APPLICATION OF THE THERMODYNAMIC SIMILARITY THEORY TO THE GENERALIZATION OF EXPERIMENTAL DATA ON HEAT TRANSFER OF BOILING ORGANIC HEAT-TRANSFER AGENTS

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The authors give a relationship for calculating the heat transfer coefficient for boiling organic heat-transfer agents based on the thermodynamic similarity theory.

One of the most promising methods of processing experimental data on heat transfer of boiling liquids is the application of the thermodynamic disimilarity theory described by Novikov [1], Borishanskii [2], Povarnin [3], and others. The thermodynamic similarity theory is based on the law of corresponding states, which holds within a certain group of thermodynamically similar substances; according to this law the thermodynamic properties of thermodynamically similar liquids obey the following general relations:

$$\chi_i = f(M/g,\ \rho_{cr},\ T_{cr},\ v_{cr})\,\psi(p/\rho_{cr},\ T/T_{cr},\ C_{v_0}/R). \quad (1)$$

The actual form of functions (1) may vary. It is essential only that the factor consisting of the most important thermodynamic parameters of the liquid and the mass of its molecule have the units of the quantity considered and that the sign of the function Ψ preceedes at least one of the three given parameters. We now show how this basic concept of the thermodynamic similarity theory can be used to generalize the experimental data on heat transfer to or from boiling liquids.

We assume that the system of differential equations, which in its general form describes the heat transfer process during boiling, yields the criterial relation

$$F(K_1,\ K_2,\ K_3,\ \ldots,\ K_n) = 0.$$

This equation can be solved with respect to the heat transfer coefficient, and the terms associated with the thermodynamic properties, on the one hand, and the terms associated with the geometric and operational parameters, on the other, can be separated, i.e.,

$$\alpha = \Phi(\mu,\ \sigma,\ \lambda,\ c_p,\ r,\ \ldots)\,\varphi(q,\ w_0,\ \beta,\ l,\ d_{eq},\ \ldots). \quad (2)$$

Analysis of numerous experimental data shows that in the conditions of developed boiling

$$\varphi(q,\ w_0,\ \beta,\ l,\ d_{eq},\ \ldots) \sim q^{0.7}. \quad (3)$$

Then, with Eqs. (1) and (3), equation (2) may be written as follows:

$$\alpha/q^{0.7} = f(M/g,\ \rho_{cr},\ T_{cr},\ v_{cr})\,\psi(p/\rho_{cr},\ T/T_{cr},\ C_{v_0}/R). \quad (4)$$

We represent the function f in (4) as a power monomial and remember the following facts: a) $v_{cr} = RT_{cr}/p_{cr}$; b) for a boiling liquid P_{cr} and T_{cr} are interrelated and, consequently, one of the parameters of the function Ψ can be eliminated; c) for liquids with identical molecular structures and the same type of interatomic bonds the effect of C_{v_0}/R may be neglected. Then Eq. (4) can be rewritten as follows:

$$\alpha/q^{0.7} = (M/g)^{n_1} p_{cr}^{n_2} T_{cr}^{n_3} R^{n_4}\,\psi(p/p_{cr}). \quad (5)$$

The exponents of the factors in front of $\Psi(p/p_{cr})$ can be selected by coordinating the units of the left-hand and the right-hand sides of Eq. (5). The determination of n_1 through n_4 thus effected yields the following equation:

$$\alpha = C\left(\frac{gR}{M}\right)^{0.15} \frac{p_{cr}^{0.3}}{T_{cr}^{0.85}}\, q^{0.7}\,\psi\left(\frac{p}{p_{cr}}\right). \quad (6)$$

Borishanskii and Kozyrev [4] obtained a similar equation. The specific form of the function $\Psi(p/p_{cr})$ was found by these workers by processing experimental data on the boiling of water and ethanol, methanol, hepthane, pentane, and benzene. As a result the following equation may be recommended:

$$\alpha = 190\,\frac{p_{cr}^{1/3}}{T_{cr}^{2.3} M^{1/3}} \left(\frac{p}{p_{cr}}\right)^{0.1} \left[1 + 4.65\left(\frac{p}{p_{cr}}\right)^{1.16}\right] q^{0.7}. \quad (7)$$

The experimental data of the authors of the present paper on the boiling of diphenyl mixture (DPM) and monoisopropyldiphenyl (MIPD) in a tube and annular channels of a circuit with natural circulation at pressures of $10^5 - 8 \cdot 10^5$ kN/m^2 and heat flow-rates of $50 \cdot 10^3 - 380 \cdot 10^3$ W/m^2 were compared with the results of calculations from (7). The comparison revealed marked differences between the heat transfer coefficients obtained by experiment and those calculated from Eq. (8). This is obviously due to the fact that the function $\Psi(p/p_{cr})$ obtained by Borishanskii and Kozyrev is not a universal equation suitable for a wide range of liquids. In fact, there is no reason to consider water, alcohols, alkanes, and polyphenyls thermally similar. Even the critical coefficients, quite apart from the structure of the molecules and the interatomic bonds, are quite different. At the same time, diphenyl mixture, monoisopropyldiphenyl and other aromatic hydrocarbons (diphenyl, diphenylbenzene, ditolylmethane)

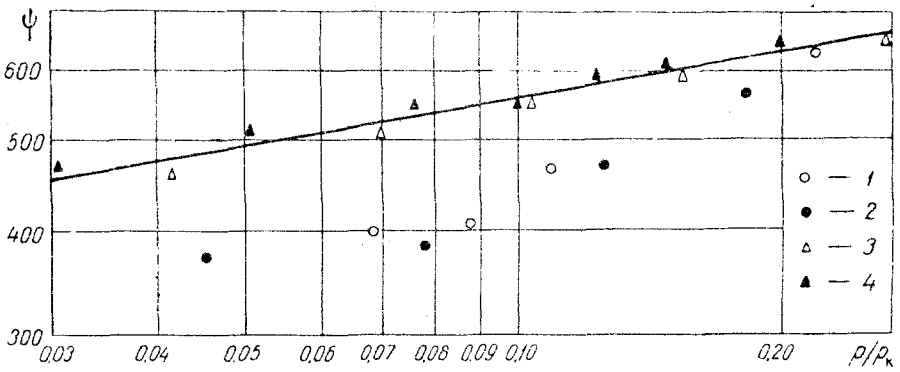

Fig. 1. Processing of experimental data on boiling of DPM and MIPD (tests carried out by the authors), water and ethanol [2] for determining the form of the function Ψ (p/p_{cr}): 1) water; 2) ethanol; 3) monoisopropyl-diphenyl (MIPD); 4) diphenyl mixture (DPM).

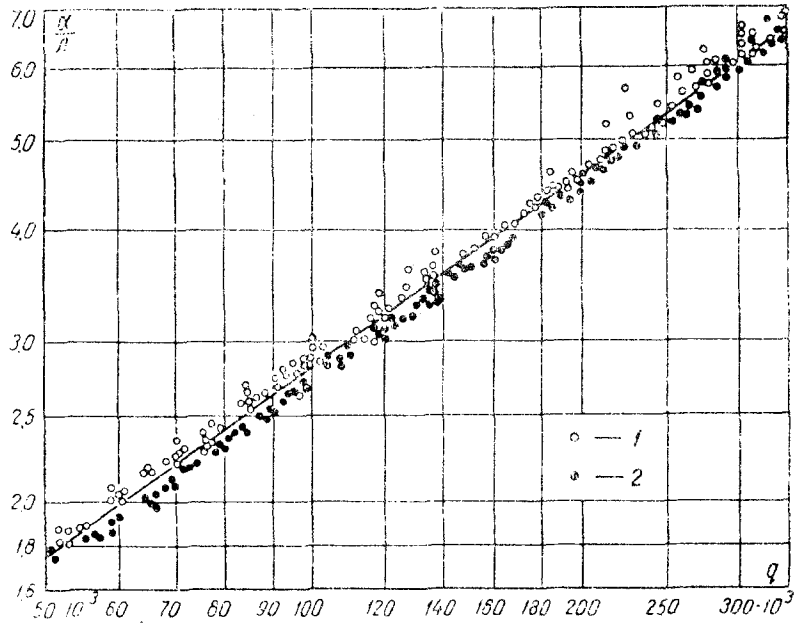

Fig. 2. Processing of experimental data p (bar), T (°K), q(W/m^2) on boiling in the coordinates of Eq. (8):

$$A = \frac{p_{cr}^{0.3}}{M^{0.12} T_{cr}^{0.51}} \left(\frac{p}{p_{cr}}\right)^{0.2};$$

1) diphenyl mixture; 2) monoisopropyl-diphenyl.

may be considered to be thermodynamically similar and the function $\Psi(p/P_{cr})$ must be the same for all these substances. In Fig. 1 the experimental data on the boiling of DPM and MIPD are given in

$$\alpha / \frac{p_{cr}^{0.3}}{M^{0.15}T_{cr}^{0.85}} q^{0.7} = \psi\left(\frac{p}{p_{cr}}\right)$$

coordinates. For comparison the graph gives Borishanskii's experimental data [2] on water and ethanol processed in the same way. The graph shows that the experimental points for boiling water and ethanol differ considerably from the experimental points obtained with DPM and MIPD, which within a scatter range of ±10% agree with the relation

$$\psi(p/p_{cr}) = B(p/p_{cr})^{0.2}.$$

Figure 3 gives the experimental data on the boiling of DPM and MIPD in the coordinates

$$\alpha / \frac{p_{cr}^{0.3}}{M^{0.15}T_{cr}^{0.85}} \left(\frac{p}{p_{cr}}\right)^{0.2} = f(q). \quad (8)$$

The graph shows that the experimental data are in a good agreement with the relation

$$\alpha = 465 \frac{p_{cr}^{0.3}}{M^{0.15}T_{cr}^{0.85}} \left(\frac{p}{p_{cr}}\right)^{0.2} q^{0.7}. \quad (9)$$

The equation thus obtained can be used to calculate the heat transfer coefficient for the boiling of organic heat-transfer agents thermodynamically similar to DPM and MIPD from data on the critical parameters of the boiling liquid and its molecular weight.

NOTATION

χ_i—arbitrary thermodynamic constant; μ—viscosity; σ—surface tension; λ—thermal conductivity; c_p—specific heat at constant pressure; c_{v_0}—molar specific heat in the ideal gas state; r—heat of evaporation; M—molecular weight; g—acceleration due to gravity; p—pressure; p_{cr}—critical pressure; T—temperature; T_{cr}—critical temperature; v_{cr}—critical specific volume; R—universal gas constant; q—specific heat flowrate; w_0—circulation velocity; β—true volume steam vapor content; l—linear dimension of heating surface; d_{eq}—equivalent diameter.

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