ASPECTS REGARDING THE DETERMINATION OF PRESSURE DROP IN THE FLOW OF TWO-PHASE GAS-LIQUID MIXTURES

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Abstract *The present paper aims to review the most common methods of determining pressure drop in the flow of two-phase mixtures. At the same time, the present study aims to analyse the motion structure of the two-phase gas-liquid flow, two-phase fluid pressure drops and the two-phase vertical flow. In the end, a calculation model of pressure drop in the flow of a two-phase mixture through a horizontal pipe is provided.*

Keywords: Biphasic mixture, Flow regime, Pressure drop, Fluid movement biphasic, Horizontal pipes

1. Motion structure of two-phase gas-liquid flow

The separat ion of flow areas depending on gas and liquid flow rate values in the case of horizontal pipes can be measured using Baker's diagram [1, 5], which allows the classification of flow regimes depending on liquid flow Q, gas flow rate Q_g and K_1 and K_2 constants. Constant values are determined via the following expressions [4, 5, 7]:

$$K_1 = \frac{\sigma}{\sigma_l}\left[\left(\frac{\eta_l}{\eta}\right)^2\left(\frac{\rho_l}{\rho}\right)\right]^{1/6}\left(\frac{\rho_g}{\rho_a}\right)^{0,5}$$
$$K_2 = \left[\left(\frac{\rho}{\rho_l}\right)\left(\frac{\rho_a}{\rho_g}\right)\right]^{0,5} \tag{1}$$

where ρ_g, ρ_l, σ_l, η_i represent gas and liquid densities, and respectively surface tension and dynamic viscosity of water at the operating pressure in the system, and ρ_a, ρ, σ, η - the same values corresponding to atmospheric pressure.

According to the Baker diagram, the following flow regimes may occur:

a) *bubble flow*, which moves to the top of the pipe at a speed close to that of the liquid; the field is limited by the superficial liquid velocity ranging from 1.5 to 4.6 m/s and by superficial gas velocity ranging from 0.3 to 3.1 m/s;

b) *flow featuring large gas bubbles* or stoppers, arranged in the upper section of the transport pipe, which are moving at a speed higher than that of the fluid;

c) *piston-type flow*, characterized by the interruption of the liquid phase's continuity by means of gas stoppers that fill an entire section of the transport pipe; superficial liquid velocity is lower than 0.61 m/s, and that of gas – lower than 0.91 m/s;

d) *stratified flow*, characterized by the fact that an approximately flat separation surface occurs between the gas and liquid volume (it is a free surface flow, except for the fact that the gas phase is pressurized); superficial liquid velocity is lower than 0.15 m/s, and superficial gas velocity ranges from 0.61 to 3.1 m/s;

e) *wave flow*, similar to the stratified flow, except for the fact that high gas velocities lead to highly pronounced undulations of the surface of the liquid, which in certain situations tend to form unstable liquid stoppers that get reintegrated into the liquid mass; superficial liquid velocity is lower than 0.31 m/s; superficial gas velocity should be approximately 4.6 m/s;

f) *flow with liquid separators* occurs in wave flow regime when the liquid waves reach the top of the pipe; this flow regime leads to vibrations inside the system because of the impact of liquid separators – propelled by the gas at high speed– with the pipe fittings;

g) *annular flow*, when the fluid coats the pipe wall, and the gas flows at high speed through the middle section; gas velocity must exceed 6.1 m/s;

h) *atomized or dispersed flow*, when the liquid is sprayed in the form of fine droplets in the gas phase and consequently drawn in the gas flow; this flow regime only occurs when gas velocity exceeds 60 m/s;

i) *foamed flow* occurs under certain conditions (high surface tension values), when the liquid foams and the mixture flows through the pipe.

Except for stratified flow, the other flow regimes also occur on an incline flow direction.

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Depending on the flow regime of the two-phase gas-liquid flow, apparent fluid density and viscosity are defined as shown in table 1.

Table 1. *Density and viscosity definition [7, 8]*

Interface and boundary conditions	Density	Viscosity
Rigid surface bubble regime	$\rho_n = \rho(1-C) + \rho_g C$	$\eta_n = \eta(1+2{,}5C)$
Elastic surface bubble regime	$\rho_n = \rho(1-C) + \rho_g C$	$\eta_n = \eta\left(1+\frac{2{,}5\eta_g+\eta}{\eta_g+\eta}C\right)$
Pressurized flow regime with contact surface	$\rho_n = \rho(1-C) + \rho_g C$	$\eta_n = \eta(1-C)+\eta_g C$
Dry wall regime	$\rho_n = \rho_g$	$\eta_n = \eta_g$
Piston-type flow regime or flow regime with liquid separators	$\rho_n = \rho(1-C) + \rho_g C$	$\eta_n = \eta$

For the classification of vertical flow regime Griffith's diagram [2, 6, 9] is used, where the concentration $C = Q_g(Q_g+Q)$, based on the Froude number, is given by the following equation:

$$Fr_m = \left[\frac{(Q_g + Q)}{A}\right]^2 \left(\frac{l}{g \cdot D}\right) = \frac{v_{nm}^2}{g \cdot D} \tag{2}$$

where A is the cross-section area of the pipe of diameter D.

The following flow regimes can be distinguished:

a) *annular or film flow*, characterized by liquid flowing on the pipe wall in thin layers, leaving the middle section free for gas flow with fine liquid droplets;

b) *piston flow,* for gas velocities ranging from 0.61 to 9.15 m/s;

c) *emulsified flow*, when the gas flows mixed with the liquid in forwarded turbulent regime; the regime occurs when superficial liquid velocities are lower than 0.61 m/s and gas velocities higher than 9.15 m/s, while the transportation regime of liquid droplets occurs at higher gas speeds of about 21.4 m/s.

2. Calculation models of pressure drop in two-phase flows

In order to define the flow regime of two-phase gas-liquid flows the Reynolds number of the gas phase as well as the Reynolds number of the liquid phase are determined, calculated as though the fluids flowed separately through the pipeline.

The equivalent flow method (single phase) or the Wood/Lockhart and Martinelli methods are detailed below:

a. The equivalent fluid method (single phase) or Wood method regards the mixture as a single-phase fluid. The method, applicable to small concentrations of gas, consists of considering the validity of the general laws of pressure drop (Darcy) for a homogeneous fluid whose physical properties can be taken as average values according to the calculation relations of equivalent variables [2, 6, 9, 10]:

$$\frac{1}{\eta_n} = \frac{C}{\eta_g} + \frac{1-C}{\eta}, \quad \frac{1}{\rho_n} = \frac{C}{\rho_g} + \frac{1-C}{\rho} \tag{3}$$

where η and ρ stand for the dynamic viscosity and liquid density (without indexation), gas density (*g* index) and the two-phase fluid (*n* index). *C* represents the density concentration of the gas phase as given by the following equation:

$$C = \frac{Q_g}{Q_g + Q} \tag{4}$$

where Q_g and Q represent gas density flow and liquid density flow, respectively.

Linear load loss is calculated using Darcy's formula: $\frac{\Delta p}{\gamma} = \frac{L}{D}\frac{v^2}{2g}\lambda$ where v is the velocity of the two-phase fluid, and L and D are the length and diameter of the pipe.

For two-phase gas-liquid fluids flowing through pipes of a diameter between 80 and 400 mm, the λ_n Darcy coefficients are used: λ corresponding to the two-phase fluid and water, $\lambda_n = \lambda\,(2.08C^{1.7} + 1)$.

For the determination of the Reynolds number the apparent kinematic viscosity coefficient is used, where $\upsilon_n = \eta_n/\rho_n$, the dynamic viscosity η_n being given by equation (3).

The Wood method provides satisfying results for low Froude numbers Fr<4 and low concentrations, C<0.4.

A version of this method is the so-called two-phase factor method. The method eliminates the problem of establishing a flow type via arbitrary criteria, considering the two-phase mixture as a homogeneous fluid (pseudo-fluid) whose weight is equal to that of the mixture. The two-phase factor $\lambda_n^{'}$ is defined by the relation:

$$\lambda_n^{'} = \frac{2gD}{v^2 L}\frac{\Delta p}{\gamma} \tag{5}$$

and the Reynolds two-phase number via the following equation:

$$Re_n = \left(\frac{Dv_g \rho_g}{\eta_g}\right)^{\delta} \left(\frac{Dv\rho}{\eta}\right)^{\beta} = Re_g^{\delta} Re^{\beta} \quad (6)$$

where δ and β are constants that depend upon density concentration C of the gas in the liquid, according to the following equation:

$$\delta = \frac{C}{C+1}, \quad \beta = e^{-0,1 \cdot C} \quad (7)$$

If C tends to infinity (gas phase flow), then $\delta \longrightarrow 1, \beta \longrightarrow 0$ and the Reynolds number given by relation (6) tends to its value for gas. If $C \longrightarrow 0$ (liquid homogeneous phase), $\delta \longrightarrow 0, \beta \longrightarrow 1$ and the Reynolds two-phase number is close to that of liquid. Given these boundary conditions, it is evident that the two-phase factor λ'_n tends to the λ coefficient for a single phase coefficient, λ_{gas} or λ_{liquid}.

In order to calculate the λ'_n coefficient, the following functional relation is used:

$$\lambda'_n = \Phi\left[Re_g^{\delta} Re^{\beta}\right] \quad (8)$$

In order to calculate the pressure drop distributed on a straight pipe section λ'_n is inserted in place of the λ coefficient in Darcy's equation.

In situations 1 ... 4 of table 1, dynamic viscosity is dependent upon the two-phase fluid concentration; the λ_n load-loss coefficient is given by the equation below:

$$\lambda_n^{-0,5} = \left(\sqrt{2}\right)^{a+4}\left[\lg(Re)\lambda_n^{0,5} - (0,11a + 0,5b + 1,1)\right] \quad (9)$$

In the case of regime 5 surface tension depends upon kinematic flow parameters; Darcy's coefficient is calculated via the following formula:

$$\lambda_n^{-0,5} = \left(\sqrt{2}\right)^{a+4}\left[\lg(We)\lambda_n - (0,2a + 0,3b - 1,1)\right] \quad (10)$$

where constants a and b are whole numbers whose values depend on flow regime, and We is the dimensionless Weber number.

b. Lockart and Martinelli's method. The proposed method is grounded on Martinelli's research on gas-liquid two-phase fluid for horizontal pipes [10]. The previously mentioned research demonstrated that the loss of pressure in the two-phase fluid flow through the pipes does not depend upon the flow configuration that appears in different flow regimes, as long as the following assumptions are true: 1- flow is constant; 2 - there is no sign of radial gradient pressure in the pipe; 3 - static pressure loss in the liquid phase is identical to that of the gaseous phase.

All these considerations are not applicable in the case of piston-type, bubble, or stratified flow regimes.

In principle, the method used for calculating pressure drop in a pipe section involves:

- calculating Δp_{liquid} phase pressure drop and Δp_{gas} drop under the assumption that these homogeneous phases flow independently through the pipe;
- coefficient calculation

$$\chi = \sqrt{\frac{J_{lichid}}{J_{gaz}}} = \sqrt{\frac{\Delta p_{lichid}}{\Delta p_{gaz}}} \quad (11)$$

- calculating the Reynolds numbers for the Re_g gas and Re liquid phases, as though these homogeneous phases flowed individually through the entire cross section of the pipe; the liquid Re_g and Re values are used to determine fluid flow regime;
- the flow regime and the χ coefficient values determine the values of dimensionless coefficient Φ; there are four possible regimes depending on the combinations of the laminar and turbulent mechanism of each isolated phase. In order to calculate pipe section pressure loss the following equation is used:

$$\Delta p_n = \Phi(\Delta p)_{gaz\ sau\ lichid} \quad (12)$$

where Δp_n represents the pressure loss of the two-phase fluid flow, determined either via the pressure drop of the liquid phase flow or the gas one. Both methods lead to the same result.

3. Vertical two-phase flow

In order to calculate the vertical flow parameters of two-phase gas-liquid fluids with multiple applications in industrial and technical areas, a method based on the following characteristics is used:

a) the assumption is that the two phases represent a single "pseudo-phase" having a specific mixture weight calculated via the average formula;

b) gas solubility is taken into consideration, as well as the changes in its values, which occur as a consequence of pressure drop;

c) the method cannot be applied to flows featuring significant turbulent conditions.

The method is based on the calculation of the λ'_v coefficient as defined by the following relation:

$$\lambda'_c = 2gD\left(\frac{\Delta p}{\gamma}\right) w_m^{-2} (h_2 - h_1)^{-1} \quad (13)$$

where $(h_2 - h_1)$ represents the vertical flow distance in a pipe of diameter D, and w_m represents the flow rate obtained as an average value integrated via the isothermal relaxation formula from pressure p_1 to pressure p_2.

$$w_m = \frac{1}{p_1 - p_2} \int_{p_1}^{p_2} w dp \,(14) \quad (14)$$

For certain individual cases, the literature [3, 4, 5, 7] mentions laws of variation with velocity *w* calculated as $w = F(p_0, T_0, p, T, and, C, \alpha)$, where p_0, T_0, p, T represent the pressure and temperature of the initially input point and, at a random point, C represents concentration, α - the compressibility degree of the gas, and s_i – the solubility of gas in the liquid.

4. Calculation models

The calculation model of pressure drop in the flow of two-phase water-air mixtures is determined for a horizontal pipe of diameter D=150 mm, length=2000 m and liquid mass flow Q_{Mg}= 0.10 kg/s at a temperature of 10°C.

Water and air density is ρ = 1000 kg/m3 and ρg = 1,244 kg/m3, respectively, while dynamic viscosity η = 1,3*10-3 N·s/m2 and η = 1,75*10-5 N·s/m2, respectively.

1) Volumetric flow rates are determined:

$$Q = Q_M / \rho = 10/1000 = 10^{-2}\, m^3/s$$
$$Q_g = Q_{Mg} / \rho_g = 0,10/1,244 = 0,0804\, m^3/s. \quad (15)$$

2) The fictive flow rate of both liquid and gas is calculated:

$$v = \frac{Q}{\frac{\pi \cdot D^2}{4}} = \frac{4 \cdot 0,01}{\pi \cdot 0,15^2} = 0,5658\ \mathrm{m/s}$$
$$v_g = \frac{4 \cdot Q_g}{\pi D^2} = \frac{4 \cdot 0,0804}{\pi \cdot 0,15^2} = 4,5497\ \mathrm{m/s}. \quad (16)$$

3) The Reynolds numbers are determined:

$$\mathrm{Re} = \frac{\rho v D}{\eta} = \frac{1000 \cdot 0,5658 \cdot 0,150}{1,31 \cdot 10^3} = 64786,26$$
$$\mathrm{Re}_g = \frac{\rho_g v_g D}{\eta_g} = \frac{1,244 \cdot 4,5497 \cdot 0,150}{1,75 \cdot 10^{-5}} = 48512,8. \quad (17)$$

In turbulent flow the Blasius relationship is applied.

4) Pressure loss calculation. The value of parameter χ is determined using the following relationship:

$$\chi = \left(\frac{v}{v_g}\right)^{7/8} \cdot \left(\frac{\rho}{\rho_g}\right)^{3/8} \cdot \left(\frac{\eta}{\eta_g}\right)^{1/8} =$$
$$\left(\frac{0,5658}{4,5497}\right)^{7/8} \cdot \left(\frac{1000}{1,244}\right)^{3/8} \cdot \left(\frac{1,31 \cdot 10^{-3}}{1,75 \cdot 10^{-5}}\right)^{1/8} = 3,4. \quad (18)$$

Coefficient Φ_l is determined via the following formula:

$$\Phi_l = \sqrt{1 + \frac{20}{\chi} + \frac{20}{\chi^2}} = \sqrt{1 + \frac{20}{3,4} + \frac{1}{3,4^2}} = 2,6398 \quad (19)$$

Coefficient λ is is calculated using the Darcy equation (Re<10^5):

$$\lambda = \frac{0,3164}{\mathrm{Re}^{1/4}} = \frac{0,3164}{64786,26^{1/4}} = 0,01983. \quad (20)$$

The liquid pressure loss will be:

$$\left(\frac{\Delta p}{l}\right)_l = \lambda \frac{l}{D} \cdot \frac{v^2}{2g} \cdot \gamma = 0,01983 \frac{0,5658^2}{0,15 \cdot 2 \cdot 9,81} \cdot 9810 = 21,16\ \mathrm{N/m^3}$$
$$\left(\frac{\Delta p}{l}\right)_n = \Phi_f^2 \cdot \left(\frac{\Delta p}{l}\right)_l = 2,6398^2 \cdot 21,16 = 147,46\ \mathrm{N/m^3}. \quad (21)$$

The pressure loss in the transport pipe will be:

$$\Delta p_n = \left(\frac{\Delta p}{l}\right)_n \cdot l = 147,45 \cdot 2000 = 2,949 \cdot 10^5\ \mathrm{N/m^2}. \quad (22)$$

4. Conclusions and recommendations

1. According to the Baker diagram, the following flow regimes were outlined: *bubble flow*; *large-dimension bubble flow; piston-type flow*; *stratified flow*; *wave flow*; *liquid separator flow*; *annular flow*; *atomised or dispersed flow*; *foamed flow*. Except for stratified flow, all the other flow regimes occur on an incline flow direction. (14)

2. In order to define the flow regime of two-phase gas-liquid fluids the Reynolds number of the gas phase as well as the Reynolds number of the liquid phase are determined, calculated as though the fluids flowed separately through the pipeline. The present paper analysed the *equivalent flow method (single phase)* or the *Wood*, as well as *Lockart/Martinelli* methods in order to determine pressure drop in two-phase mixture flow.

3. The determination of pressure drop in two-phase mixture flow is done in five stages:

- the volumetric flow rates are calculated via relation 14; (16)
- fictive flow rates of mixture phaese are determined using relation 16;
- the Reynolds number is calculated in order to determine flow regime (relation 17);
- after flow regime determination, the pressure loss coefficients are calculated (relations 18 – 20);
- liquid and pipe pressure loss is calculated.

4. The present paper presents a calculation model of pressure drop in the flow of two-phase water-air mixtures for a horizontal pipe of diameter D=150 mm and length=2000 m. (17)

(18)

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