TRUE VAPOR AND GAS CONTENTS OF UNHEATED FLOWS OF MIXTURES IN TUBES

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An equation for the determination of the true vapor and gas contents in unheated tubes is constructed on the basis of the theory developed in the preceding reports and a number of relationships noted in experiments. This equation generalizes the existing experimental material.

Since the publication of [1] the experimental data and the equation

$$\varphi = \beta \left\{ 1 - \frac{0.342\,(1-\dot{\gamma})\,(1-\beta)}{[1 + 0.0235\sqrt{\mathrm{Fr}}\,(1-\dot{p})^{-2}]^2\,(1.04-\beta)} \right\} \tag{1}$$

obtained in it have been used in calculations of the hydrodynamics of mixtures and have been analyzed (see [2-8], for example).

It follows from the analysis conducted in these reports that the values determined by Eq. (1) are in full satisfactory agreement with the experimental values in the range of $\dot{p}$ and Fr studied in [1] but do not extend to low pressures and small velocities. In addition, one can determine φ from Eq. (1) only for vapor–liquid flows and not for gas–liquid flows, such as oil–gas, gas–condensate, and gas–water mixtures, since besides the other parameters φ depends on $\dot{p}$.

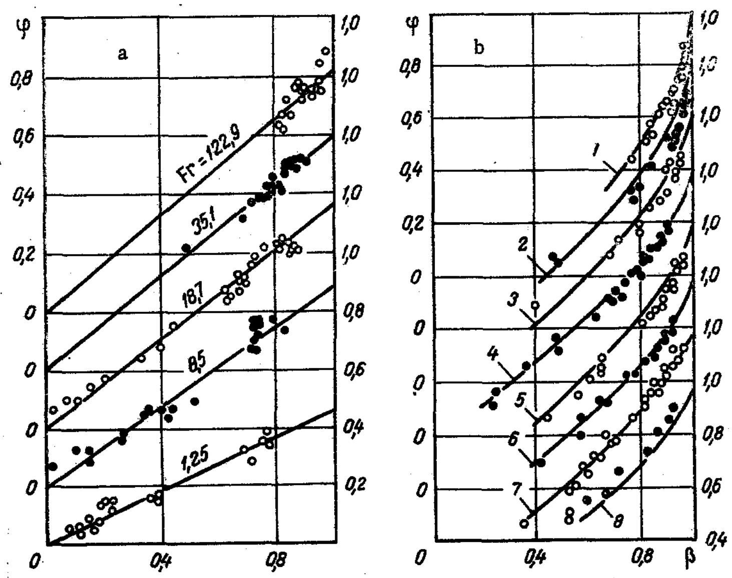

Fig. 1. Comparison of Eq. (9) with experimental data for vertical flows: a) authors' data for vapor–water flow with p = 1.96 bar, d = 18 mm; b) data of [7] for oxygen stream. Tube 9.4 mm, p = 2.2 bar: 1) w_0 = 0.18 m/sec; 2) 0.63; 3) 0.48; 4) 0.625. Tube 14.9 mm, p = 1.6 bar: 5) w_0 = 0.075 m/sec; 6) 0.12; 7) 0.18; 8) 0.23.

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The results of experimental studies are presented below and an equation free of the above-mentioned drawbacks is constructed.

Experimental studies were conducted with the flow of a vapor–water mixture under a pressure of 1.96 bar in a vertical tube with an inner diameter of 18 mm and a height of 3 m. The true vapor contents were determined by irradiating the tube with a broad beam of gamma-rays at four cross sections of the experimental section by the method described in [11], as well as by the method of cutting off a section of the tube with two fast-acting valves. The results of the studies of the true vapor content are presented in Fig. 1a.

In general all the hydrodynamic values are functions of the visually observed structures or forms of the flow of the mixture. However, it is not always justified to distinguish all the structures since the principal hydrodynamic relationships are practically identical for a number of structures. The studies showed that for the determination of φ it is sufficient to distinguish three modes: plug flow, annular flow, and stratified flow. Those flows for which a clear boundary of separation between phases is absent are assumed to be plug flows, i.e., plug flow proper, plug flow with foaming, bubbling flow, etc.; annular flow includes annular flow proper and disperse-annular or core flow; stratified flows include those with flat and wavy surfaces of phase separation. With the classification adopted only the plug and annular modes of motion of a mixture can develop in vertical and inclined tubes, while in horizontal and slightly inclined tubes all three modes can develop.

An analysis of the theoretical and semiempirical studies and the existing experimental material makes it possible to establish a number of relationships for the flow of a mixture. Taking them into account, one can write the following functional dependence for the determination of the true vapor and gas contents:

$$\varphi = \left[1 - (1-\bar{k})\frac{a-\beta}{b-\beta}\right]\beta. \tag{2}$$

In [1, 6, 8] it is shown that in the region of plug flow there is a dependence between φ and β when $Fr = const$ which is close to linear, i.e., in this region the a and b entering into (2) must be equal, so that

$$\varphi = \bar{k}\cdot\beta. \tag{3}$$

Here $\bar{k}$ depends on Fr, increasing with an increase in Fr, and on the physical properties of the liquid and gas.

The self-similarity of $\bar{k}$ with respect to the Froude number is established in [6]. In a test with air–water flows at near atmospheric pressures it is shown that starting with $Fr \geq 4$ the coefficient $\bar{k}$ ceases to increase and remains constant with a further increase in Fr: $\bar{k} = k = 0.81$. This relationship is also graphically confirmed by the experimental studies of [14, 15].

An analysis of the experimental data on vapor–water flows for different pressures in the form of the dependence of $\bar{k}$ on $\bar{Fr}$ made it possible to establish the self-similar values $Fr = Fr_s$ of the Froude number starting with which $\bar{k}$ ceases to grow and remains almost constant and equal to k.

Since k and Fr_s are constant for each given mixture it is clear that they must depend only on the physical properties of the liquid and gas. These dependences can be written in the form

$$k = 0.8\,(1 + 1.5\sqrt{\bar{\gamma}})(1 + \sqrt{\bar{\gamma}})^{-1};\ Fr_s = 2\cdot 10^{-5}\,Ga\,(1-\gamma). \tag{4}$$

Using k and Fr we can determine

$$\bar{k} = k\,[1 - \exp(-n\sqrt{Fr\,Fr_s^{-1}})]. \tag{5}$$

Here the coefficient n must be such that $\bar{k} \approx k$ when $Fr = Fr_s$. By requiring that when $Fr = Fr_s$ the ratio $\bar{k}\cdot k^{-1}$ differs from unity by no more than 1-1.5% we find from (5) that n = 4.4.

In the region of annular flow the dependence between φ and β is nonlinear [1, 6] and is described by Eq. (2) when $a \neq b$.

The values of a and b entering into (2) must satisfy certain requirements. In the plug mode of flow they must equal one another while in annular flow they must provide for a given curvilinear nature of the dependence of φ on β. The requirements imposed on a and b will be satisfied if one takes b = 1.04 and

$$a = 1.04 - 0.03\,Fr\cdot Fr_*^{-1} \quad \text{for} \quad Fr \leqslant Fr_*, \tag{6}$$

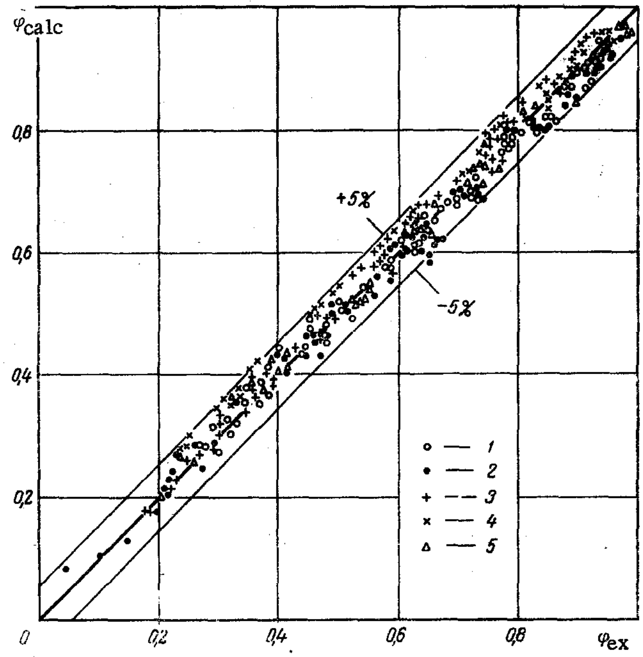

Fig. 2. Comparison of Eq. (9) with experimental data [1] for vapor–water flows in vertical tubes with Froude numbers from 7 to 2200. Tube 17 mm: 1) p = 19.6 bar; 2) 39.2. Tube 30 mm: 3) p = 39.2 bar; 4) 68.7; 5) 117.7.

$$a = 1 + 0{,}01\,\mathrm{Fr}_*\cdot\mathrm{Fr}^{-1} \quad \text{for} \quad \mathrm{Fr} > \mathrm{Fr}_*. \tag{7}$$

Here the numbers Fr_* are constructed with the help of the critical gas (vapor) velocity w_* with respect to reversal. On the basis of the nonlinear theory of the motion of layers of a viscous liquid together with a gas stream [9] the following equation is derived [10] and confirmed by the available experimental data for the determination of w_*:

$$w_* = 3{,}3\left[\frac{g\sigma\rho_1^2}{(\rho_1-\rho_2)\,\rho_2^2}\right]^{1/4}. \tag{8}$$

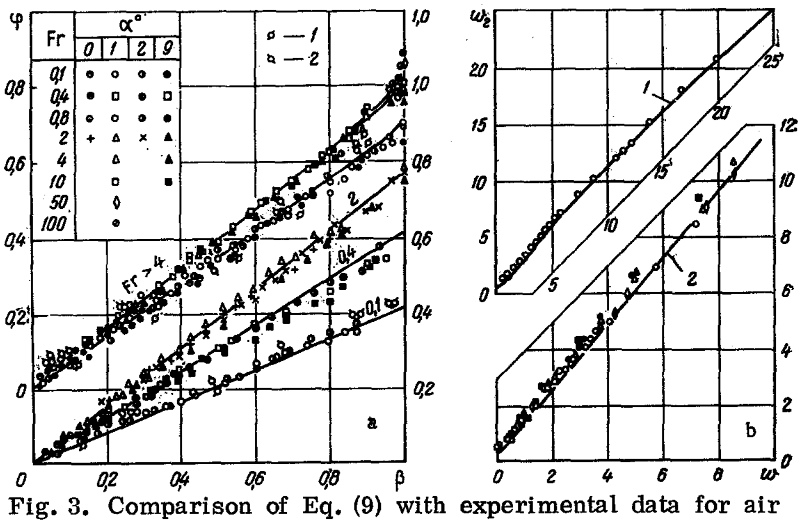

Fig. 3. Comparison of Eq. (9) with experimental data for air–water flows. a: data of [6] for horizontal and inclined ascending flows, d = 56 mm: 1) data of [21], vertical tube, Fr = 0.1, d = 250 mm; 2) the same, d = 500 mm. b: vertical flows: 1) data of Wallis et al., taken from [3, 22], d = 25 mm, w_{01} = 0.03 m/sec; 2) data of Smissert taken from [3], d = 51 mm, w_{01} from 0 to 0.03 m/sec.

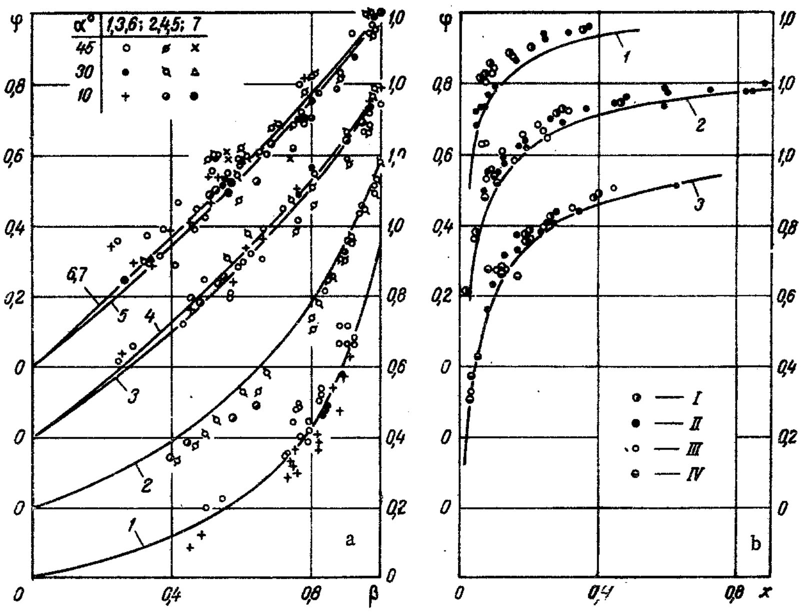

Fig. 4. Comparison of Eq. (9) with experimental data for vapor–water flows. a: data of [19] for ascending flows in inclined tubes, d = 48 mm, pressure 107.8 bar: 1) w_0 = 0.17 m/sec; 2) 0.33; 3) 0.57; 4) 0.97; pressure 176.4 bar: 5) w_0 = 0.77 m/sec; 6) 0.96; 7) 1.52. b: data of [20] for vertical tube of 7.7 mm: 1) p = 19.6 bar; 2) 35.3; 3) 68.7; I) $w\rho$ = 400 kg/(m^2·sec); II) 800; III) 2000; IV) 3000.

If $w_2 > w_*$ the liquid in the form of an annulus moves upward along the wall in the direction of the gas stream and stable annular flow occurs. If $w_2 < w_*$ the liquid flows down along the surface of the wall, increasing in thickness and forming plug flow in inclined and vertical tubes and plug or layered flow in horizontal and slightly inclined tubes. The angle of inclination of the tube does not affect w_*, since the annular form of flow arises at high velocities of the mixture [12].

Finally, we obtain

$$\varphi=\left\{1-\left[1-0.8\frac{1+1.5\sqrt{\gamma}}{1+\sqrt{\gamma}}\left(1-\exp\left(-4.4\sqrt{\frac{\mathrm{Fr}}{\mathrm{Fr}_s}}\right)\right)\right]\frac{a-\beta}{1.04-\beta}\right\}\beta. \tag{9}$$

Here $\mathrm{Fr_s}$ and a are determined from (4), (6), and (7).

In the case when $\mathrm{Fr}_* \gg \mathrm{Fr} \gg \mathrm{Fr_s}$ and $0 \le \beta \le 1$ or $\mathrm{Fr} \ge \mathrm{Fr_s}$ and $0 \le \beta < 0.9$, then (9) takes the simple form $\varphi = k\beta$.

Equation (9) satisfies all the boundary conditions: when Fr = 0 we have $\varphi = 0$; when $\gamma = 1$ we have $\varphi = \beta$; when $\beta = 0$ we have $\varphi = 0$; when $\beta = 1$ we have $\varphi \le 1$; when $\beta = 0$ ($\varphi = 0$) w_2 takes on the limiting final value. The existence of points with $\beta = 1$ and $\varphi \le 1$ is confirmed by the experimental data of [6, 5, 7, 16, 17].

The effect of the tube diameter on φ in Eq. (9) is taken into account by the Froude number of the mixture. The dependence of φ on the diameter as well as on ν_1 occurs only at relatively low mixture velocities when $\mathrm{Fr} < \mathrm{Fr_s}$. This dependence decreases asymptotically with an increase in the mixture velocity and for $\mathrm{Fr} \gg \mathrm{Fr_s}$ the diameter and ν_1 have almost no effect on φ.

In Figs. 1-4 the dependences determined from Eq. (9) (solid lines) are compared with the experimental data. On the whole their agreement is within the limits of the experimental error.

The dependence of φ on x (Fig. 4b) calculated from (9) for $w\rho$ = 400 and 2000 kg/(m^2·sec) at p = 19.6 bar merged into the single curve 1, while the dependence for $w\rho$ = 400 and 3000 kg/(m^2·sec) at p = 35.3 bar and for the same $w\rho$ at p = 68.7 bar merged into curves 2 and 3, respectively.

Comparisons which are not presented in this article showed that Eq. (9) agrees no worse than Eq. (1) with the experimental data of [1]. Equation (9) is in full satisfactory agreement with the experimental data

(Fig. 2 of [15] and Fig. 9 of [14]) for air–water flows in vertical and horizontal tubes 26 mm in diameter for mass flow rates of water of from 300 to 5000 kg/h. Equation (9) agrees well with the data of [2] for vapor–water flows in a vertical tube 50 mm in diameter at a pressure of 11.3 bar, while for pressures of 40–94 bar it agrees no worse than the equation of the author of [2]. The experimental data (Fig. 30 of [18]) for flows of a vapor–water mixture at a pressure of 138.7 bar in vertical tubes from 25 to 60 mm in diameter, as well as the data of the All-Union Scientific-Research Institute of the Gas Industry (Fig. 66 of [6]) obtained for the bubbling ($\beta = 1$) of air through a dynamic water layer in tubes from 12.5 to 75 mm in diameter which were vertical or inclined at angles of 1, 2, and 9° to the horizontal, are described quite satisfactorily by Eq. (9).

Thus, Eq. (9) is verified for ascending flows which are vertical and inclined at different angles and for horizontal flows of mixtures in all forms except the stratified form. Here there were the following ranges of variation: tube diameters from 7.7 to 75 mm and in one case 250 and 500 mm; Fr from 0.1 to 6000; γ from 0.001 to 0.23; σ from 74 to 3 MN/m; ν_1 from 1.63 to 0.126 cSt.

NOTATION

φ and β	are the true and flow rate volumetric vapor contents;
w	is the velocity of the mixture;
w_2	is the mean velocity of the gas (vapor);
w_{01}	is the reduced velocity of the liquid;
w_0	is the circulation velocity;
w_*	is the critical gas velocity with respect to reversal;
$w\rho$	is the mass velocity;
p	is the pressure;
p_{cr}	is the critical pressure;
$\dot{p} = pp_{cr}^{-1}$;	
ρ_1 and ρ_2	are the densities of the liquid and gas;
$\gamma = \rho_2\rho_1^{-1}$;	
ν_1	is the coefficient of kinematic viscosity of the liquid;
σ	is the coefficient of the surface tension;
d	is the tube diameter;
α	is the angle of inclination of the tube to horizontal;
g	is the acceleration of gravity;
$Fr = w^2(gd)^{-1}$	is the Froude number of the mixture;
$Fr_* = w_*^2(gd)^{-1}$;	
Fr_s	is the self-similar value of the Froude number (Eq. (4));
$Ga = g/\nu_1^2(\sigma/g\rho_1)^{3/2}$	is the Galilean number.

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