POSSIBILITY OF STUDYING PSEUDOBOILING AS A TWO-PHASE SYSTEM

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It is shown that surface tension acts at the boundaries of pseudobubbles. This makes it possible to regard pseudoboiling as a two-phase system.

Heat transfer to liquids under supercritical pressures (SCP) and high temperature gradients is accompanied by significant changes in the thermophysical properties of the liquid, but no phase transformations occur in this instance. This makes it possible to analyze the heat transfer using methods developed for single-phase systems [1].

However, if the heat transfer at SCP occurs when the liquid is heated to a temperature significantly below the pseudocritical temperature and the heat-transfer surface is heated to a temperature significantly in excess of this temperature, i.e., when there is "cold liquid" away from the wall of the vessel and "hot gas" near the wall, then the heat transfer cannot be described by the laws used for single-phase systems. In this case so-called pseudoboiling occurs. The characteristics of pseudoboiling are similar to heat transfer in the case of subheated boiling at subcritical pressures: both process take place with high heat fluxes, when $T_q < T_s < T_w$ (subheated boiling), and when $T_q < T_m < T_w$ (pseudoboiling); they differ in the heat-transfer rates, which are reduced sharply at certain heat fluxes; in the turbulent pipe flow of liquids, these processes cause an increase in hydraulic resistance and, under certain conditions, may be accompanied by spontaneous thermoacoustic oscillations.

All of the above-mentioned features become less pronounced with an increase in pressure.

Several works [2-8] have studied heat transfer with pseudoboiling, but no methods of calculating it have yet been developed. This is probably due to uncertainty over which methods of analysis should be used as a basis for the calulation: methods developed for two-phase systems or methods developed for single-phase systems.

The features of heat transfer with pseudoboiling are not described by the laws of heat transfer in single-phase systems even if allowance is made for the specific changes in the thermophysical properties of the liquid in the region of pseudocritical temperatures. However, the use of the laws of heat transfer in two-phase media to analyze this process is incorrect from the point of view of equilibrium thermodynamics, in accordance with which phase transformations cannot take place at SCP.

But can the process of heat transfer with pseudoboiling be regarded as a single-phase system. Numerous photographs of the process show that this system is two-phase, with the pseudobubbles having boundaries as distinct as the boundaries of vapor bubbles in the case of subheated boiling. This does not contradict equilibrium thermodynamics, since its laws cannot be extended to cover such a strongly nonequilibrium process as pseudoboiling.

The distinctness of the boundaries of the pseudobubbles and their spherical form are due to the action of surface tension. The surface tension in turn is due to the large difference in the densities of the main mass of "cold liquid" and the mass of "hot gas" in the pseudobubbles. This also does not contradict thermodynamics, the laws of which regarding the absence of surface tension at SCP cannot be applied to the process of pseudoboiling.

The surface tension arises because the molecules in some layer of the substance are not in an equilibrium state; they are subjected to a greater attraction from one direction than from another, and this generates forces which tend to contract the molecules in the volume with the higher density (with the greater mutual attraction) and reduce the size of the phase boundary, i.e., make it spherical.

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Laplace saw the connection between surface tension and the density difference, which is a reflection of the difference in the mutual attractions between the molecules. This relationship is most clearly expressed by the Van der Waals equation of state

$$\left(p + \frac{a}{v^2}\right)(v - b) = RT,$$

in which the quantity a/v^2 determines the mutual attraction of the molecules, increasing with an increase in density.

On the basis of the relationship between the mutual attraction of the molecules and the density of the substance, Bachinskii proposed a formula for determining the surface tension between a liquid and its vapor on the saturation line

$$\sigma = c(\gamma_q - \gamma_v)^4.$$

In our opinion, this formula can be used to approximately determine the surface tension on the boundary between volumes of liquid with different densities, i.e., for pseudoboiling in the present case, if the difference $(\gamma_q - \gamma_v)$ is replaced by the difference $(\gamma_q - \gamma_w)$.

When the temperature difference $(T_w - T_q)$ at which pseudoboiling occurs is large, the difference in the densities of the "cold liquid" and "hot vapor" is of the same order of magnitude as the difference in densities between a liquid and vapor on the saturation line. Thus, the surface tension will also be of the same order of magnitude. The surface tension, constricting the pseudobubbles, is variable over time because the temperature of the liquid inside and outside the pseudobubble is also variable. But the surface tension acting on the vapor bubbles in the case of heat transfer with subheated boiling is characterized by the same feature. The boundaries of the pseudobubbles may not always be distinct, since the transitional layer from the "cold liquid" to the "hot gas" may be fairly thick. However, the presence of the transitional layer does not preclude the appearance of surface tension and does not change its magnitude. It is known that the surface tension between a liquid and its vapor acts not on an ideal geometric phase boundary but rather on a certain transitional layer of finite thickness. The thickness of this layer, in which the density of the substance changes continuously from the density of the liquid to the density of the vapor, increases with an increase in pressure.

Unfortunately, it is either impossible or very difficult to measure surface tension at the boundary between pseudobubbles. However, it does not follow from this that there is no surface tension there. In subheated boiling, it is also impossible to measure the surface tension at the boundary between vapor bubbles.

The above considerations allow us to conclude that pseudoboiling is physically similar to subheated boiling and that it is best calculated using the heat-transfer laws for two-phase media, of course with allowance for the features of pseudoboiling.

It is known that the heat-transfer coefficient in the boiling of a liquid can be expressed as a function of the temperature difference between the wall and the liquid to the power 2.33. Using this relation, we proposed the following empirical formula for the heat-transfer coefficient in pseudoboiling [8]

$$\alpha/\alpha_0 = 1 + \left(\frac{T_w - T_q}{T_m}\right)^{2.33}.$$

This formula agrees satisfactorily with test data for a large number of liquid hydrocarbons in a broad range of regime parameters.

The heat flux at which heat transfer deteriorates sharply might be calculated as a "pseudocrisis," by analogy with the critical heat flux at supercritical pressures. However, at present there is not sufficient test data to make such a calculation.

NOTATION

a, b, c, constants; T_q, T_m, T_s, T_w, temperature of liquid, pseudocritical transformations, saturation, and wall, respectively; v, specific volume; α, heat-transfer coefficient; α_0, heat-transfer coefficient with T_w close to T_q; γ_q, γ_v, γ_w, specific weight of the liquid, the vapor, and the liquid at T_w; σ, surface tension.

LITERATURE CITED

1. B. S. Petukhov, "Heat transfer in a single-phase medium with near-critical state parameters," Teplofiz. Vys. Temp., 6, No. 4, 732-745 (1968).
2. Ackerman, "Heat transfer in the pseudoboiling of water in the supercritical region during flow in smooth and finned tubes," Teploperedacha, 92, No. 3, 183-190 (1970).
3. N. L. Kafengauz, "On the mechanism of pseudoboiling," in: Studies of the Mechanics and Heat Transfer of Two-Phase Systems [in Russian], ÉNIN, Moscow (1974), pp. 229-235.
4. I. T. Alad'ev, V. D. Vas'yanov, N. L. Kafengauz, et al., "Experimental study of the mechanism of pseudoboiling in n-heptane," Inzh.-Fiz. Zh., 21, No. 3, 289-395 (1976).
5. Sh. G. Kaplan, "Heat-transfer mechanism in the turbulent flow of a liquid at supercritical pressures," Inzh.-Fiz. Zh., 21, No. 3, 431-436 (1971).
6. L. Tsuge, "Heat transfer in the forced convection of a liquid in pipes near the critical point," Nihon Kikai Gakkai Rombunsyu, 40, No. 33, 1363-1372 (1974).
7. Ito Nisikava, "Free-convection heat transfer to a liquid with supercritical parameters," Teploperedacha, No. 2, 42-47 (1972).
8. N. L. Kafengauz, "Heat transfer to a turbulent liquid flow in pipes at supercritical pressures," Inzh.-Fiz. Zh., 44, No. 1, 14-19.

WEAK EVAPORATION OR CONDENSATION PROCESS ON A FLAT SURFACE WITH EXCITATION OF THE INNER DEGREES OF FREEDOM OF MOLECULES TAKEN INTO ACCOUNT

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The evaporation (condensation) rates and temperature jump are calculated in a vapor in contact with its intrinsic condensed phase. The contribution of the vapor molecule inner degrees of freedom is analyzed.

The solution of the problem of the Knudsen layer for a monatomic gas has been obtained in many papers. Investigation of the influence of the internal degrees of freedom of the molecules on the magnitude of the temperature jump, and if there is an evaporation (condensation) process, then on the magnitude of the evaporation rate is of interest. Expressions have been obtained in [1] for the density jumps, the tranlational—rotational and vibrational temperatures on a flat impermeable surface. Here the possible nonequilibrium of the molecule rotational degrees of freedom in the Knudsen layer is not taken into account. The temperature jump and temperature distribution near the wall in a monatomic gas are calculated in [2]. A model kinetic equation of Morse type [3] is used, in which the collision integral is replaced by two terms of relaxation type that model the elastic and inelastic collisions, respectively. The results of numerical computations are presented in the form of tables. In addition to the temperature jump in [4], a weak evaporation (condensation) process is considered with excitation of the molecule rotational and vibrational degrees of freedom taken into account. A numerical result is obtained for a diatomic gas with rotational degrees of freedom. Exactly as in [2], all the computations were performed on the basis of the model Morse equation [3]. This equation, which is one of the first for a gas with internal degrees of freedom, does not contain the necessary set of relaxation times and does not yield a correct description of all the distribution function moments of physical importance.

The purpose of this paper is to obtain analytical expressions for the evaporation rate and the temperature jump of a polyatomic gas with slow evaporation and condensation processes on a plane interphasal interface taken into account. Excitation of both the rotational and the vibrational degrees of freedom of the molecules are here taken into account. A model third-order kinetic equation [5] is used to solve the problem, which permits obtaining exact equations for all moments of the distribution function that have physical meaning, and as-

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