%$ at a confidence of 0.95.

The law of corresponding states allows one to obtain similarity not only of the physical properties of the substances in reduced coordinates, but also similarity of the thermo-hydraulic characteristics of such a complicated process as boiling in the same coordinates because of the similarity of the physical properties. Therefore, the use of the method of thermodynamic similarity for the calculation of the heat exchange during the boiling of many substances, especially little-studied substances, has given positive results. In this light it seems interesting to analyze the data on heat exchange during N_2O_4 boiling in a coordinate system of thermodynamic similarity with allowance for the effect of the phase composition on the heat exchange:

$$\alpha = Aq^n F(\pi) K_\alpha(T_{wa}), \quad (7)$$

where $A = 6.4$ and $n = 0.65$ when $0.01 \leq \pi \leq 0.1$; $K_\alpha = K_{\alpha_1}$ when $300 \leq T_{wa} \leq 360^\circ K$; $A = 40$ and $n = 0.5$ when $0.1 \leq \pi \leq 0.8$; $K_\alpha = K_{\alpha_2}$ when $360 \leq T_{wa} \leq 425^\circ K$;

$$F(\pi) = \pi^{0.18} (1 + 0.8\pi + 2.0\pi^2 + 3.0\pi^3). \quad (8)$$

With a fixed heat flux the heat-exchange coefficient is found by the iteration method, since K_α is a function of T_{wa} . Equation (8) is similar to the dependence of [11] which

describes the effect of the pressure on the heat exchange during the boiling of thermodynamically similar substances (water, alcohols, etc.) in reduced coordinates, and it differs from the latter by ~20%. The results of the generalization of the experimental data in accordance with the dependence (7) are presented in Fig. 4b.

The structure of Eq. (7) allows one to explain the peculiarities of the heat-exchange characteristics observed in the experiments as the effect of the interaction of the heat flux, the physical properties at the line of saturation [the parameter $F(\pi)$], and the properties of nucleation in a dissociating liquid (the parameter K_α).

II. The results of the study of heat exchange during the forced movement of nitrogen tetroxide were analyzed with allowance for the modes of flow of a vapor-liquid stream.

The experimental data obtained with surface boiling of the liquid which is underheated with respect to the saturation temperature are described satisfactorily by Bogdanov's equation [15], which can be recommended in the range of $-0.3 \leq x \leq 0.05$ and $0.15 \leq \pi \leq 0.5$:

$$\alpha = C_0 \left(\frac{p_{cr}}{p} \right)^{0.12} \left(\frac{T_s}{T_{cr} - T_s} \right)^{2/3} q^{0.7} \left[1 + x \left(\frac{w_{mix}}{w_*} \right)^{0.16} \right]^{-2.8}, \quad (9)$$

where $C_0 = 0.55$ for N_2O_4 and w_* is the stream velocity at which the transition from a laminar to a turbulent mode occurs.

The bubbling mode of flow during the forced movement of a two-phase stream is preserved in the region of vapor contents of $x \leq 0.1$. The heat-exchange coefficients obtained differ slightly from α for boiling under the conditions of natural circulation and free convection, although a better generalization of the experimental data (with a deviation of $\pm 25\%$) for high velocities and $x \approx 0.05$ is achieved by the empirical dependence

$$\begin{aligned} \alpha_{d,b} &= (38.06 - 2.92\pi^{-1}) q^{0.57} \text{ when } \pi \leq 0.15 \leq \pi \leq 0.49, \\ \alpha_{d,b} &= (90.7 - 28.6\pi^{-1}) q^{0.57} \text{ when } \pi \leq 0.49 \leq \pi \leq 0.78. \end{aligned} \quad (10)$$

The heat exchange in a disperse-annular mode of flow is usually calculated from empirical functions, since a strict analytical solution of this problem does not exist owing to its extreme complexity and the absence of sufficient factual material on the detailed characteristics of the process. A most simple means of allowing for the mutual effect of the boiling process and the directed movement of the stream, which in one form or another has found wide application in the description of heat exchange in two-phase streams in the presence of heating, has been proposed by Kutateladze [16] and by Borishanskii et al. [17]. Taking this method as the basis and allowing for the peculiarities of the effect of the pressure on the heat exchange during N_2O_4 boiling by a special multiplier, an empirical function was obtained which satisfactorily (with a 40% deviation at a confidence of 0.95) generalizes the test results in the region of the disperse-annular mode of flow (Fig. 5):

$$\frac{\alpha}{\alpha_{d,b}} = \sqrt{1 + \pi^{(0.5-\pi)} \cdot 10^{-7} \left(\frac{w_{mix} \rho' \Delta H}{q} \right)^{3/2}}. \quad (11)$$

As indicated above, in a vapor-generating channel of considerable length one observes an anomalous increase in the heat exchange to a two-phase stream, which can be explained as follows. In the presence of a certain combination of the velocity of the vapor-liquid stream and the rate of vapor formation the intensive removal of liquid from the boundary layer sets in and the thickness of the liquid film decreases considerably. A calculation of the trajectories of movement of drops in the channel showed that intensive sprinkling of the channel wall occurs in this region and evidently a certain balance of the mass fluxes sets in: of evaporating and removed liquid and of precipitating drops. Bubble boiling is also possible with small vapor contents in the liquid film, and, in addition, the precipitating drops of liquid turbulize the film: these factors decrease the thermal resistance of the liquid boundary layer. The intensive mass exchange between the core of the stream and the wall, the high intensity of convective heat exchange of the vapor phase of N_2O_4 , and the small thermal resistance of the film lead to the observed effect. This phenomenon in such a clearly expressed form is evidently peculiar to the N_2O_4 system and as far as we know it has not been studied experimentally and theoretically before.

As the vapor content increases, the core-wall mass exchange deteriorates, the boiling in the film is suppressed, and the heat exchange gradually deteriorates down to the region of purely convective heat exchange of the gas phase.

A possibility of a transition to a mode with improved heat exchange is found from the condition $(q/\Delta H \rho'' w_{\text{mix}})/\pi \leq 3.45 \cdot 10^{-3}$. The velocity of the mixture at which the transition to a mode with improved heat exchange occurs is well determined by the following semiempirical dependence:

$$w_{\text{cr,mix}} = 74.5 \cdot 10^{-4} \frac{\sigma}{\mu''} \left(\frac{\rho'}{\rho''} \right)^{0.5} [1 + 10^{-6} (\pi w \rho')^2] (1 + 10^{-3} q/\Delta H)^{-1.5} \left[\frac{1}{(1-\pi)^2} - 3\pi \right]. \quad (12)$$

The experimental data in the zone of improved heat exchange were generalized with the help of the dependence of I. I. Paleev and F. A. Agafonova, obtained for a disperse vapor-liquid stream and transformed in application to N_2O_4 :

$$\text{Nu} = 55 \left[\frac{10^3 + q/\Delta H}{w \rho} \left(\frac{1-x}{x} \right) \right]^{0.5} \text{Re}_{\text{mix}}^{0.6} \text{Pr}_{\text{mix}}^{0.38} \frac{c_{p,\text{eff,mix}}}{c_{p,\text{mix}}}, \quad (13)$$

where

$$\begin{aligned} \text{Re}_{\text{mix}} &= \left(\frac{w' d_r}{v'} + \frac{w'' d_r}{v''} \right); \quad \text{Pr}_{\text{mix}} = \frac{\text{Pr}' \text{Pr}''}{x \text{Pr}' + (1-x) \text{Pr}''}; \\ \text{Nu} &= \frac{\alpha d}{\lambda_{f,\text{mix}}}; \quad \lambda_{f,\text{mix}} = \frac{\lambda' \lambda''}{x \lambda' + (1-x) \lambda''}; \\ c_{p,\text{eff,mix}} &= \frac{c'_p c''_{p,\text{eff}}}{x c'_p + (1-x) c''_{p,\text{eff}}}; \quad c_{p,\text{mix}} = \frac{c'_p c''_{p,\text{f}}}{x c'_p + (1-x) c''_{p,\text{f}}}. \end{aligned}$$

In Eq. (13) additional allowance was made for the effect of the heat flux, the vapor content, and the mass flow rate on the heat exchange (the factor in brackets). The effect of the heat of the chemical reaction of dissociation on the convective heat exchange of the vapor phase of the coolant (1) is taken into account in the right side of Eq. (13) through the ratio of the effective heat capacity of the mixture to the "frozen" heat capacity.

Equation (13) applies to the region of vapor contents $x_{\text{b0}} \leq x \leq 0.95$, where x_{b0} can be found from w_{cr} and the operating parameters of the stream ($p, \rho w, q$).

Satisfactory agreement between the experimental results and a calculation of the wall temperature with deteriorated heat exchange is obtained using the method of Forslund and Rohsenow [18]. Changes which allow for the properties of heat exchange in the gas phase of N_2O_4 under the conditions of the occurrence of the first stage of the reaction are introduced into this method [19].

The graphs I, II, and III, constructed on the basis of calculations by Eqs. (11), (12), and (13), are plotted in Fig. 2 as an illustration. The satisfactory agreement of the calculated and experimental results is seen.

It should be pointed out that this method of generalization of the experimental data on the bubble boiling of N_2O_4 is based on the thermodynamic approach to the explanation of the observed effects and does not allow for the surface conditions, whose role may be decisive in a certain region of the parameters. For example, in [13] an attempt is made to explain the properties of N_2O_4 heat exchange by the presence of high-boiling admixtures and a small wetting angle. At the heating surface, especially in the presence of process admixtures in the coolant (HNO_3 and H_2O), a number of complicated unstable compounds of the solvate and hydrate type are formed which sharply alter the properties of the system (the viscosity, saturation temperature, etc.).

Measurements which have been made [20] have shown an increased (by 5-10 times at $x = 0.8-0.9$) content of high-boiling process admixtures ($\text{HNO}_3, \text{H}_2\text{O}$) in the boundary layer of liquid during the movement of a vapor-liquid stream in a heated pipe, and in [5] an increased rate of corrosion of stainless steels in the zone of phase transitions of N_2O_4 is noted which is evidently interrelated. A quantitative analysis of the effect of these factors on the heat exchange during the boiling of the N_2O_4 system is difficult at present and will become possible after the accumulation of additional experimental material.

Thus, the analysis of the results of studies of the heat exchange during the boiling of the N_2O_4 system under different conditions and modes of flow made it possible to construct empirical and semiempirical functions which generalize the experimental data with a certain

reliability. However, far from all the aspects of the mechanism of heat and mass transfer during the boiling of chemically reacting systems are sufficiently clear, which demands the performance of additional experimental and theoretical studies and the corresponding refinement of the proposed functions.

NOTATION

p , pressure; T , temperature; α , heat-exchange coefficient; α^a , degree of dissociation of N_2O_4 phases at the saturation line; q , heat flux density; $\pi = p/p_{cr}$, reduced pressure; w , velocity; $x = (H - H_g)/\Delta H_g$, vapor content by weight; H , enthalpy; ρ , density; r , ΔH , heat of evaporation; σ , coefficient of surface tension; ν , coefficient of kinematic viscosity; μ , coefficient of dynamic viscosity; ρw , mass velocity; c_p , specific isobaric heat capacity; λ , coefficient of thermal conductivity; Nu , Re , Pr , $Nusselt$, $Reynolds$, and $Prandtl$ numbers, respectively. Indices: ', liquid phase; ", vapor phase; mix, mixture; wa, heating surface; cr, critical parameters; eff, effective properties; f, "frozen" properties; s, properties at saturation line; d.b, developed boiling.

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