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TRUE VOLUMETRIC VAPOR CONTENT OF TWO-PHASE FREON FLOWS

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An analysis is made and generalized data presented on the true volumetric vapor content of boiling two-phase flows of Freon-12.

In many heat exchangers, boiling of the refrigerant occurs in horizontal or vertical tubes.

To calculate heat transfer and hydraulic resistance in such units and optimize their operating regimes, it is necessary to know the characteristics of the two-phase flows: volumetric vapor content φ or true phase velocities. The quantity φ makes it possible to most accurately predict flow regimes and to refine physical representations on heat-transfer processes with flows of different structure.

As is known, analytic relations have not found wide use for calculating actual parameters, while the empirical equations obtained have been found mainly in studies of vapor–water (or gas–water) flows circulating at rates $w_0 > 0.2$ m/sec.

There have been practically no studies of the values of φ for refrigerants (we know only of [1]). Of the greatest interest for refrigeration technology are studies at low flow rates $w_0 < 0.2$ m/sec. Flow at these rates is characterized by a number of features. In the case of horizontal tubes, there are zones of laminar and wave flow. In vertical pipes, there are zones of strong pulsations caused by "inversion" of the flow.

We designed and made a stand for experimentally determining the true vapor content of refrigerants and observing flow regimes in horizontal and vertical tubes (with forced flow).

The experimental conditions were as follows: working substance — Freon-12, w_0 = 0.03-0.43 m/sec, q = 2-20 kW/m^2, t_0 = −20 to +20°C, x = 0.005-0.95, d_0 = 6 and 10 mm.

The actual vapor content was determined by the intercept method. The experimental unit consisted of a hydrodynamic stabilization section and thermal and observation sections. The observation section was a tube made of transparent quartz glass 240 mm long. Spherical cutoff valves connected by a tie were installed on both sides of the observation section. The unit, mounted on the rigid frame of a rotation mechanism, was connected to the stand by means of flexible hoses, making it possible to place the entire structure in the horizontal or vertical position.

Vapor content was established by electric heating by one of two methods: in the stand vapor generator or in the thermal section located between the visualization and observation sections. The heater installed in the thermal section was used to study small vapor contents x < 0.1 m and allowed us to determine the effect of heat flux on the value of φ.

In the experiments with horizontal tubes, after cutoff the entire unit was turned to the vertical position, and the value of φ was determined from the measured height of the liquid column in the glass tube. The mean accuracy of the determination of φ was ±3%.

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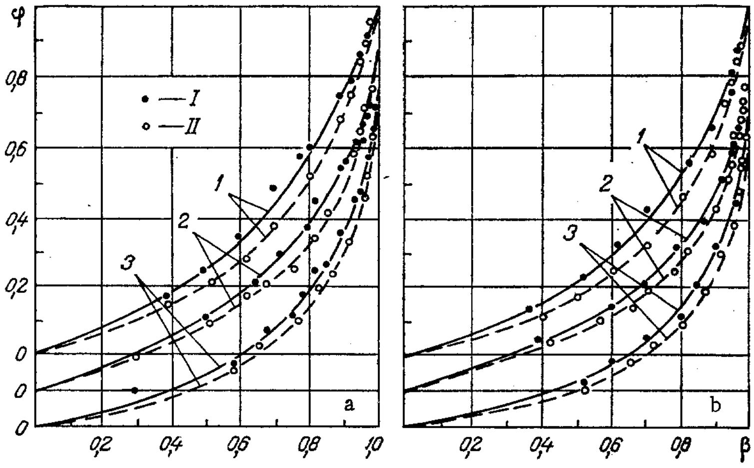

Fig. 1. The functions $\varphi = f(\beta)$ for vertical (I) and horizontal (II) tubes, d_0 = 10 mm: a) t_0 = +20°C (1 — w_0 = 0.183 m/sec; 2 — 0.068; 3 — 0.035); b) t_0 = −10°C (1 — w_0 = 0.17 m/sec; 2 — 0.07; 3 — 0.035).

Repeated measurements of φ (15-20 measurements) conducted with a constant value of x allowed us to judge oscillations in the true vapor content $\Delta\varphi$ relative to $\bar{\varphi}$ with different structures of vapor—liquid mixtures.

Thus, with a shell regime of flow in the horizontal tubes, the value of $\Delta\varphi$ ranged within ±6%. The range for the vertical tubes was 0-20% (with x = const). The indicated value of $\Delta\varphi$ in the second case occurred at w_0 = 0.03-0.07 m/sec. At higher flow rates, it decreased to 6-8%.

The greatest fluctuations in φ were seen in the wave regime of flow ($\Delta\varphi \simeq$ 40%). With annular and laminar regimes, $\Delta\varphi$ did not exceed ±2%.

It follows from an analysis of the test data that the main factors affecting the true vapor content are w_0 and t_0. The value of φ increases with these quantities, approaching the values of β. This is evidence of a decrease in slip between the phases. Tube diameter and heat flux were not observed to have had an effect on true vapor content in the tests, which is evidently explained by the narrowness of the investigated range of d_0 and q.

The values of φ were somewhat higher in the vertical tube than in the horizontal (Fig. 1), which can be attributed to the difference in the structures of the flows in the first and second cases. Bubble and shell flow regimes, in which the vapor phase is distributed throughout the volume of the liquid in the form of individual occlusions, existed in the vertical pipe within a broad range of vapor contents. Other conditions being equal, in the horizontal tube we observed wave and laminar regimes of flow, with separate flow of the phases. Slip is assumed to be greater in the second case, which means that the value of φ is lower. With the transition to annular flow, the true vapor content gradually equalled out in both cases.

The initial data obtained was compared with calculated data obtained from several formulas (Fig. 2).

It follows from the comparison of theoretical and empirical values of φ that all of the formulas ensure the requisite accuracy in both vertical and horizontal tubes only when w_0 > 0.2 m/sec. At w_0 < 0.1-0.2 m/sec, the theoretical values of φ differ appreciably from the experimental. This is probably because the theoretical formulas used were obtained with large values of w_0 and do not take into account the above-noted specifics of slip at low circulation rates.

The following equation was taken as the initial equation in generalizing the test data:

$$\beta - \varphi = f_1(\beta,\ \mathrm{Re}_0,\ \mathrm{Fr}_0,\ \mathrm{Ga}^*,\ \mu'/\mu'',\ \rho'/\rho''), \tag{1}$$

where

$$\mathrm{Re}_0 = w_0 d_0/\nu';\ \mathrm{Fr}_0 = w_0^2/(g d_0);\ \mathrm{Ga}^* = g\left\{\sqrt{\frac{\sigma}{g(\rho' - \rho'')}}\right\}^3/(\nu')^2.$$

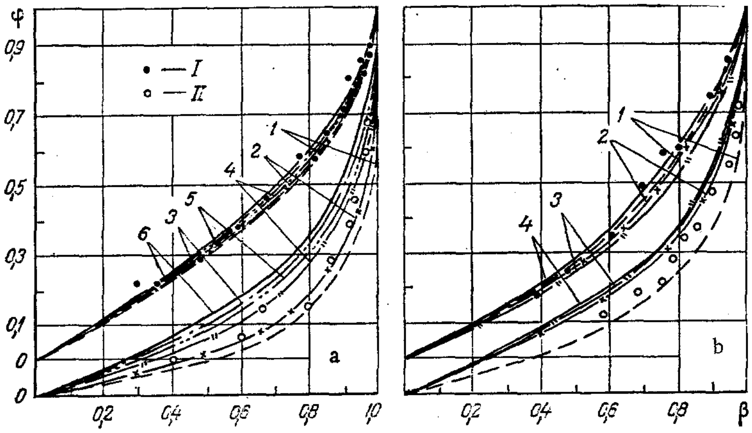

Fig. 2. Comparison of test data with calculated data: a) horizontal tube [test: I) d_0 = 6 mm, w_0 = 0.4 m/sec, t_0 = +20°C; II) d_0 = 10 mm, w_0 = 0.037 m/sec, t_0 = −18°C; calculation: 1) [5]; 2) [6]; 3) [7]; 4) [1]; 5) [9]; 6) [8]]; b) vertical tube, d_0 = 10 mm; t_0 = +20°C [test: I) w_0 = 0.183 m/sec; II) w_0 = 0.035 m/sec; calculation: 1) [6]; 2) [9]; 3) [7]; 4) [1]].

For the generalization, we supplemented our test data on Freon-12 with the data from other authors on vapor–water flows: the results from [2] in horizontal tubes (d_0 = 15.7 mm) and from [3, 4] in vertical tubes (d_0 = 17 and 30 mm).

During analysis of the test data we established the similarity of $\beta-\varphi$ with regard to Re_0, μ'/μ'', and ρ'/ρ'', and Eq. (1) took the form

$$\beta-\varphi=f_2(\beta,\ Fr_0,\ Ga^*). \quad (2)$$

As a result, we obtained the following equations to generalize the test data on Freon-12 and water:

horizontal tubes: d_0 = 6-16 mm, $0.019 < Fr_0 < 14$; $Ga^* = 2.55\cdot10^5$-$20\cdot10^5$,

$$\beta-\varphi=2.55\beta(1-\beta)^{0.36}(Fr_0Ga^*)^{-0.11}, \quad (3)$$

vertical tubes: d_0 = 6-30 mm, $0.019 < Fr_0 < 50$; $Ga^* = 2.94\times10^5$-$20\cdot10^5$,

$$\beta-\varphi=2.37\beta(1-\beta)^{0.36}Fr_0^{-0.14}(Ga^*)^{-0.123}. \quad (4)$$

The mean relative error with the use of Eqs. (3) and (4) is ±5%, which is comparable to the accuracy of the experiment. Equation (3) generalizes about 700 empirical points for Freon-12 and water, while Eq. (4) generalizes about 130 points.

NOTATION

w_0, circulation rate, m/sec; q, heat flux, W/m^2; t_0, boiling point, °C; d_0, inside diameter of tube, m; x, mass-flow-rate vapor content; β, volume-flow-rate vapor content; $\bar{\varphi}$, mean value of true vapor content; $\Delta\varphi$, deviation of true vapor content from $\bar{\varphi}$; σ, surface tension, N/m; μ', μ'', dynamic viscosities of liquid and vapor, N·sec/m^2; ρ', ρ'', densities of liquid and vapor, kg/m^3; g, acceleration due to gravity, m/sec^2.

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DISTRIBUTION OF DISPERSE-PHASE VAPORS IN A HIGH-TEMPERATURE GAS FLOW

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The distribution of disperse-phase vapors is obtained in the case where this phase is introduced unevenly into the flow.

The design and analysis of a whole range of production processes requires knowledge of the distribution of disperse-phase vapors in a gas flow when the disperse phase is introduced unevenly into the flow in space. Such introduction naturally leads to a significantly nonuniform distribution of the disperse fraction along and across the flow [1].

It was shown in [2] that the evaporation of drops (particles) occurs much more slowly than their deceleration within a broad range of flow parameters. Thus, the problem of determining the distribution of a disperse phase and its vapors in a gas flow can be broken down into two steps. First we find the mass distribution function of the polydisperse condensed phase in the flow without allowance for the change in the diameters of its constituent particles. We then solve the problem of determining the distribution of the vapor in the gas flow with sources prescribed by the particle distribution function with allowance for polydispersity and differences in the dynamics of evaporation of different-size particles. The study [1] obtained a mass distribution function $g_m(r, \delta)$ for a disperse phase in a gas flow (the mass of drops with diameters from δ to $\delta + d\delta$ in a volume element dV containing a point with the coordinate r is given as $dm = g_m(r, \delta)\cdot d\delta dV$).

In selecting a model for the diffusion process, we note that the rate of molecular diffusion is too low and that during the time the vapor has been carried several meters by the flow it has diffused by fractions of a millimeter across the flow. As regards turbulent diffusion, it is intense in the core of the flow but approaches zero going toward the wall. Thus, in this region diffusive transport across the flow becomes less than convective transport along the flow. This fact allows us to ignore the effect of the walls and to thereby reduce the diffusion boundary-value problem to a Cauchy problem. It should also be noted that the turbulent diffusion in a developed flow is almost constant up to distances on the order of 20% of the tube radius going from the tube wall [3]. Moreover, agitating grids are often used, which leads to equalization of the turbulent diffusion coefficients across the flow. Thus, in solving the diffusion problem, we will assume it to be constant.

We choose the coordinate system as follows: the X axis is directed along the gas flow, the Y axis is directed over the diameter of the gas flow from the wall to the core, and the Z axis is directed perpendicular to the XY plane. Then, with allowance for the above assumptions, the steady-state problem of determining the distribution of disperse-phase vapors ρ_v in the gas flow takes the form

$$\frac{\partial \rho_v}{\partial x} = a^2 \Delta \rho_v + \Phi. \tag{1}$$

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