EXPERIMENTAL STUDY CONCERNING THE HYDRODYNAMICS OF VAPOR – WATER FLOW THROUGH HORIZONTAL PIPES

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A study has been made concerning the dependence of the true vapor content and the referred friction coefficient on the flow-rate vapor content, on the Froude circulation number, and on the thermal flux in a vapor–water mixture flowing horizontally under a pressure of 1.5-3.0 bar. Empirical formulas have been derived on the basis of test data.

An analysis and a bibliography of experimental studies concerning the flow of mixtures through horizontal pipes are given in [1]. Here, both the true and the flow-rate vapor content as well as the referred friction coefficient of a vapor–water mixture were studied experimentally under adiabatic flow conditions and under conditions of flow with heating in a horizontal pipe. The hydrodynamics of vapor–water mixtures within the given ranges of pressure, thermal flux, and Froude circulation number had never been analyzed before.

The test apparatus constituted a closed system whose main component was a heatable seamless steel pipe with an 18 mm inside diameter. The true vapor content was measured by the cutoff method in four successive segments, total length 12 m, with five cutoff valves pneumatically actuated and electromagnetically synchronized. Viewing units, as well as stabilization units each 2 m long, were installed at both the entrance to and the exit from the pipe. Electric heaters were installed along the entire test line, with equally spaced special thermometers for controlling the heater power. At the end of the main electric heater was placed a throttle valve, to ensure the generation of a vapor–water mixture as a result of spontaneous boiling.

Eight pressure drops along the main pipe, the excess pressure at the end section, thermal fluxes, and flow rates were also measured.

In order to examine separately the effect of the Froude circulation number $Fr_0 = G^2/gDf^2\gamma_1^2$ and the effect of the thermal flux, the authors performed the experiment in four variants.

I. Adiabatic flow of the mixture at four different mass flow rates corresponding to four values of the Froude circulation number: Fr_0 = 0.85, 1.50, 2.35, and 4.10 (curves 1-4 in Figs. 1 and 2).

II. Flow with a constant thermal flux qG = 2520 W/m (0.6 kcal/m · sec) and with the same values of the Froude number as in variant I (curves 5-8).

III. Flow with a constant thermal flux density $qD/r = 0.336 \cdot 10^{-4}$ (q = 1 kcal/kg · m) and with the same values of the Froude number as in variant I (curves 9-12).

IV. Flow with a constant Froude circulation number Fr_0 = 1.5 and with four different thermal flux densities $qD/r = 0.336 \cdot 10^{-4}$ (curves 10), $0.672 \cdot 10^{-4}$ and $1.008 \cdot 10^{-4}$ (test data not shown here), $1.68 \cdot 10^{-4}$ (curves 6) corresponding to q = 1, 2, 3, and 5 kcal/kg · m, respectively.

In this way, only 14 series of tests were performed with various initial vapor contents at the entrance to the apparatus. Most of the tests were performed according to two different procedures. In the first procedure stable mode was obtained by a gradual increase of the initial vapor content in the stream from zero to the prescribed level. In the second procedure first a stream with a maximum vapor content was produced and then the vapor was gradually reduced down to the desired flow mode. In all tests the

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pressure at the end section of the test segment was maintained within 1.4-1.6 bar. In order to produce adiabatic conditions, the main heaters were used as standby heaters.

A preliminary evaluation of test data was based on the complete differential equations of motion and energy for a one-dimensional two-phase stream:

$$-\frac{dp}{dz}=\frac{G^2}{gf^2}\cdot\frac{d}{dz}\left(\frac{F_1}{\gamma_\varphi}\right)+\frac{\lambda_{\text{mix}}G^2}{2gDf^2}\cdot\frac{F_1}{\gamma_\varphi}, \tag{1}$$

$$-\frac{d}{dz}\left(i_\beta+\frac{G^2}{2gf^2}\cdot\frac{F_2}{\gamma_\varphi^2}\right)-q=\frac{\lambda_{\text{mix}}G^2}{2gDf^2}\cdot\frac{F_2}{\gamma_\varphi^2}, \tag{2}$$

where $F_1=\frac{(1-\eta)^2}{1-x}+\frac{\eta^2}{x}$, $F_2=\frac{(1-\eta)^3}{(1-x)^2}+\frac{\eta^3}{x^2}$.

Calculations for each test were made by the method of successive approximations. The equilibrium vapor contents β were calculated, to the first approximation, by the energy equation (2) without the terms representing the work of viscous forces and the changes in kinetic energy. The resulting approximate equation

$$-di_\beta=qdz \tag{3}$$

was then used for calculating i_β at the cutoff points on the basis of the heat balance in the cooler and on the basis of the thermometer readings. The vapor content was determined under the assumption of a thermodynamic equilibrium in both phases at every section. The values of λ_{mix} were then calculated, to the first approximation, according to Eq. (1).

The second approximation was made in an analogous manner, but already using the complete energy equation (2) with i_β, λ_{mix} found in the first approximation. The entire calculation procedure was repeated until the prescribed accuracy had been reached at all sections under study. All necessary parameters were determined, afterwards, including the referred friction coefficient of the mixture ψ_β, for which the friction coefficient of a one-phase stream $\lambda(\text{Re}_\beta)$ was determined first from Re_β calibration curves.

The derivatives of these parameters, whose mean-over-the-section values had been known from tests or calculations, were determined from polynomials of the kind

$$p=\sum_{k=0}^{n}A_kz^k, \tag{4}$$

with the coefficients A_k found from the known values of the parameters at a few sections. The mean-over-the-section values of the true vapor content were, on the other hand, calculated as follows. Integrating Eq. (3) yielded

$$-\Delta i_\beta=q\Delta z,$$

and this formula could, on the basis of known relations, be reduced to

$$\beta=\frac{A_\beta+B_\beta z}{1+C_\beta z}, \tag{5}$$

with the coefficients A_β, B_β, and C_β expressed in terms of the thermal flux and the physical properties of the phases. Considering that the longitudinal profile of the true vapor content was the same as the β-profile, one could write

$$\varphi=\frac{A_\varphi+B_\varphi z}{1+C_\varphi z}. \tag{6}$$

Equation (6) was used for calculating the mean-over-the-section values of φ. Coefficients A_φ, B_φ, and C_φ were determined for each test from a system of equations which in turn had been obtained from the mean-over-the-length values of the true vapor content in the cutoff method. All calculations were performed on a computer.

The results of this test data evaluation concerning the true vapor content are shown in Fig. 1a-c in the form of $\varphi = f(\beta)$ curves, indicating three ranges of different relations between φ and β. Within the first range of low vapor contents, during adiabatic flow φ is an almost linear function of β and independent of Fr_0. With heating, the values of φ in this range become higher than during adiabatic flow at the same levels of the equilibrium vapor content β. Visual inspection has shown that within this first range the vapor phase flows through the pipe essentially

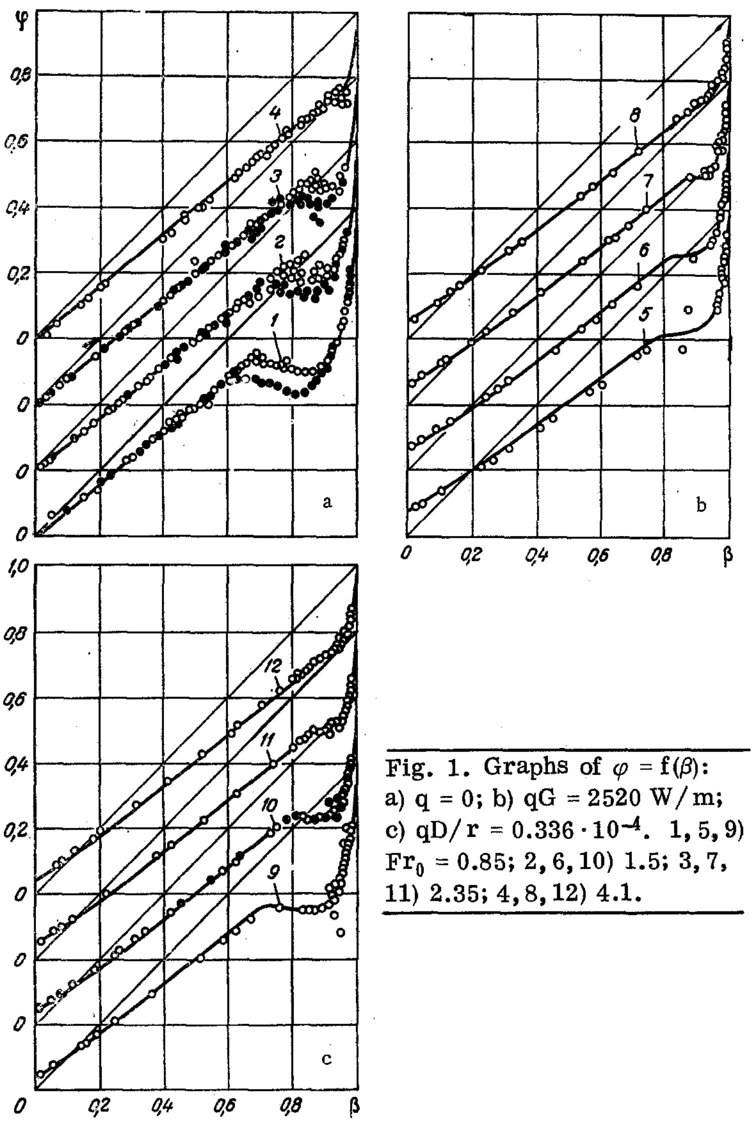

Fig. 1. Graphs of $\varphi = f(\beta)$: a) q = 0; b) qG = 2520 W/m; c) $qD/r = 0.336 \cdot 10^{-4}$. 1, 5, 9) $Fr_0 = 0.85$; 2, 6, 10) 1.5; 3, 7, 11) 2.35; 4, 8, 12) 4.1.

along the upper generatrix in the form of fine bubbles and separate lumps. The right end of this range corresponds to flow modes with rather large regular lumps of vapor appearing across almost all the pipe section but still pulling toward the upper generatix. This end is, on the basis of test data, defined as

$$\beta_I = 0.975 - \exp\left[-\left(1.3 + 18.95\sqrt{\frac{qD}{r}}\right)\sqrt{Fr_0}\right]. \tag{7}$$

During adiabatic flow, the relation between φ and β within this first range is

$$\varphi_I = 0.8\beta, \tag{8}$$

resembling the equations by Armand [2] and by Odishariya [3] for water–air mixtures with the Froude number not higher than 4. The increase in the true vapor content with heating can be explained by the thermodynamic nonequilibrium between phases [4], as a result of which the vapor content β determined from the heat balance is not equal to the flow-rate vapor content β'. The following equation has been obtained relating these two vapor contents:

$$\beta' = \beta + b\,\frac{\beta_I - \beta}{c + \beta}, \tag{9}$$

where

$$b = \frac{4\beta_I\varphi_0^2}{(0.8\beta_I - \varphi_0)^2}, \quad c = \frac{3.2\beta_I^2\varphi_0}{(0.8\beta_I - \varphi_0)^2},$$

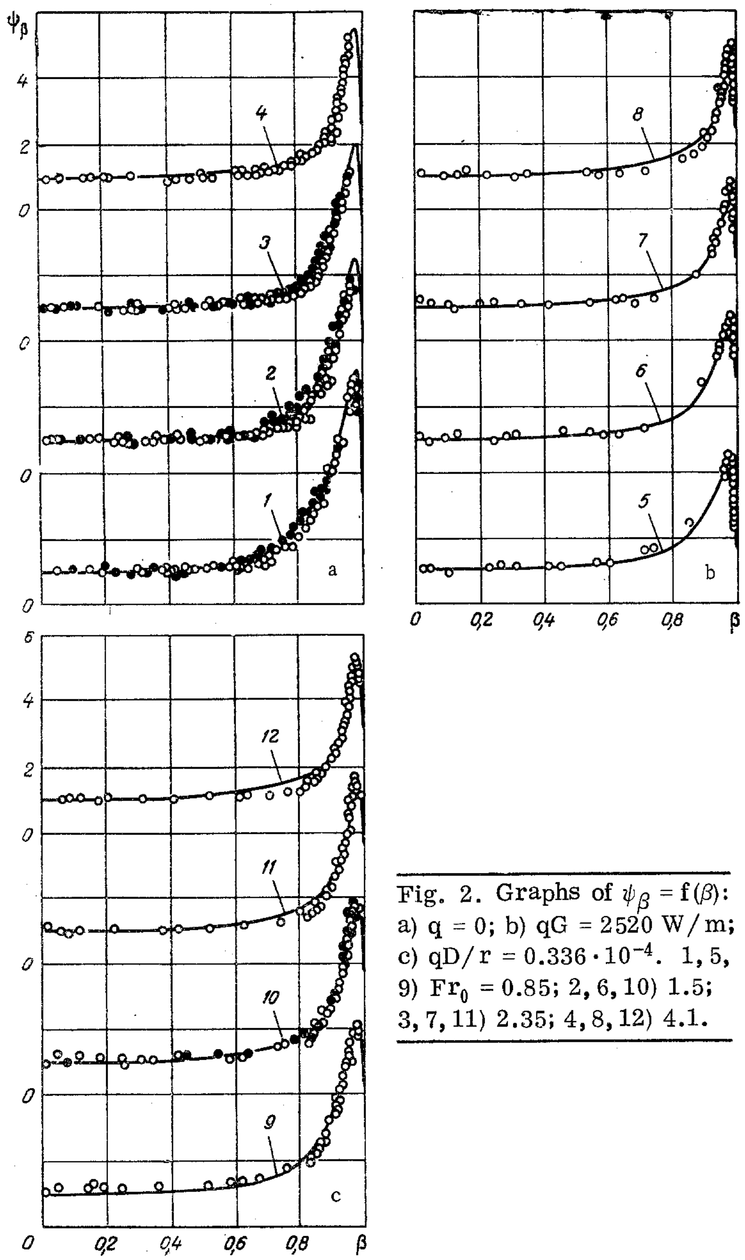

Fig. 2. Graphs of $\psi_\beta = f(\beta)$: a) q = 0; b) qG = 2520 W/m; c) $qD/r = 0.336 \cdot 10^{-4}$. 1, 5, 9) $Fr_0 = 0.85$; 2, 6, 10) 1.5; 3, 7, 11) 2.35; 4, 8, 12) 4.1.

and where φ_0 denotes the true vapor content at $\beta = 0$ determined from test data according to the formula

$$\varphi_0 = \frac{0.8\sqrt[3]{\frac{qD}{r}}}{0.581 + \sqrt[3]{\frac{qD}{r}}}. \tag{10}$$

Relation (9) has been derived under the following assumptions: that within the first range φ is the same function of the flow-rate vapor content β' during heating and during adiabatic flow, that within the first range the phases are always in thermodynamic equilibrium, that at $\varphi = 0$ also the derivative $\partial\varphi/\partial\beta = 0$ in a flow with heating (which indicates that φ increases smoothly), and that at the end of the first range for a flow with heating the phases are in thermodynamic equilibrium (which has been confirmed by tests).

In this way, for all modes adiabatic and with heating

$$\varphi_I = 0.8\beta' \tag{11}$$

within the $\beta \leq \beta_I$ range.

TABLE 1. Values of ψ_q vs β', Fr_0, and q

Fr_0	β'										
	qD/r	0,2	0,6	0,8	0,9	0,92	0,95	0,96	0,97	0,98	0,99
0,85	$0{,}336\cdot10^{-4}$	1,000	1,000	0,929	0,908	0,983	0,918	0,914	0,906	0,901	0,893
	$2{,}220\cdot10^{-4}$	0,999	0,996	0,799	0,731	0,777	0,712	0,697	0,674	0,648	0,615
1,50	$0{,}336\cdot10^{-4}$	1,000	1,000	0,943	0,928	0,924	0,928	0,923	0,917	0,912	0,901
	$0{,}672\cdot10^{-4}$	1,000	0,999	0,929	0,884	0,878	0,883	0,872	0,864	0,850	0,835
	$1{,}008\cdot10^{-4}$	1,000	0,999	0,927	0,853	0,842	0,839	0,831	0,817	0,803	0,775
	$1{,}680\cdot10^{-4}$	0,999	0,997	0,923	0,806	0,789	0,771	0,761	0,745	0,719	0,687
2,35	$0{,}336\cdot10^{-4}$	1,000	1,000	0,998	0,919	0,921	0,923	0,925	0,923	0,912	0,904
	$1{,}344\cdot10^{-4}$	1,000	0,998	0,991	0,789	0,828	0,807	0,798	0,789	0,767	0,737
4,10	$0{,}336\cdot10^{-4}$	1,000	1,000	0,998	0,994	0,928	0,932	0,929	0,929	0,921	0,906
	$1{,}008\cdot10^{-4}$	1,000	0,999	0,993	0,981	0,900	0,868	0,860	0,841	0,820	0,799

Within the third range of high vapor contents the flow structure becomes quasiannular. The vapor moves in very long lumps with relatively short intervening foamy segments. The liquid phase has here a wavy boundary surface around the entire perimeter. Extending Eq. (9) to this range has yielded an empirical formula for adiabatic flow and for flow with heating:

$$\varphi_{III} = \beta'\left(1 - k\frac{1-\beta'}{1{,}0285-\beta'}\right), \qquad (12)$$

where

$$k = \frac{0{,}76}{(1+0{,}2\sqrt{Fr_0})^2 + 272\left(\frac{qD}{r}\right)^{0{,}75}}.$$

It is interesting to note that formula (12) is very similar to the formula suggested in [5] for vertical vapor–water streams. This coincidence can be explained by the convergence of both flow structures. The validity range for this formula is defined as $\beta \geq \beta_{II}$, where

$$\beta_{II} = 0{,}975 - \exp\left[-\left(2{,}9 + 43\sqrt{\frac{qD}{r}}\right)\sqrt[3]{Fr_0}\right]. \qquad (13)$$

The magnitude of β_{II} determines the lower end of the third range.

Within the second range – the transition range – the test points for adiabatic flow split according to the test procedure, as they do not within the other two ranges. For the same value of the Froude number Fr_0, the test points obtained by the first procedure (indicated by blank circles on the diagrams) lie above the test points obtained by the second procedure (indicated by black circles on the diagrams). For $Fr_0 = 4.1$ (Fig. 1a, curve 4) no tests were performed by the second procedure. In the case of flow with heating no such split of test points is noted and, therefore, the test points here (Fig. 1c, curve 10) have been plotted with various notations only for one test series.

Within this range, an increase in β causes a buildup of the large vapor lumps, while the small lumps and bubbles vanish by merging, because evaporation is faster inside a large lump with little curvature of the interphase surface than inside a bubble. This leads to more gliding and a lower vapor content φ, which ensures a smooth transition from one kind of the $\varphi = f(\beta)$ relation (first range) to the other kind (third range). It may be assumed tentatively that the overall flow structure within the second range consists of first-range and third-range structures, each affecting the $\varphi = f(\beta)$ relation in its way but proportionally to its relative content within this second range. A simple assumption of linear proportionality yields the formula

$$\varphi_{II} = \frac{\varphi_I(\beta_{II}-\beta') + \varphi_{III}(\beta'-\beta_I)}{\beta_{II}-\beta_I}, \qquad (14)$$

in satisfactory agreement with test data for flow with heating and for adiabatic flow according to the first procedure. Here φ_I and φ_{III} are determined from Eqs. (11) and (12).

Results of calculations by formulas (11), (12), and (14) for the respective test series are indicated in Fig. 1 by solid lines.

Test data on hydraulic drag have also been evaluated and are shown in Fig. 2a-c. Under adiabatic conditions here, too, one notes a split of test points, but not so wide, according to the test procedure. In tests with heating no such split is noted.

During adiabatic flow within the range of low vapor contents, the referred friction coefficient ψ_β of the mixture increases very slowly at all Fr_0 values, while at high values of β the increase is very sharp. As Fr_0 increases, ψ_β decreases. For flow with heating (Fig. 2b, c) the trend of the curves remains essentially the same as for adiabatic flow. The basic difference within the range of high vapor contents is that the curves for flow with heating lie somewhat lower and have a peak ($\psi_\beta = 4$-6) which decreases as q increases. No such peak was reached in the tests with adiabatic flow.

Hydraulic drag data from tests with heating and tests with adiabatic flow at the same Fr_0 values and of flow-rate vapor contents β' determined according to Eq. (9) are compiled in Table 1 in terms of the ratio $\psi_q = \lambda_q/\lambda_0$, with the friction coefficients of the mixture λ_q when heated and λ_0 when flowing adiabatically. It is evident here that the $\psi_q = f(\beta')$ relation is very complex. This is explained by the different flow structures in the mode with heating and in the adiabatic mode, respectively, at equal values of β'. If ψ_β is expressed as a function of both the true and the flow-rate vapor content, then the following single empirical formula will be obtained

$$\psi_\beta = \frac{(a-\varphi) + 0.1\,(a-\beta')}{1.1\,(a-\beta')}, \tag{15}$$

in satisfactory agreement with test data for both flow modes over the entire range of tested vapor contents. In this formula

$$a = 1.0125 + 36\frac{qD}{r}. \tag{16}$$

It must be noted that only the thermal flux appears in expression (15) explicitly. The effect of the Froude number is fully implied by the relations between φ and β'.

Results of calculations by formula (15) are indicated in Fig. 2 by solid lines and agree closely with the test data.

NOTATION

z	is the longitudinal coordinate in the stream, m;
p	is the pressure, N/m^2;
G	is the gravimetric flow rate of the mixture, N/sec;
g	is the gravitational acceleration, m/sec^2;
f	is the area, m^2;
D	is the inside diameter, m;
$\gamma_\varphi = \gamma_1(1-\varphi) + \gamma_2\varphi$	is the true specific weight of the mixture, N/m^3;
$\varphi = f_2/(f_1+f_2)$	is the true volumetric vapor content;
γ	is the specific weight of a phase, N/m^3;
$i_\beta = i_1(1-\eta) + i_2\eta$	is the equilibrium heat content of the mixture, J/N;
η	is the equilibrium gravimetric vapor content;
x	is the true gravimetric vapor content;
β	is the equilibrium volumetric vapor content;
$\beta' = Q_2/(Q_1+Q_2)$	is the flow-rate volumetric vapor content;
Q	is the volumetric flow rate of a phase, m^3/sec;
i	is the saturation heat content of a phase, J/N;
r	is the latent heat of evaporation, J/N;
$\psi_\beta = \lambda_{mix}/\lambda(Re_\beta)$	is the referred friction coefficient of the mixture;
λ_{mix}, $\lambda(Re_\beta)$	are the friction coefficient of the mixture and of a one-phase stream, respectively;
q	is the quantity of heat referred to a unit weight of mixture per unit length, $J/N\cdot m$;
v	is the mean velocity of the mixture, m/sec;
ν	is the kinematic viscosity of a phase in saturation, m^2/sec;
$Re_\beta = vD[(1-\beta)/\nu_1 + \beta/\nu_2]$	is the Reynolds number of the mixture.

Subscripts

1 denotes the liquid phase;
2 denotes the vapor phase.

LITERATURE CITED

1. V. A. Mamaev, G. É. Odishariya, N. I. Semenov, and A. A. Tochigin, Hydrodynamics of Gas–Liquid Mixtures in Pipes [in Russian], Nedra, Moscow (1969).
2. A. A. Armand, Izv. Vsesoy. Tekh. Inst., No. 1 (1946).
3. G. E. Odishariya, Author's Abstract of Candidate's Dissertation [in Russian], VNIIGaz, Moscow (1969).
4. Z. L. Miropol'skii, Teplofiz. Vys. Temp., No. 1 (1971).
5. N. I. Semenov and A. A. Tochigin, Inzh.-Fiz. Zh., 4, No. 7 (1961).