11. R. I. Nigmatulin, Principles of the Mechanics of Heterogeneous Media [in Russian], Moscow (1978).
12. I. M. Émanuel' and D. G. Knorre, Course in Chemical Kinetics [in Russian], Moscow (1984).
13. P. G. Bedrikovetskii, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 102-111 (1982).

CALCULATION OF THE DENSITY OF VAPORIZATION CENTERS AT THE HEATING
SURFACE WITH AN ALLOWANCE FOR THEIR MUTUAL INTERACTION

V. I. Skalozubov   UDC 536.24

An expression is proposed for calculating the density of vaporization centers at the heating surface that accounts for the superheating, the roughness and material of the surface, the pressure, and the interaction between centers based on the Kenning model.

The monograph by V. F. Prisnyakov [1] provides an analysis of the known experimental and theoretical investigations of the density n_w of vaporization centers acting at the heating surface during boiling. This analysis has shown convincingly that one of the main reasons for the unsatisfactory results obtained in calculating n_w by using the well-known expressions is that the known theoretical considerations do not take into account the actual structure (roughness) of various surfaces and the method used for their treatment.

V. F. Prisnyakov assumed that the number of acting (active) vaporization centers is proportional to the total number of potential centers at the heating surface. The latter quantity depends on the roughness of the surface and the method used for processing it. As a result, an expression was derived in [1] for calculating the density of the acting centers at the heating surface:

$$n_w = n_{\max}\Phi; \quad \Phi = A \int_{H_{\max}}^{H_{\min}} H \exp\left(-aH^2\right) dH, \tag{1}$$

where $A = 0.2865/\nu_h^3$ and $a = 0.2525/\nu_h^2$, ν_h is the fill factor indicating the extend to which the profile of the surface is occupied by troughs, which depends on the type of surface treatment [1] ($\nu_h = 0.2-0.7$), where $H = h/h_{me}$, where $h(\Delta T_w)$ is the trough height corresponding to the assigned superheat of the surface ΔT_w [1], h_{me} is the mean depth of troughs corresponding to the class of surface finish and $n_{\max}$ is the maximum density of centers at the onset of crisis:

$$n_{\max} = 2 \left\{\pi \sin^2\theta\left[1 + \pi\beta\,(\mathrm{Ja})\right]\right\}^{-1} R_{bo}^{-2}.$$

Using relationship (1), Prisnyakov was able to generalize the experimental data for different sets of conditions pertaining to saturated boiling. The difficulty in practical utilization of (1) and (2) is that, in most cases, the parameter θ is a quantity which is not known beforehand. If $\theta \approx 0$, expressions (1) and (2) lead to unlikely high values of n_w. Moreover, the solution of (1) does not account for the interaction between centers, which can be considerable for sufficiently large values of n_w and sufficiently large bubble dimensions. Interaction generally leads to both activation and deactivation of new vaporization centers. The mutual effect of two artificial centers in water boiling was investigated experimentally in [2]. It was found that for $\ell < 6R_{bo}$, the interaction is negative the centers deactivate each other), while, for $\ell > 6R_{bo}$, it is positive (the centers activate each other). If $\ell \gg R_{bo}$, there is no interaction. The work described in [2] was carried further in experiments performed by Judd and collaborators [3-5]. They investigated the interaction between natural vaporization centers at the surface in cases of saturated and underheated
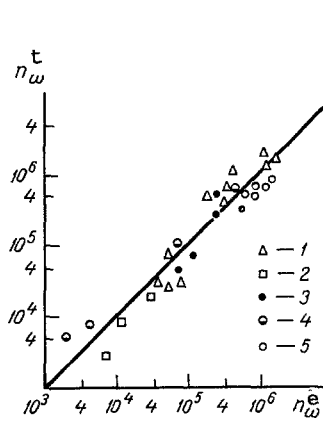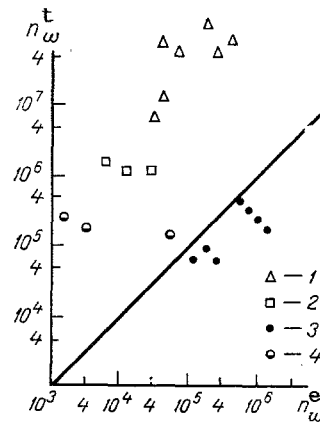
Fig. 1   Fig. 2

Fig. 1. Comparison between experimental data and the
results obtained by means of expression (5) with an al-
lowance for the interaction between centers. 1) Data
from [10]; 2) [7]; 3) [8]; 4) [9]; 5) [11]; dimension
of n_w^t and n_w^e: m^{-2}.

Fig. 2. Comparison between experimental data and the
results obtained by means of expression (1) without an
allowance for the interaction between center ($\alpha_0 = 0$);
the notation is the same as in Fig. 1.

boiling of water and organic liquids. As a result, it was found in experiments that negative
interaction occurred for $\ell \leq 2R_{bo}$, while it was absent for $\ell > (4-8) R_{bo}$.

An attempt was made in [6] to consider analytically the interaction between active
centers. Without considering the mechanisms of interaction between centers, Kenning and Del
Valle [6] assumed that an acting center "susppresses" the generation of neighboring centers
at distances $\ell \leq R_s$, while interaction is altogether absent if $\ell > R_s$. Furthermore, it was
assumed on the basis of available data that the potential bubble centers are distributed
with the mean density n_{w_0}. It is understood in [6] that potential centers are those which
are capable of becoming activated without mutual interaction. After fairly cumbersome trans-
formations, an approximate expression for n_w accounting for the interaction between centers
was derived in [6]:

$$n_w = n_{w_0} \exp \left\{ -\frac{5.4\alpha_0}{\alpha^2 R_p^2} [1 - (1 + 0.61\alpha R_p^2) \exp(-0.61\alpha R_p^2)] \right\}. \tag{3}$$

The exponential cofactor in (3) reflects formally the effect of interaction between cen-
ters on their number. As n_{w_0} and the maximum dimensions of bubbles at the walls (under our
conditions, these are the break-off bubble dimensions) increase, the exponential cofactor
diminishes. For sufficiently small values of n_{w_0} and R_{bo}, it follows from (3) that $n_w \approx n_{w_0}$,
i.e., there is no interaction.

Considering the results obtained in [6], we can broaden the scope of applicability of
expression (1). We assume the following: 1) The density of centers n_{w_0} without an allowance
for their mutual interaction is described by (1); 2) the density of acting centers is des-
cribed by (3); 3) the value of n_{max} in (1) is defined as follows [6]:

$$n_{max} = \frac{2}{\sqrt{3} K R_p^4 R_{bo}^2}. \tag{4}$$

According to the results obtained in [6], $R_p = R_s/R_i \approx 1$. For such values of R_p, we can as-
sume that $\alpha = \alpha_0^{0.24}$. Then, for the above assumptions, we finally obtain the following from
expressions (1) and (3):

$$n_w = n_{max} \Phi \exp(-\alpha_0 A_1), \tag{5}$$

where $A_1 = 5.4\alpha^{-2}[1-(1+0.61\alpha)\exp(-0.61\alpha)]$. Considering the approximate nature of Eq. (5), we determine the value of K experimentally. We used the known experimental data [7-11] on the density of vaporization centers at the heating surface for saturated or slightly underheated boiling. The experimental data in [7, 9, 11] were obtained by using carefully polished copper surfaces under atmospheric pressure. The experiments in [10] were performed on a horizontally positioned nickel plate with class-8 surface finish under pressures of up to 10.0 MPa. The value of R_{bo} was calculated according to the recommendation given in [12], while the modulus β in the relationship $R = \beta t^n$ was determined on the basis of data from [13]. Calculations based on (5) and experimental data from [7-11] show that the parameter K depends on R_{bo} and is defined by

$$K = 4.6 \cdot 10^{-5} R_{bo}^{-1.5}. \tag{6}$$

Figure 1 provides a comparison between the experimental values n_w^e and the theoretical values n_w^t on the basis of Eqs. (4)-(6). Considering that the experiments were performed under different sets of conditions, where different methods were used for recording the vaporization density, the agreement can be said to be satisfactory. In Fig. 2, these experimental data are compared with the theoretical results based on expressions (1) and (4) without an allowance for the interaction between centers. In most cases, the theoretical values based on (1) and (4) are considerably higher than the corresponding experimental data (see Fig. 2). The most elevated theoretical values based on (1) and (4) are those which pertain to data from [11] and they are, therefore, omitted in Fig. 2. Some of the theoretical values n_w^t that do not account for the interaction are fairly well correlated with experimental data, even for relatively high bubble concentrations at the surface. This is possibly connected with the fact that interaction between bubbles produces not only a negative, but also a positive, effect (see above). In particular, similar phenomena were observed in [3, 4]. Under certain conditions, these effects cancel each other out.

The basic advantages of Eq. (5) in comparison with the well-known expression (1) are the following:

1. Expression (5) accounts for the interaction between centers at the heating surface, which is in many cases of fundamental importance.

2. The value of R_{bo} in (5) is determined without taking into account the interaction between centers. This simplifies the problem considerably and provides a better substantiation of the well-known relationships for calculating R_{bo}, especially if $n_w \to n_{max}$.

3. Expression (5) does not use the contact wetting angle θ. In fact, the value of θ in (1) was varied arbitrarily in different experiments, which actually allowed the author of this expression to generalize individual experiments. However, as was mentioned above, the a priori indeterminacy of θ values makes the practical application of expression (1) difficult.

Equation (5) can be used in thermohydraulic calculations of boiling systems.

NOTATION

n_w, density of vaporization centers per unit surface area; θ, contact wetting angle; $R = \beta t^n$, present reduced dimension of a bubble; a_L, temperature diffusivity of the liquid; R_{bo}, break-off dimension of a bubble; ℓ, distance between bubbles; $\alpha_0 = \pi n_{w_0} K R_{bo}$; $\alpha = \alpha_0 n_w / n_{w_0}$; $R_b = R_{bo}\sqrt{K}$, action radius of a bubble; R_s, radius of suppression of the action of neighboring bubbles; ΔT_w, wall superheat.

LITERATURE CITED

1. V. F. Prisnyakov, Boiling [in Russian], Kiev (1988).
2. V. V. Chekanov, Teplofiz. Vys. Temp., No. 1, 121-127 (1977).
3. R. Judd and A. Lavdas, Teploperedacha, No. 1, 81-86 (1980).
4. D. Sultan and R. Judd, Teploperedacha, No. 1, 1-9 (1983).
5. A. Calka and R. Judd, Intern. J. Heat Mass Transfer, 28, No. 12, 2331-2342 (1985).
6. D. Kenning and V. Del Valle, Intern. J. Heat Mass Transfer, 24, No. 6, 1025-1032 (1981).
7. R. Gartner and D. Westwater, Problems Physics of Boiling [Russian translation], Moscow (1964), pp. 300-330.
8. M. Shukri and R. Judd, Teploperedacha, No. 4, 61-67 (1978).

9. A. Singh, B. Mikic, and W. Rohsenow, Sixth Intern. Heat Transfer Conference, Toronto, 1978, pp. 119-126.
10. D. A. Labuntsov, B. A. Kol'chugin, and V. S. Golovin, Heat Exchange in Power Plant Units [in Russian], Moscow (1966), pp. 156-166.
11. N. V. Sitnikova and V. F. Prisnyakov, Problems of High-Temperature Technology [in Russian], Dnepropetrovsk (1979), pp. 4-21.
12. B. I. Verkin, Yu. A. Kirichenko, and K. V. Rusanov, Heat Exchange in Boiling [in Russian], Kiev (1987).
13. Yu. M. Pavlov and S. A. Potekhin, Transactions of the Moscow Power Institute (Trudy MÉI) [in Russian], Vol. 478 (1980), pp. 43-54.

EQUATION TO COMPUTE THE SATURATED VAPOR PRESSURE

ON THE BASIS OF THE PRINCIPLE OF CORRESPONDING STATES

A. M. Shelomentsev

UDC 536.423.15

A generalized equation is developed for the saturated vapor pressure computation of individual substances. The integral error of the computed data is within 1-3%.

The most effective approaches for the computation of the thermodynamic properties of substances are based on application of the principle of corresponding states (PCS). It is known that substances for which the intermolecular interaction is described by spherically symmetric pairwise additive potential are called simple. They are subject to a simple PCS in which two governing parameters are sufficient for determination of the properties. If the substance behavior deviates from the simple PCS, one, two, or more correlation factors are introduced.

It is sufficient to use just one correlation factor for normal (non-associated) substances. Then the equation for the saturated vapor pressure of such substances is written in the form

$$P_R = P_R(T_R, A),\qquad(1)$$

where $P_R = P/P_C$ and $T_R = T/T_C$ are the pressure and temperature referred to the critical values, and A is the correlation factor. Let us note that the correlation factors determined on the basis of the dependences of P_R and T_R on the saturation line are utilized successfully in a single-phase domain also. In order to find the explicit form of A it is necessary to have an analytic expression for the temperature dependence of the saturated vapor pressure with one correlation factor. An approximate exponential Boltzmann formula was used in [1] by reducing it to the dimensionless form

$$\ln P_R = S\left(1 - \frac{1}{T_R}\right) + \ln T_R.\qquad(2)$$

Knowledge of a single point on the saturation line is sufficient for finding the numerical value of S of a specific substance.

The normal boiling point is chosen for determination of the value S since, as a rule, it is known with higher accuracy than any other point on the saturation line. Consequently, the correlation factor is

$$S = \frac{\ln(P_{RB}/T_{RB})}{1 - \dfrac{1}{T_{RB}}},\qquad(3)$$