

MULTIPHASE FLOW MIXTURE IN 180° PIPE BENDS

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This paper presents the results of research regarding measurements of the values of pressure drops during horizontal flow of gas-liquid and gas-liquid-liquid mixture through 180° pipe bends. The conducted insightful analysis and assessment during multi-phase flow in pipe bends has enabled to develop a new method for determination of their values. This new method for determining pressure drops ensures higher precision of calculation in comparison to other methods presented in literature and can be applied for calculation of these parameters during multi-phase flows in pipe bends with various geometries.

Keywords: hydrodynamics, gas-liquid flow, pipe bends

1. INTRODUCTION

In the investigations of multi-phase flow in pipe bends one has to bear in mind that pipe bends constitute elements of armature that affect locally the multi-phase flow. As a result of centrifugal force and gravity force pipe bends tend to deepen the separation of phases in multi-phase flow and transform the value of its flow structure both behind and following a pipe bend. It is demonstrated by an abrupt fall in the value of pressure in the bent sections of an installation (Fig. 1). Such disturbances can adversely affect operating conditions and operation of a number of apparatuses, as well as lead to corrosion and failure of a tubular insert. In the consideration of the above the familiarity with changes in pressure drops during multi-phase flow in U-pipes starts to play a key role in the design of process apparatuses.

As a result of analysing multi-phase flow in U-pipes an attempt is made at finding a physical relation between the parameters of such flow and pressure drops in order to qualitatively account for pressure drops in pipe bends. In order to reduce the numbers in potential correlation equations the efficiency of each of the phases in multi-phase flow is, just as in usual cases, substituted by fluxes of specific phases and their volume or mass fractions. Despite the fact that volume and mass fractions are not rational numbers, they form dominant parameters upon which the correlation equations are dependent. The physical properties of the phases, i.e. density and viscosity are usually referred to by means of a mathematical expression that gives their ratios in numbers. However, since in a flow of a multi-phase mixture we have to do only with a trace influence of the dynamic viscosity of the gas phase on the flow of the remaining phases; hence its influence is only slightly accounted for compared with the dynamic viscosity of the liquid.

The parameters that affect the values of pressure drops during multi-phase mixture flow in U-pipes include: streams of the phases, void fractions of the phases, physical properties of the phases, geometric parameters of the pipe bend (diameter, angle of bending, radius of the curvature) and gravitational force

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(in case of a horizontal pipe bend). In turn, pressure losses are not unduly affected by the roughness of the pipe wall and surface tension of the liquid and, hence, they are disregarded in calculation models.

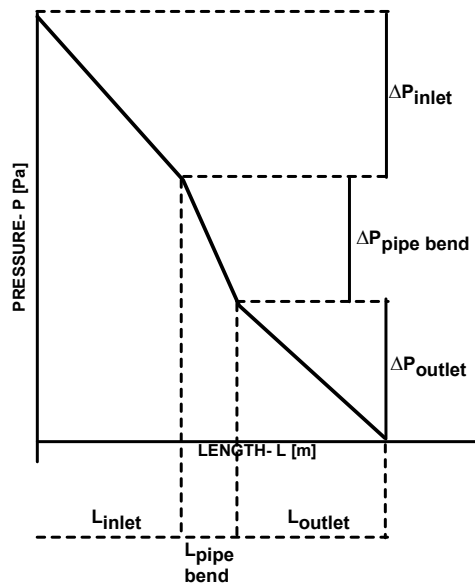


Fig. 1. The schematic diagram of pressure drop in U-pipe

For the case of multi-phase flow the available research material is relatively scarce. Only few calculation models and correlations regarding two-phase flow in pipe bends are described in the literature of the subject. These topics were undertaken by Chen (2005), Chisholm (1985), Domanski and Hermes (2008), Geary (1975) and Hapanowicz (2001). In addition, the literature lacks descriptions of the relations between pressure drops and flow structures as well as actual values of the volume fractions of phases. This results in an incomplete description of phenomena occurring during multi-phase flow in pipe bends and forms an impediment in generalisation of qualitative and quantitative description of multi-phase flow in this type of elements.

In connection with these problems an attempt was made to describe multi-phase flow in U-pipes in order to determine values of pressure drops and ultimately, develop a model applicable for their calculations.

2. EXPERIMENTAL TECHNIQUES

Research of multi-phase flow in U-bends was conducted using three flowing media: air, water and oil. The oily liquid used in this research involved Itherm 12 and L-AN 15 oil for which, depending on the temperatures $t_o = 15 - 30$ °C, the respective densities and viscosities are equal to, $\rho_o = 875.5 - 884.5$ kg/m³, $\eta_o = 20 - 500$ mPa·s. Table 1 contains a summary of the conditions in which the research was conducted. Flow velocities were determined by means of apparent velocities – these are velocities resulting from the passage of stream of particular phases over the entire cross-section of the pipe.

The designed and built installation consisted of two test stands enabling to measure pressure drops during multi-phase flow in U-pipes. The first stand was used to investigate multi-phase flow in a pipe bend with the internal diameter of 0.016 m, while the other one (one with two measurement channels) to analyse multi-phase flow in a pipe bend with the internal diameters of 0.022 and 0.030 m. The common parts between the two stands included: oil and water tanks, pumps, rotameter batteries, separator and pneumatic feeding system. The diagram of the test stand is presented in Fig. 2.

Table 1. Parameters of flow

Phase i	$w_{i,0}$ [m/s]	Re_i [-]	ε_i [-]
Air	0.038-5.4	38-7557	0.07-0.96
Water	0.018-0.92	289-20219	0.07-0.97
Oil	0.014-0.92	0.38-670	0.01-0.97

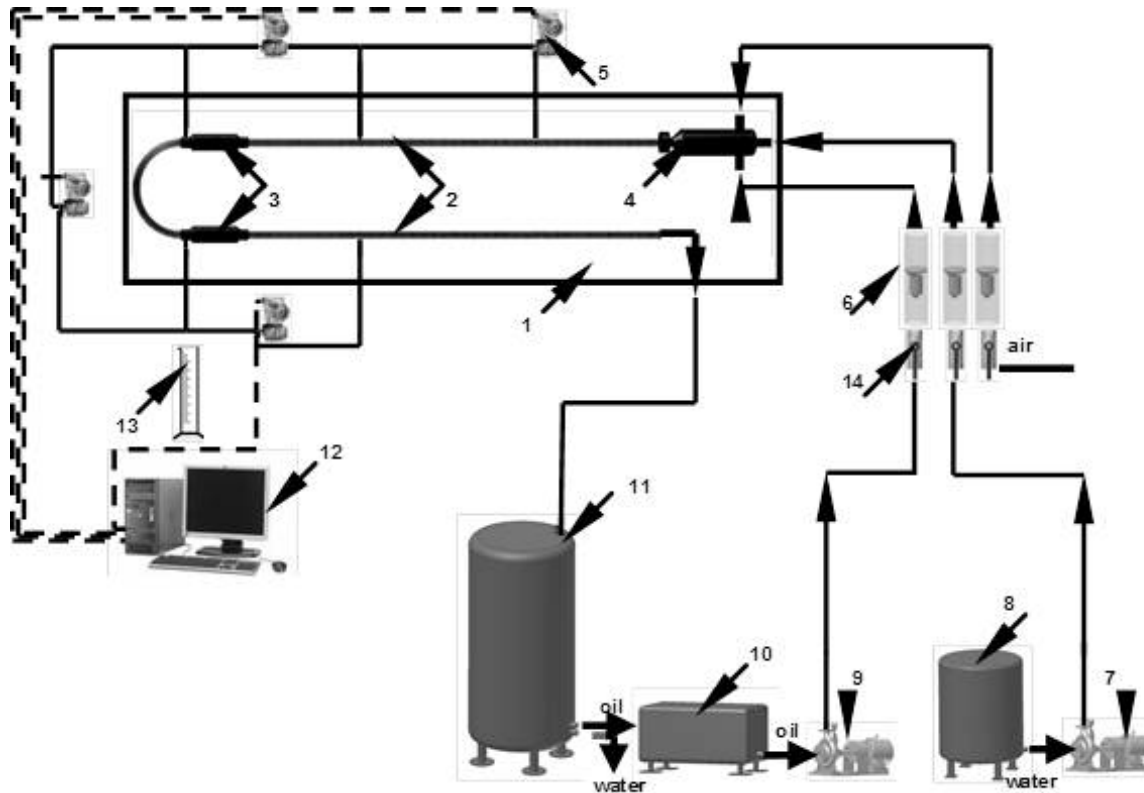


Fig. 2. Diagram of the test stand;

- 1- rotary carrying plate, 2- pipes, 3- tympanic valves, 4- mixing chamber, 5- differential pressure transducers, 6- flow meters, 7- water pump, 8- water tank, 9- oil pump, 10- oil tank, 11- separator, 12- computer, 13- cylinder, 14- control valves

The test stand used in the hydrodynamics research in pipe bends consists of: oil and water pump (9, 7), oil tank (10), water tank (8), agitator (4), test section (2), separator (11) and a battery of rotameters (6). The principal element of the stand was a test channel made of two axial plexiglas pipes (2), and diameters of $d = 0.016, 0.022, 0.03$ m and lengths of $L = 1.5, 3.5, 3.5$ m, respectively, connected by pipe bends. The radius of pipe curvature was selected so that the ratio of the curvature was $R/d = 7$. The bend angle φ was equal to 180° . The entire channel was mounted on a rotary carrying plate (1). In the measurements of a bend with a diameter of 16 mm, rotation of the carrying plate (1) was possible, and consequently both vertical and upward and downward flows were analysed. The oil liquid tank was equipped with an agitator and heater assembly, which made it possible to heat the oil to the required temperature and, as a result, obtain its various density and viscosity levels. Variable volume fractions of liquid flows were obtained owing to control valves (14) and rotameters (6). The circulating media were pumped from the tanks into the agitator, which was additionally fed by compressed air from the grid. A multi-phase mixture formed in this ways was subsequently passed through the measurement channel and was finally fed into a separator where the phases were separated. The separated oil was returned into the tank and was circulating again, while the water was disposed of into the sewage.

3. RESULTS

The analysis of pressure drop measurement results showed that the reasons for their variability are very complex. These alterations result from changes occurring in a mixture flowing through a pipe bend and they were associated not only with the effects of mutual relations between two non-mixing liquids but also with the location of the pipe bend. It turned out that the values of pressure drop are influenced by such variables as variability of the structures of multi-phase flow, volume fractions of the phases, possible changes in the system type from O/W to W/O and a discernible interfacial slippage in specific circumstances. The notion of the system type from O/W to W/O denotes here flow structures forming for the dominant water phase and structures forming for the dominant oil phase, respectively.

The structures of three-phase flow were grouped depending on the type of the dominant phase in the flow. The symbols applied in the description of the flow structures denote the following: type of gas-liquid mixture flow, flow structure of the liquid components of the mixture and the type of the phase that is dominant in the liquid. As a result of identification of flow structures in three-phase mixture in a pipe bend, Figs. 3 and 4 present the diagrams of the structures distinguished in such flow. For the dominant water phase in three-phase flow the following structures were identified: P-DrO/W- plug flow with oil drops in water, Sl-DrO/W- slug flow with oil drops in water, Sl-DO/W- slug flow with oil dispersed in water, F-DO/W- foam flow with oil dispersed in water, A-DO/W- annular flow with oil dispersed in water. For the dominant oil phase the following structures were identified in three-phase flow: B-DrW/O- bubbly flow with water drops in oil, P-DrW/O- plug flow with water drops in oil, Sl-DrW/O- slug flow with water drops in oil, F-DW/O- foam flow with water dispersed in oil, A-DW/O- annular flow with water dispersed in oil.

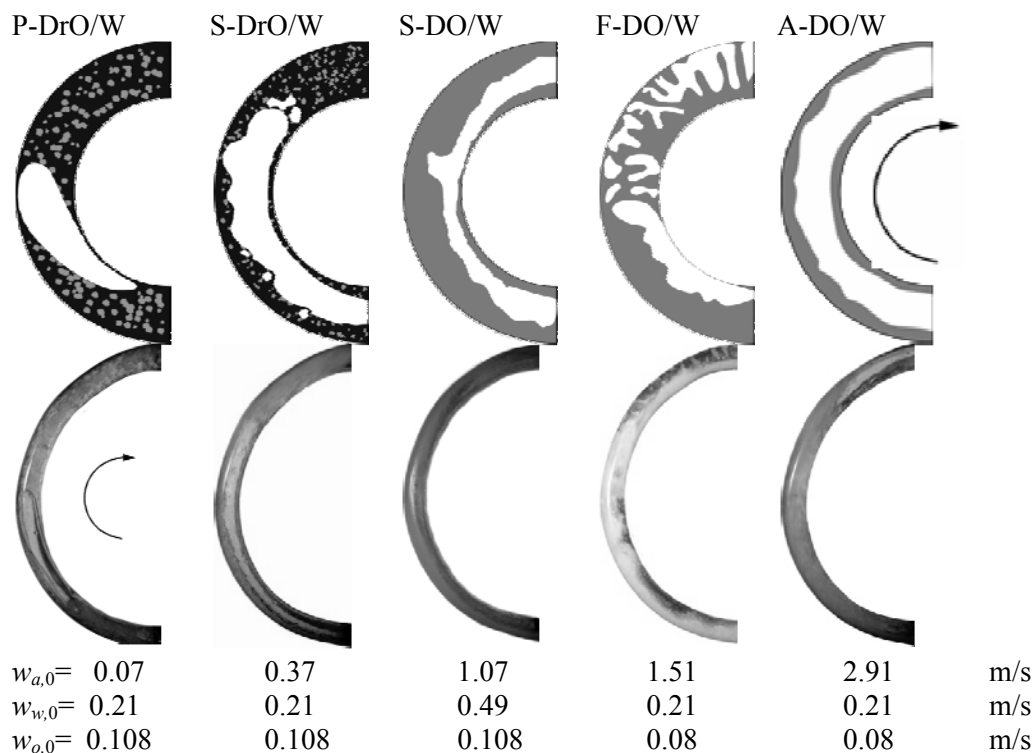


Fig. 3. Flow patterns in upward oil-water-air three-phase flow through a pipe bend ($d = 0.016$ m, $D = 0.22$ m) for the dominant water phase

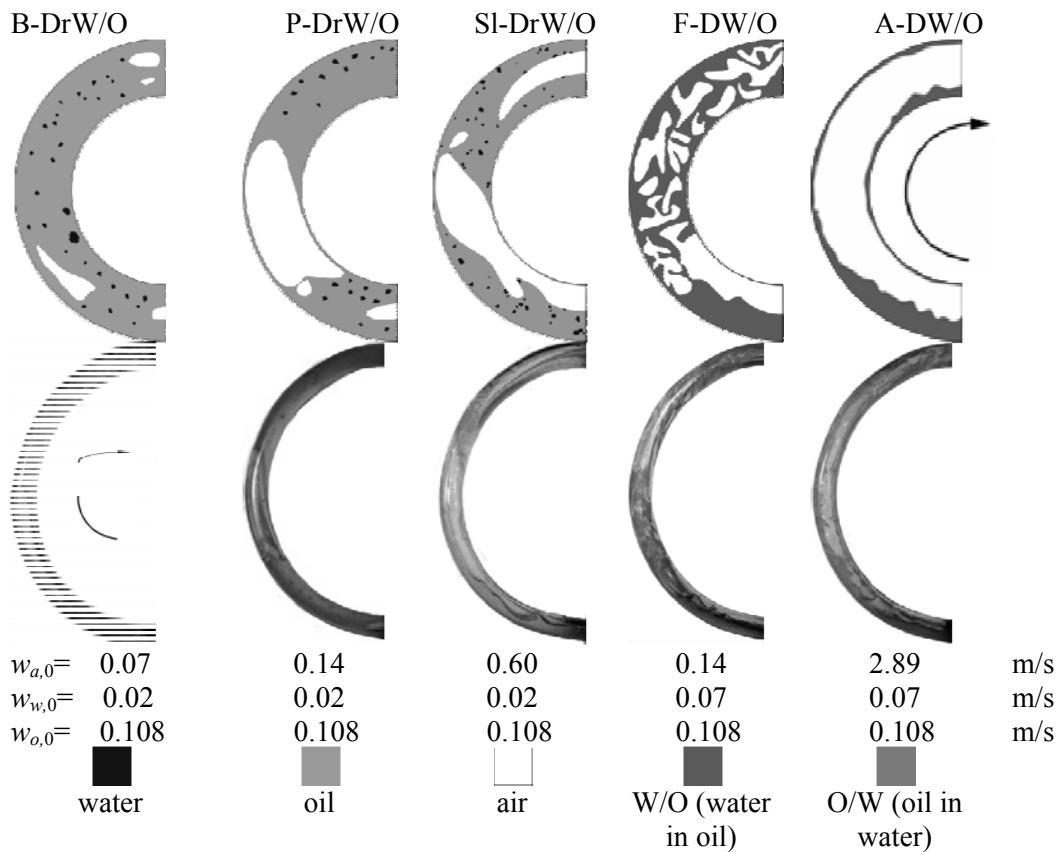


Fig. 4. Flow patterns in upward oil-water-air three-phase flow through a pipe bend ($d = 0.016$ m, $D = 0.22$ m) for the dominant oil phase

As a result of investigations of multi-phase flow in a pipe bend the effect of pressure drop reduction was observed. This phenomenon was sufficiently covered for the case of multi-phase flow in axial pipes and discussed in papers by Dyga (2006), Hapanowicz and Troniewski (1998), Nowak (2005) and Troniewski et al. (2006). The effect of pressure drop reduction was observed for the three-phase gas-liquid-liquid mixture flow (Fig. 5) in a horizontal pipe bend.

From the distribution of the lines in Fig. 5 one can conclude that for a constant value of the stream of water we have to do with an initial increase, later decrease and a further increase of total pressure drop in a horizontal pipe bend. In summary, an increase of the total stream of the liquid mixture within a certain range of variability of flow parameters results in a decrease of the total pressure drop. It suggests that water is responsible for this specific change in flow parameters, as the water phase has a smaller viscosity and density than the oil phase. It is explained by the fact that if clear oil (which forms the liquid phase) is supplemented with a small portion of water, the latter forms small drops which are virtually not in contact with the wall of the channel, but are carried on the surface of oil. However, if water is gradually added to this system, at a certain stage it will start to dominate over the oil and thereby its contact with the pipe walls will eventually be considerable, which will lead to the overall pressure drop during the flow for a concurrent increase of the stream of the liquid phases. In a certain boundary case, when the stream of water and also its void fraction will increase even further, we will have to do with a recurrent increase of the total pressure drop. This theory is completely correct if we consider two-phase liquid-liquid system. For the case of gas-liquid-liquid system the mechanism is different. It appears that along with an increase of the velocity of water flow, which is not necessarily accompanied by an increase of its volume fraction, its smaller dispersal in the oil phase follows and, thus, water (the phase with a smaller viscosity) remains in considerable contact with the wall of the pipe bend, which results in the reduction of the total pressure drop of the three-phase mixture. This decrease occurs until the complete dispersal of the oil phase in water. When it is achieved, the air

passing at a high speed determines the repeated increase of the total pressure drop during three-phase flow through a pipe bend.

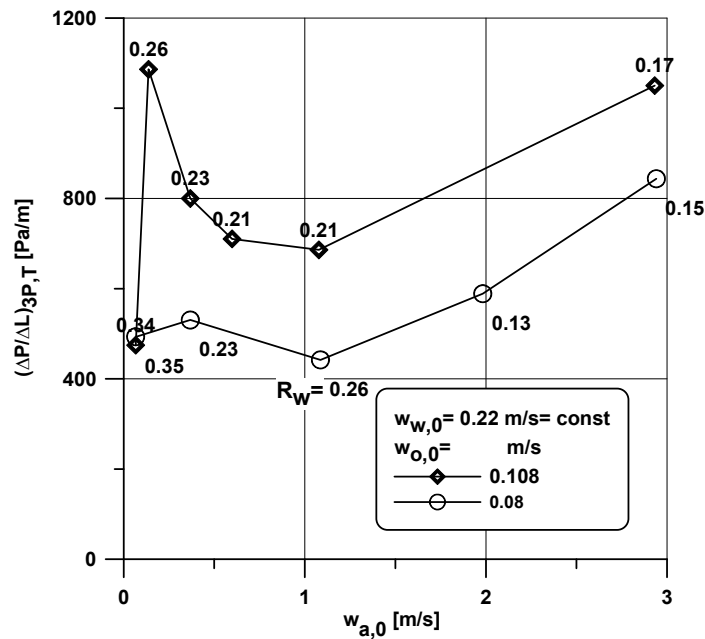


Fig. 5. Reduction effects of three-phase oil-water-air flow

The statement regarding the determination of the effect of reducing total pressure drop by the liquid phase (i.e. one with the smaller density and viscosity than the oil phase) is confirmed by the data presented in Fig. 6. This chart illustrates the variability of the values of specific total pressure drops in a horizontal pipe bend for three-phase air-water-oil flow in relation to the apparent velocities of the air and oil and water fractions.

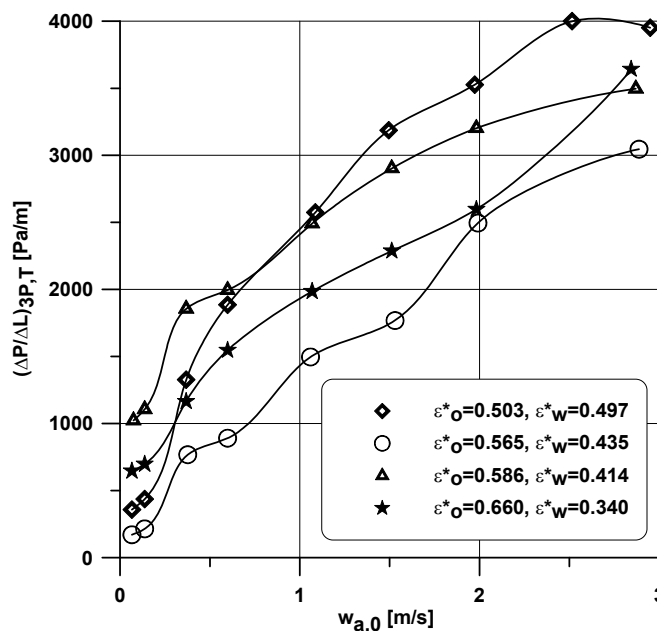


Fig. 6. Effect of phase concentrations on the values of total pressure drop during three-phase flow through a pipe bend ($\rho_o = 859 \text{ kg/m}^3$, $\eta_o = 20 \text{ mPa}\cdot\text{s}$)

From the data in Fig. 6 one can conclude that a decrease of the concentration of water in a water-oil system leads to a constant increase of total pressure drop of three-phase mixture in a horizontal pipe bend. In the same manner, the total pressure drop of three-phase mixture, just as for the case of axial

pipes, is governed by the relations between the liquid phases in a three-phase system. The gas phase is only the driving force for the liquid phases and causes its mixing and dispersion, depending on the type of the dominant phase – water in oil and oil in water. To sum up, the scale of total pressure drop reduction during three-phase flow will be predominantly decided by the fact, which of the liquid phases will be the dominant one in the system, and that is, the flow structure and type of the liquid-liquid system.

This is further confirmed by data in Fig. 7 from which one can conclude that an increase in the concentration of water in water-oil system accompanied by a concurrent increase of concentration of oil results in a steady increase of total pressure drops of three-phase mixture in a horizontal pipe bend. For this reason, one can conclude that total pressure drops in three-phase flow just as in the case of straight pipes are predominantly influenced by the relations between the liquid phases in a three-phase system. Thereby, the gas phase plays the role of a motor that drives the liquid mixture and causes its dispersion, depending on the dominant phase – water in oil and oil in water. To summarise, the scale of the reduction of total pressure drop in three-phase flow is mostly affected by the liquid phase which is dominant in the system and, thereby, by the very structure of the flow and only partially by the type of liquid-liquid system. From Fig. 5 it also results that for $\varepsilon_w^* = 1$ and $\varepsilon_o^* = 0$ (two-phase air-water flow) the values of total pressure drops are smaller than for $\varepsilon_o^* = 1$ and $\varepsilon_w^* = 0$ (air-oil flow). Concurrently, in both cases total pressure drops are smaller than the values gained for three-phase flow.

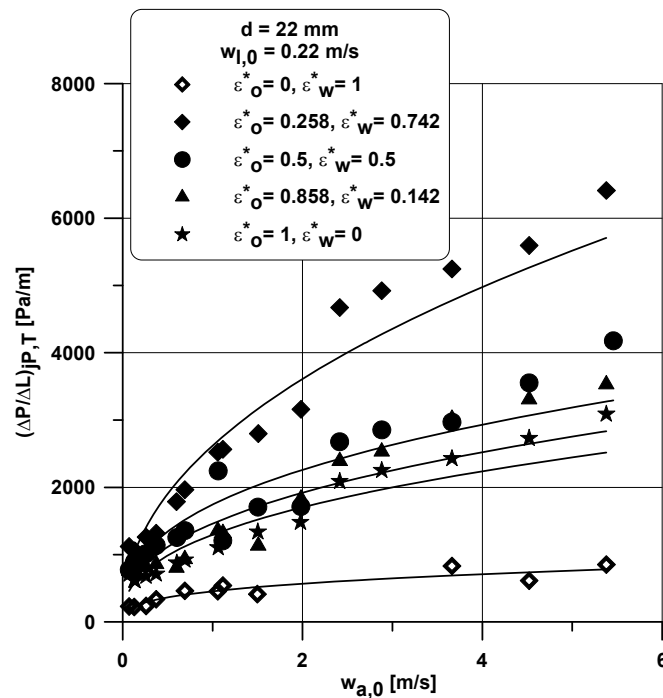


Fig. 7. The concentration influence of phases on values of total pressure drops in U-pipe about internal diameter 0.022 m ($\rho_o = 859$ kg/m³, $\eta_o = 20$ mPa·s)

In the quest for finding sufficiently precise mathematical relations to define the value of pressure drops of multi-phase mixtures in pipe bends an attempt was made to apply several equations found in the literature. However, the results indicate that these equations do not ensure good consistency when the results were compared with empirical data. The results of the conducted statistical analysis are presented in Tables 2 and 3. For three-phase gas-liquid-liquid flow the properties of the liquid phase, i.e. density and viscosity were calculated with regard to the void fractions of water and oil in the flowing mixture.

On the basis of the author's original results of measurement Equation (1) was developed for the determination of the local pressure drop friction factor for air-oil flow and air-water flow in a vertical

pipe bend accounting in a pipe bend whose geometry changes are expressed by means of the ratio (d/D):

$$\xi_{2P} = 7.6 \cdot 10^4 \left(\frac{d}{D}\right)^{0.5} Re_g^{-1.42} Re_l^{0.95} Mo^{0.36} \quad (1)$$

where

$$Re_g = \frac{w_{g,0} d \rho_g}{\eta_g} \quad (2)$$

$$Re_l = \frac{w_{l,0} d \rho_l}{\eta_l} \quad (3)$$

$$Mo_l = \frac{g \eta_l^4}{\rho_l \sigma_l^3} \quad (4)$$

Table 2. Statistic analysis for two-phase flow

Type of flow		gas-liquid	
No	Method developed by	$\overline{\delta_{\Delta P}} = \frac{1}{n} \sum_{i=1}^n \frac{\Delta P_{exp} - \Delta P_{cal}}{\Delta P_{exp}} \cdot 100\%$	$ \overline{\delta_{\Delta P}} = \frac{1}{n} \sum_{i=1}^n \left \frac{\Delta P_{exp} - \Delta P_{cal}}{\Delta P_{exp}} \right \cdot 100\%$
1	Hapanowicz (2001)	-125	+193
2	Chisholm (1980)	-133	+201
3	Yu et al. (1989)	-84	+175
4	Azzi et al. (2000)	-109	+173
5	Ulbrich, Witczak (1990)	+14	+52

Table 3. Statistic analysis for three-phase flow

Type of flow		gas-liquid-liquid	
No	Method developed by	$\overline{\delta_{\Delta P}} = \frac{1}{n} \sum_{i=1}^n \frac{\Delta P_{exp} - \Delta P_{cal}}{\Delta P_{exp}} \cdot 100\%$	$ \overline{\delta_{\Delta P}} = \frac{1}{n} \sum_{i=1}^n \left \frac{\Delta P_{exp} - \Delta P_{cal}}{\Delta P_{exp}} \right \cdot 100\%$
1	Chisholm (1967)	-5.5	+62
2	Chisholm (1980)	-180.5	196.5
3	Domanski and Hermes (2008)	-34.5	+94
4	Hapanowicz (2001)	-136	+144
5	Sookprasong (1980)	-140	+166
6	Usui et al. (1983)	-70	+98

With the input of local pressure drop ΔP_{2P} during two-phase gas-liquid flow in a pipe bend, it is possible to calculate from Equation (5), by the substitution of Equation (1) in the place of ξ_{2P} . This gives the value of the pressure drop in a horizontal pipe bend

$$\Delta P_{2P,T} = \xi_{2P} \frac{w_{2P}^2}{2} \rho_{2P} \quad (5)$$

The density ρ_{2P} and velocity w_{2P} of the two-phase mixture in Equation (5) has to be determined from the relation:

$$\rho_{2P} = R_{g,B} \rho_g + (1 - R_{g,B}) \rho_l \quad (6)$$

$$w_{2P} = w_{g,0} + w_{l,0} \quad (7)$$

The void fraction of the air $R_{g,B}$ during the flow of two-phase air-water and air-oil mixture in a pipe bend can be determined on the basis of an original relation (8)

$$\frac{R_{g,B}}{R_{g,S}} = 1.071 \varepsilon_g^{-0.317} Fr_{l,B}^{0.035} \quad (8)$$

while Stomma (1979) method is taken as the reference relation:

$$R_{g,S} = 1 - \frac{\varepsilon_g^2 - x_g^2}{2 \left[\ln \left(\frac{1 - x_g}{1 - \varepsilon_g} \right) - (\varepsilon_g - x_g) \right]} \quad (9)$$

and the equivalent Froude number is determined from the equation:

$$Fr_{l,B} = \frac{w_{l,0}^2}{gR} \quad (10)$$

The results of statistical research indicate that 82% of measurement points are found to be in the range $\pm 30\%$ of the relative error, which provides a very high precision range for the two-phase gas-liquid mixture flow. In Fig. 8 one can see the results of a comparison between the measured values of coefficient ζ_{2P} with the values calculated on the basis of Equation (1).

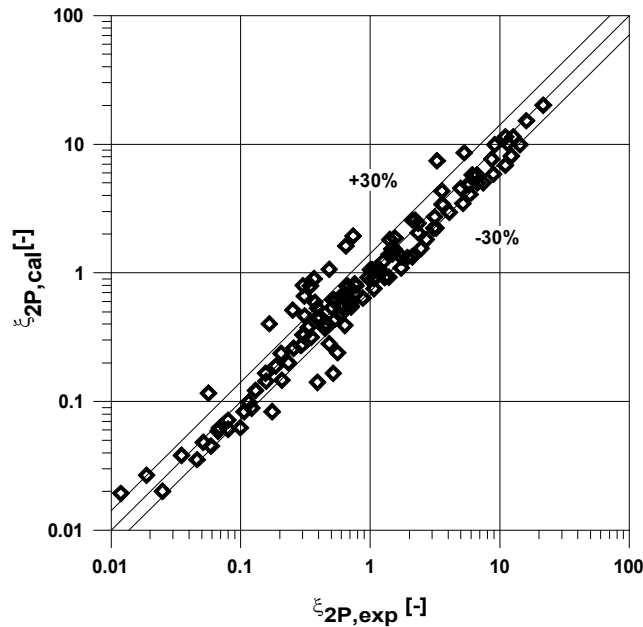


Fig. 8. Comparison of measured and calculated values of local friction factor ζ_{2P} of gas-liquid flow in pipe bends

Since the consistency of the measured points with the computed ones derived from Equation (1) was found to be satisfactory, a decision was made in a subsequent step to develop a new correlation for three-phase flow on the basis of the existing form of the correlation for two-phase gas-liquid flow.

As a result of the undertaken correlation calculations the following relation was established (11)

$$\xi_{3P} = 2.53 \cdot 10^3 \left(\frac{d}{D} \right)^{0.5} \text{Re}_g^{-0.55} \text{Re}_{l,2P}^{1.33} \text{Mo}_{l,2P}^{0.79} \quad (11)$$

where the value of the Reynolds number for liquid was determined from Equation (12)

$$\text{Re}_{l,2P} = \frac{w_{l,2P} d \rho_{l,2P}}{\eta_{l,2P}} \quad (12)$$

where

$$w_{l,2P} = w_{w,0} + w_{o,0} \quad (13)$$

in which the equivalent properties of the water-oil mixture was determined by Equations (14) and (15)

$$\rho_{l,2P} = \rho_w R_w^* + \rho_o R_o^* \quad (14)$$

$$\eta_{l,2P} = \eta_w R_w^* + \eta_o R_o^* \quad (15)$$

in which the void fractions of the components of the two-phase liquid phase are calculated on the basis of the relations for three-phase flow in pipe bends, for the liquid taking the form:

$$R_w^* = (\varepsilon_w^*)^{0.8} \quad (16)$$

$$R_o^* = 1 - R_w^* \quad (17)$$

Morton number, Mo , was calculated for the equivalent properties of the liquid

$$\text{Mo}_{l,2P} = \frac{g \eta_{l,2P}^4}{\rho_{l,2P} \sigma_{l,2P}^3} \quad (18)$$

where:

$$\sigma_{l,2P} = \sigma_w R_w^* + \sigma_o R_o^* \quad (19)$$

A comparison of the measured values of the coefficient of local friction factor ξ_{3P} with the values derived on the basis of the proposed method are presented in Fig. 9. It was indicated that over 80% of the measured are found within the boundary of $\pm 35\%$ of the relative error, which is a precision range that is standard with regard to methods of calculating three-phase flow friction factor in axial pipes.

Using Equation (10) it was possible to calculate the value of pressure drops for various configurations of the pipe bend, i.e. for flow in horizontal and vertical planes for downwards and upward flow of three-phase air-water-oil stream. The value of the local friction factor was derived from the general formula:

$$\Delta P_{3P,T} = \xi_{3P} \frac{w_{3P}^2}{2} \rho_{3P} \quad (20)$$

in which the density of three-phase mixture ρ_{3P} was calculated in accordance with the relation

$$\rho_{3P} = \rho_g R_g + \rho_w R_w + \rho_o R_o \quad (21)$$

$$w_{3P} = w_{g,0} + w_{w,0} + w_{o,0} \quad (22)$$

And the void fractions of the specific phases were determined on the basis of equations developed by the author (23)-(27).

$$\frac{R_{g,B}}{R_{g,P}} = 1.151 e^{-0.574} \text{Fr}_{l,2P}^{0.065} \quad (23)$$

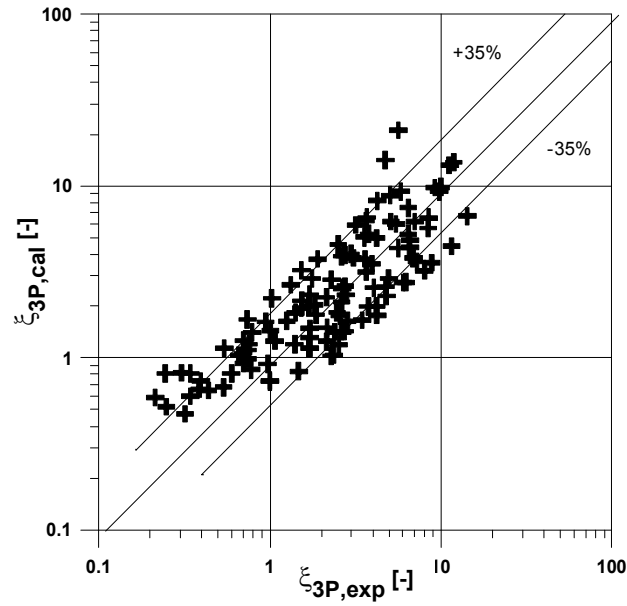


Fig. 9. Comparison of measured and calculated values of local friction factor ξ_{3P} of oil-water-air flow in pipe bends

In Equation (23) the Pendyk (2002) method was applied as the reference relation:

$$R_{g,P} = \frac{\varepsilon_g^{0.37}}{1 + \left(\frac{1}{\varepsilon_g} - 1\right)} \left(\frac{1 - \varepsilon_w}{1 + \varepsilon_o}\right)^{0.43} \quad (24)$$

By analogy to the Pendyk (2002) method, the void fractions of water and oil, for three-phase flow are calculated from the relation:

- void fraction of water (liquid with lower viscosity)

$$R_{w,B} = (\varepsilon_w^*)^{0.8} (1 - R_{g,B}) \quad (25)$$

- void fraction of oil (liquid with higher viscosity)

$$R_{o,B} = (\varepsilon_o^*)^{0.6} (1 - R_{g,B}) \quad (26)$$

In order to avoid the problems associated with the calculations of the dominant liquid component in multi-phase flow, it is recommended that the value of the volume fraction of the liquid with lower viscosity should be derived from the relation bellow:

$$R_{w,B} = 1 - R_{g,B} - R_{o,B} \quad (27)$$

which accounts for the fact that the total of volume fractions of all components is equal to 1.

The actual value of the pressure drop for a horizontal pipe bend is equivalent to pressure losses (20), while for the pipe bend situated in a vertical plane the value of the pressure drop was derived accounting for the value of the hydrostatic drop in pressure, which is equal to:

- for upward flow

$$\Delta P_{jP,T} = \xi_{jP} \frac{w_{jP}^2}{2} \rho_{jP} + \check{g} \rho_{jP} D \quad (28)$$

- for downward flow

$$\Delta P_{jP,T} = \zeta_{jP} \frac{w_{jP}^2}{2} \rho_{jP} - \tilde{g} \rho_{jP} D \quad (29)$$

The literature studies conducted on polyphasic flows reveal the lack of sufficient knowledge of U - pipes. The aim of improvement of agreement of calculation pipe bends loss coefficient for multiphase flows were worked out the new methods. New methods were worked out for two-phase gas-liquid flow (1) and separately for three-phase gas-liquid-liquid flow (11). The created methods permit with good agreement to calculate the pipe bends loss coefficient of multiphase flow.

In multiphase flows there are different opinions in an interpretation and description of flow phenomena. The literature review indicated a lack of calculation methods for pressure drop values of multiphase mixture flow in curved channels.

4. CONCLUSIONS

- New methods were worked out for two-phase gas-liquid flow (1) and separately for three-phase gas-liquid-liquid flow (11), (28), (29).
- The created methods permit with good accuracy to calculate the pressure drops of multiphase flow in U - pipes for different configurations.

SYMBOLS

D	diameter of pipe bend, m
d	internal diameter of pipe, m
Fr	Froude number, -
g	mass flux of mixture, $\text{kg m}^{-2} \text{s}^{-1}$
\tilde{g}	gravitational acceleration, m s^{-2}
L	length of pipe, m
Mo	Morton number, -
R	mean void fraction, -
Re	Reynolds number, -
w	velocity, m s^{-1}
x	mass fraction, -
ΔP	pressure difference, Pa
$(\Delta P/\Delta L)$	unit pressure drop, Pa m^{-1}
ε	inlet void fraction, -
η	dynamic viscosity, Pa s
ζ	local friction factor, -
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

0	superficial quantity
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