DETERMINATION OF HEAT TRANSFER RATE IN BOILING OF SALT SOLUTIONS BY USING SIMILARITY THEORY AND MOLECULAR CHARACTERISTICS

I. A. Cherepennikov

UDC 536.423.1

An approximate dimensionless equation for the heat transfer coefficient in the boiling of solutions is obtained.

The heat transfer coefficient in the boiling of solutions is usually determined at present from the very simple empirical formula

$$\alpha_p = Aq^n p^m. \tag{1}$$

In (1) A, n, and m are found experimentally for each solution, which is extremely laborious.

Some investigators [1] propose dimensionless equations which have the same structure as the corresponding relationships for unary liquids. It is impossible to use such equations in practice, however, owing to the absence of thermophysical characteristics in the literature. These difficulties are almost completely removed by using the theory of corresponding states. This theory was used by Lukomskii, Borishanskii, Novikov, and Rychkov to determine the heat transfer rate [3].

The most effective method of applying the theory of corresponding states to boiling has been developed by Borishanskii [4-7].

This method is based on the combined use of the system of integrodifferential equations representing boiling heat transfer and the law of corresponding states for the physical characteristics of the liquid. For nucleate pool boiling [6]

$$\alpha = 190 \frac{p_{cr}^{1/3}}{T_{cr}^{5/6} M^{1/6}} \left(\frac{p}{p_{cr}}\right)^{0,1} \left[1 + 4.65 \left(\frac{p}{p_{cr}}\right)^{1,16}\right] q^{2/3}, \tag{2}$$

where T_{cr} is the critical temperature, °K; M is the molecular mass; p_{cr} is the critical pressure, N/cm^2.

In [4-7] the use of the physical constants of the medium was avoided. It is important to note that formula (2) is more accurate than the dimensionless equations obtained by the usual method. Unfortunately, this successful method cannot be applied to boiling aqueous solutions of mineral salts, since even the minimum information for them, such as p_{cr} and T_{cr}, has not been published.

A preliminary analysis [15] of NaCl, LiCl, and LiBr solutions on the basis of the data of [8, 9] showed that the properties of aqueous solutions of mineral salts and the solvent (water) vary almost similarly with temperature, to within 10% of the average. Hence, the physical constants are proportional, and so are the values of α for the solution and solvent

$$\alpha_S = \alpha_W N_\alpha, \tag{3}$$

where N is a conversion factor [10]. In addition, the dimensionless equation for boiling of a one-component liquid can be used to determine α_S.

Alteration of the concentrations of solutions produces substances with new physical parameters. Hence, the conversion factors N are a function of the concentration and properties of the dissolved component. The latter can be expressed by the molecular characteristic l_S

Institute of Chemical Engineering, Tambov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 17, No. 6, pp. 1102-1105, December, 1969. Original article submitted November 26, 1968.

$$N = f(k_v,\ l_s). \tag{4}$$

For the introduction of (4) into the dimensionless equation we put this expression in relative power form

$$N = C\left(\frac{k_v + k_{sat}}{k_{sat}}\right)^a \left(\frac{l_s}{l_w}\right)^b$$

or

$$N = C\beta^a L^b. \tag{5}$$

In view of the lack of published data for the majority of physical constants of solutions we propose to use as a characteristic dimension l_s – the diameter of a sphere with volume equal to the nominal volume of the molecule. Its volume depends on the density of packing of the molecule [14]. The properties of a substance depend on the molecular structure. The structure depends mainly on the number of atoms n in the molecule, the number of electron shells ΣC, the sum of nuclear charges ΣE, and the number of electrons in the outer electron shell ΣE. The procedure for calculation of these characteristics is given in [14].

For a one-component substance

$$l = \sqrt[3]{\frac{(\Sigma C)(\Sigma E)}{M(\Sigma E)}}. \tag{6}$$

The value of l_s for a solution depends on the concentration and is found from [15].

The equation recommended in [11] for boiling water is

$$Nu_w^* = C_1 (Re^*)_w^{n_5} Pr_w^{n_6}. \tag{7}$$

In view of the approximate similarity of the properties of water and a solution, the generalized variables of water can be expressed in terms of the solution criteria using equations of type (3). Equation (7) can be converted to the form

$$Nu_s = C_2 (Re^*)_w^{n_1} Pr_w^{n_2} \beta^{n_3} L^{n_4}. \tag{8}$$

The Nusselt number in (8) includes the thermal conductivity λ_s. There are published values of this quantity at t = 20°C for most solutions. For a characteristic temperature other than 20°C the Riedel method [2] can be used

$$\lambda_s = \lambda_{t=20} f.$$

Values of f are given in [2]. The thermal conductivity is the only constant of the solution in Eq. (8).

Treatment of the experimental data of [12] for boiling $CaCl_2$ solutions leads to the following particular form of the dimensionless equation:

$$Nu_s = 2520\, Re_w^* Pr_w^{0.333} \beta^{-6/\beta^2} L^{-6}. \tag{9}$$

Expression (9) is valid for pool boiling of aqueous solutions of mineral salts if:

$$Re_w^* = 1.6 - 3.1; \quad L = 0.956 - 1.06;$$
$$Pr_w = 1.5 - 1.7; \quad \beta = 1.03 - 1.825; \quad p = 1.013 \text{ bar}.$$

In the calculation of the dimensionless quantities and k_{sat} the temperature of the heating surface is used as a characteristic temperature (provided that the boiling liquid is water)

$$t_w = t_w'' + \Delta t, \tag{10}$$

where

$$\Delta t = \frac{q}{\alpha} = \frac{q}{3.14q}.$$

The accuracy of (9) was checked from the experimental data of [13] with the individual properties of the apparatus for KNO_3 solutions (B = 10, 20, 40%) and NaCl solutions (B = 10, 15, 20%) taken into account, and also from my experimental data for boiling $MgSO_4$ (B = 10, 15, 20%), KBr (B = 10, 20, 29.3, 37%), and KCl (B = 10, 16, 20%) solutions.

The maximum deviation of the calculated values of α_s from the experimental values was ±25%.

NOTATION

α_w, α_s	are the heat transfer coefficient for water and solution, $W/m^2 \cdot deg$;
q	is the heat flux density, W/m^2;
p	is the pressure of boiling liquid;
Nu_s, Nu_w^*, Nu_s^*	are the Nusselt number for boiling water and solution;
$Nu_w^* = \alpha_w l_w^*/\lambda_w$, $Nu_s^* = \alpha_s l_s^*/\lambda_s$, $Nu_s = \alpha_s l_s/\lambda_s$	are expressions for these three numbers in terms of initial variables;
l_w^*, l_s^*	are characteristic dimension for water and solution according to Labuntsov [11];
l_w, l_s	are proposed characteristic dimension for water and solution from [15];
Pr	is the Prandtl number;
C, C_1, etc.	are constant coefficients;
Re_w^*	is the Reynolds number from [11];
k_v	is the variable concentration, g salt/100 g of water;
k_{sat}	is the concentration of saturated solution corresponding to characteristic temperature;
β	is the variable relative concentration, $\beta = (k_v + k_{sat})/k_{sat}$;
L $L = l_s/l_w$;	is the relative characteristic dimension;
t_w^{π}	is the water saturation temperature, °C.

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