

Slip between the phases in two-phase water–oil flow in a horizontal pipe

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Received 26 April 2007; received in revised form 30 October 2007

Abstract

This paper is devoted to slip phenomenon between the phases that occurs in unstable two-phase water–oil flow systems in a horizontal pipe. The emphasis is placed on the relation between the slip and the real (in situ) water fraction in a flowing mixture, as well as the substitute physical properties of the whole two-phase system. The experimental data collected throughout research served for the evaluation of the accuracy of the methods of real phase fraction in a water–oil flow system in horizontal pipes as they were referred to in the bibliography. Subsequently we have suggested the author indicate a method of determination of the fraction for two-phase liquid systems like O/W, W/O and W + O. In order to establish the specific equations, the *drift-flux* model has been used here.
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Keywords: Two-phase flow; Horizontal pipe; Water–oil system; Slip; Fraction of phases; *Drift-flux* model

1. Introduction

Liquid two-phase systems result from mixing liquids reciprocally insoluble. A typical example of such a mixture is water and oil; that is a hydrophilic and hydrophobic phase, respectively. Water disintegration in oil (W/O type structure) or oil disintegration in water (O/W type structure) may result from the reciprocal mixing conditions of the two liquids. Regardless of the liquid–liquid type structure its mixing process results in producing stable emulsion or only an unstable dispersed structure. Emulsions originate in mixers equipped with high-speed stirrers of various shapes. Liquid unstable dispersed structures are formed mainly when they are mixed in a pipe flow, whereas in the liquid–liquid structure the stabilising agents are absent. Such conditions are often inadvisable for making emulsion as their high viscosity brings a considerable increase of pressure drop. A flow of an unstable, dispersed structures in a pipe should be treated a two-phase one that is – like in the case of a co-current gas–liquid or liquid–solid flows.

A liquid, unstable, dispersed structures flow in a pipe may be accompanied by a number of atypical phenomena that do not usually occur (or if they do, it is definitely much smaller scale) in an emulsion flow. The reasons for occurrence of such phenomena should be sought in instability of the shape and geometrical dimensions of structures formed by the dispersed phase. In an unstable flow of a liquid–liquid system there occur two-phase flow patterns that can change their character both, for their type (W/O, O/W or W + O) as well as for the drop size of the dispersed phase.

2. Slip between the phases in liquid–liquid systems

One of the typical phenomena which occur in a pipe liquid–liquid flow (as well as in other two-phase systems) is the so-called slip between the phases. It is typical for real velocities of both components constituting a certain system that are considerably different from each other. In a stationary flow the total volumetric flux of liquid–liquid mixture Q_{lq-1q} is a sum of the volumetric flux of both liquids Q_{lq-1} and Q_{lq-2} , that is

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$$Q_{lq-lq} = Q_{lq-1} + Q_{lq-2} \quad (1)$$

The average velocity of the whole two-phase system U_{lq-lq} results from a single relation

$$U_{lq-lq} = \frac{Q_{lq-1} + Q_{lq-2}}{A_p} \quad (2)$$

thus, it is a sum of the both liquids superficial velocities $U_{lq-1,o}$ and $U_{lq-2,o}$:

$$U_{lq-lq} = \frac{Q_{lq-lq}}{A_p} + \frac{Q_{lq-2}}{A_p} = U_{lq-1,o} + U_{lq-2,o} \quad (3)$$

where A_p is a cross-section area of pipe.

However, the real flow velocity of each of the liquid phases is connected only with the part of the pipe cross-section area which is occupied by the phase in the defined flow conditions. The conditions are decisive for the liquid dispersion rate and have an impact on the type of the two-phase flow structure. Photographs of sample flow patterns in liquid–liquid systems are presented in Fig. 1.

Average real velocities of both liquids U_{lq-1} and U_{lq-2} are defined by the equations

$$U_{lq-1} = Q_{lq-1}/A_{p,lq-1} \quad (4)$$

$$U_{lq-2} = Q_{lq-2}/A_{p,lq-2} \quad (5)$$

where $A_{p,lq-1}$ and $A_{p,lq-2}$ are cross-section areas of pipe occupied by each of the phases.

Average real volume fraction of each liquids (R_{lq-1} or R_{lq-2}), defined by the equation:

$$R_{lq-1} = \frac{A_{p,lq-1}}{A_p} = 1 - R_{lq-2} \quad (6)$$

is different from the apparent volume fraction (Φ_{lq-1} or Φ_{lq-2}), which results from relations between liquid streams at the pipe inlet:

$$\Phi_{lq-1} = \frac{Q_{lq-1}}{Q_{lq-lq}} = 1 - \Phi_{lq-2} \quad (7)$$

Relations between the flow's apparent and real velocities as well as apparent and real volume fractions are expressed in the equations:

$$U_{lq-1} = \frac{U_{lq-1,o}}{R_{lq-1}}; \quad U_{lq-2} = \frac{U_{lq-2,o}}{R_{lq-2}} \quad (8)$$

$$R_{lq-1} = \frac{1}{1 + \frac{\Phi_{lq-2}}{\Phi_{lq-1}} \frac{U_{lq-1}}{U_{lq-2}}} \quad (9)$$

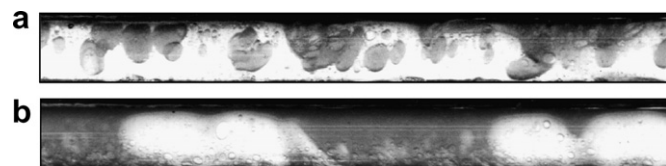


Fig. 1. Samples of flow patterns of water–oil system flowing in a horizontal pipe, by own investigation. (a) drops of oil in water, (b) drops and plugs of water in oil.

From (8), it appears that the real flow velocity of any liquid is always higher than the apparent one; simultaneously, Eq. (9) indicates that the relation:

$$R_{lq-1} = \Phi_{lq-1}; \quad R_{lq-2} = \Phi_{lq-2} \quad (10)$$

occurs only when there is no significant difference between real velocities of liquids that is when the slip disappears.

The lack of the slip is one of the basic assumptions in the two-phase homogenous model. In practice it is observed for the case of a relatively small volume of one of the phases or the minute size of the resulting drops or the other phase's high flow velocity; the phase constituting the continuous medium.

Differences between the apparent and the actual fractions of liquids that constitute a two-phase flow system ought to be considered e.g. while calculating its substitute properties, density liquid–liquid mixture ρ_{lq-lq} and viscosity η_{lq-lq} . It is particularly important when a model of homogenous system is applied in a defining liquid–liquid two-phase flow. In practice, such a model is often used in e.g. determination of liquid mixture's pressure drop; often independently on kinds of two-phase flow patterns that tend to form in it. In such a case, Eqs. (11) and (12) characterising homogenous model should involve parameter R instead of Φ .

$$\rho_{lq-lq} = \Phi_{lq-1}\rho_{lq-1} + \Phi_{lq-2}\rho_{lq-2} \quad (11)$$

$$\eta_{lq-lq} = \Phi_{lq-1}\eta_{lq-1} + \Phi_{lq-2}\eta_{lq-2} \quad (12)$$

where ρ_{lq-1} , ρ_{lq-2} , η_{lq-1} , η_{lq-2} expressing suitably density and viscosity of both liquids.

The phase real volume fractions constituting the flowing mixture ought to be treated as pipe-filling rate by each of the liquids. Thus, the rate will impact the liquid–pipe wall contact area, subsequently influencing such essential parameters as shear stress on the wall, or heat transfer conditions.

The slip phenomenon has, so far, been best examined and described for two-phase gas–liquid systems flowing through pipes with various cross-section shapes, various diameters and various inclination angles. A review of this issue is presented in e.g. Ulbrich (1989). The slip between phases can be expressed in different ways, which, for a liquid–liquid system is shown in Table 1.

It is, however, important to determine what kind of phase the slip corresponds to. For dispersed patterns usually it is the dispersed phase; yet, there still may occur prob-

Table 1
Methods of defining the slip between phases in a liquid–liquid system

Symbol	Definition	Name
S	$\frac{U_{lq-1}}{U_{lq-2}} = \frac{\Phi_{lq-1}(1-R_{lq-1})}{R_{lq-1}(1-\Phi_{lq-1})}$	Index of slip
S_{rel}	$\frac{U_{lq-1}}{U_{lq-lq}} = \frac{\Phi_{lq-1}}{R_{lq-1}}$	Relative index of slip
ΔU	$U_{lq-1} - U_{lq-2} = \frac{U_{lq-lq}(\Phi_{lq-1}-R_{lq-1})}{R_{lq-1}(1-R_{lq-1})}$	Difference of real velocities
ΔU_{rel}	$\frac{U_{lq-1}-U_{lq-2}}{U_{lq-lq}} = \frac{\Phi_{lq-1}-R_{lq-1}}{\Phi_{lq-1}(1-R_{lq-1})}$	Relative difference of real velocities

lems in determining which component of the system constitutes this very phase. This is so because in a liquid–liquid system both phases: water or oil may undergo dispersion, i.e. liquid of low or high density and simultaneously of low or high viscosity. Thus, determining dispersed phase slip in a liquid–liquid system simultaneously requires adoption a suitable criterion of the type evaluation. We may assume, as such a criterion, a generalized flow patterns map for two-phase water–oil system shown in Fig. 2. This map is a result of thorough analysis of other researchers suggestions. This is valid for liquid–liquid systems of various property relations between component phases, and includes a considerable range of flow parameters changes. A detailed flow patterns description, experimental evidence and conditions for this map to hold are presented by Hapanowicz et al. (2001).

When analysing the boundary lines position in the map in Fig. 2 it cannot go unnoticed that the line marked ① separates areas corresponding to flow patterns of different types (W/O and O/W). These flow patterns, thus, differ from each other by the type of dispersed phase. Hapanowicz et al. (2001) presented equations, that express the run of boundaries on the map of flow patterns in Fig. 2. For the boundary line ①, in force is the following:

$$g_{ol,o} = 1.3525g_{w,o}^{0.812} \quad (13)$$

where $g_{ol,o}$, $g_{w,o}$ expressing apparent mass flux suitably of oil or water.

The Eq. (13) constitutes a condition where there occurs a change of the unstable type of liquid–liquid system flowing through a horizontal pipe. The change of the continuous phase into the dispersed one and vice versa is called a

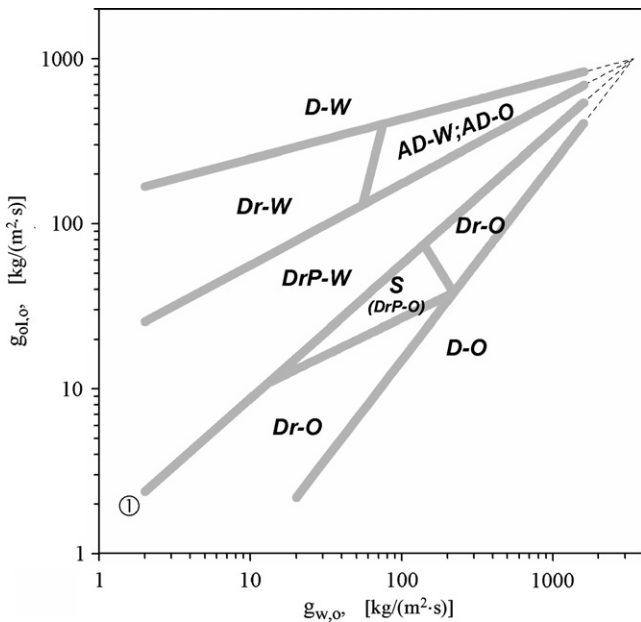


Fig. 2. Generalized flow patterns map for water–oil system flowing in the horizontal pipe, by Hapanowicz et al. (2001). *Dr* – drops, *DrP* – drops and plugs, *D* – dispersion, *S* – stratification, *AD* – annular and dispersion; *-W* – of water, *-O* – for oil.

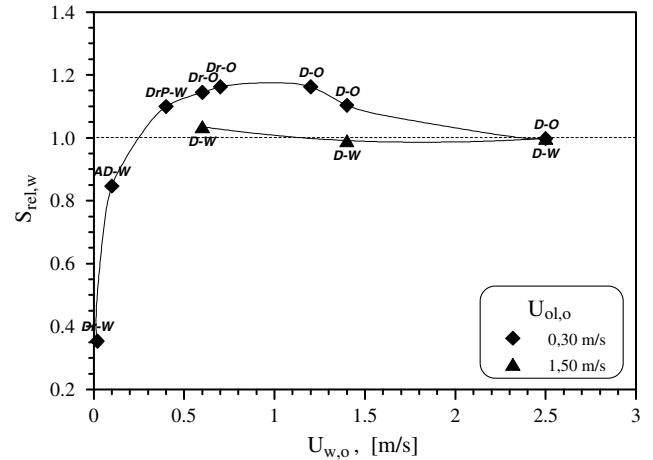


Fig. 3. Change of relative index of slip of water in water–oil system. measurement points by Rodriguez and Oliemans (2006).

phase inversion and is another typical phenomenon accompanying two-phase liquid–liquid flows. The slip and the affiliated difference between apparent and real volume fraction of liquids constituting a given system depend on its flow conditions and, thus, on the type of flow patterns being formed. This is confirmed in the literature by a lot of experimental evidence. In Fig. 3 the changes of the relative index of slip of water for two measurement sessions presented by Rodriguez and Oliemans are discussed (2006). The flow patterns resulting from the flow map in Fig. 2 are ascribed to the consecutive points on the graph. As it appears from the point positioning on the $S_{rel,w}$ value considerably changes only within low velocities range of the liquid two-phase mixture flow, which corresponds to weak conditions of blending. An increase of water or oil dispersion caused by an increase of the whole system’s velocity results in $S_{rel,w} = 1$, which means reaching balance of Φ fractions against R .

3. Calculating methods for the actual phase fraction in a liquid–liquid system

Despite considerable significance of the real phase fraction for the correct description of the phenomena occurring in a flowing liquid–liquid system the bibliography does not suggest generally accepted methods of its calculation. Apparently, it is due to the fact that the majority of the research and analyses concerning liquid two-phase flows is carried out for emulsions where the dispersion rate of one liquid’s stable drops is very high. In such conditions the phase slip may usually be neglected, regardless of the velocity of the whole two-phase flow system. In relatively rare publications that take up the problem of the slip volume in an unstable liquid–liquid system flowing through a pipe, calculation methods devoted to the case are dramatically scarce. Instead, there are some attempts to adopt (or to directly use) equations compatible with those suitable for gas–liquid systems. The work of Pendyk and Witczak

(2006) may be taken as an example of such an approach. The authors of this work revised usefulness of gas–liquid system applicability requirements for oil in water type liquid systems (O/W). They particularly focused on the use of equations whose form is consistent with the experimentally tested gas–liquid system relations suggested by Chisholm (1974)

$$R_{ol} = \frac{1}{1 + \left[x_{ol} \frac{\rho_w}{\rho_{ol}} + (1 - x_{ol}) \right]^{0.5} \frac{1 - x_{ol}}{x_{ol}} \frac{\rho_w}{\rho_{ol}}} \quad (14)$$

and by Stomma (1979)

$$R_{ol} = 1 - \frac{\Phi_{ol}^2 - x_{ol}^2}{2 \left[\ln \left(\frac{1 - x_{ol}}{1 - \Phi_{ol}} \right) - (\Phi_{ol} - x_{ol}) \right]} \quad (15)$$

In the Eqs. (16) and (17) mass fraction of oil is defined by

$$x_{ol} = \frac{\Phi_{ol} \rho_{ol}}{\Phi_{ol} \rho_{ol} + (1 - \Phi_{ol}) \rho_w} \quad (16)$$

and subscripts “ol” and “w” denotes oil or water, respectively.

According to Pendyk and Witczak (2006) the estimation of Eqs. (14) and (15) was unsatisfactory in comparison to their own experimental research. Moreover, it appeared that the equations could only be applied when the liquid phase’s densities are different. Otherwise, in the case of (14) we will always obtain $R_{ol} = \sigma_{ol}$, and the denominator in (15) will be equal to zero.

A model of the stratified system is sometimes applied in case of a need for mathematical model of describing a liquid–liquid flow system. It is the Lockhart–Martinelli parameter (Lockhart and Martinelli (1949)) that is often applied in this model for a gas–liquid system; the parameter, which is normally (for liquid–liquid systems) defined by the equation

$$X_{lq-lq} = \left(\frac{\Delta P_{ol,o}}{\Delta P_{w,o}} \right)^{0.5} \quad (17)$$

where $\Delta P_{ol,o}$ and $\Delta P_{w,o}$ are expressing apparent pressure drop determined the basic superficial velocities of oil and water.

Such a form of the definitions by the fact that just like in the liquid in a gas–liquid system it is the oil in a liquid–liquid system that reveals higher viscosity. At an identical phase flow velocity, bigger pressure drop values will be induced by the phase of higher viscosity. Therefore, in both gas–liquid and liquid–liquid system cases, the parameter X value will be higher than 1. Using the parameter X_{lq-lq} in typical for gas–liquid system interrelations, e.g. in Wallis (1969) the equation allows to put it as

$$R_{ol} = (1 + X_{lq-lq}^{0.8})^{-0.375} \quad (18)$$

Parameter X_{lq-lq} was used by Angeli and Hewitt (2000) in the proposed in their equation defining actual fraction of oil

$$\ln R_{ol} = 0.4134 \ln X_{lq-lq} - 0.6004 \quad (19)$$

The form of Eq. (19) was worked out from the results of experiments on liquid–liquid system flow in a horizontal pipe. It is noteworthy, however that for $X_{lq-lq} > 4.27$ the R_{ol} values calculated according to the Eq. (19) become bigger than 1, which does not have a physical sense. Thus, the function (19) does not constitute a universal interrelation but only a mathematical generalization of the research results obtained in defined conditions.

Its experimentally confirmed correctness gained the theory based method of real phase fractions calculation proposed by Brauner (1991). The method’s applicability range, however, is limited only to annular-dispersed flow patterns.

In the literature there are methods of real liquid volume fraction, in a flowing mixture, calculation that stay in accordance with the gas–liquid *drift-flux* model proposed by Zuber and Findlay (1965). General form of the equations corresponding to the above model and valid for a liquid–liquid system is expressed in the following relations

$$\begin{cases} \frac{U_{d,o}}{R_d} = C_d U_{lq-lq} + U_{d-(lq-lq)} \\ R_d + R_c = 1 \end{cases} \quad (20)$$

where subscripts “d” and “c” denotes to dispersion and continuous phase.

Still, using the system of Eq. (20) related to a specific two-phase system requires pre-determining the parameters occurring in it, i.e. dispersity of dispersion phase C_d and drift velocity of dispersion phase to liquid–liquid system $U_{d-(lq-lq)}$. Therefore, in order to determine the detailed form of equations corresponding to the discussed model and valid in a defined two-phase system, it is essential to use experimental output.

Having analysed their own research results concerning O/W type flow systems in a horizontal pipe, Pendyk and Witczak (2006) conclude that out of the equations that are true for gas–liquid systems and compatible with the *drift-flux* model, the best accuracy of phase fraction calculation in a liquid–liquid system can be obtained by means of the equations proposed by Dix (1971)

$$C_d = \Phi_d \left[1 + \left(\frac{1}{\Phi_d} - 1 \right)^\alpha \right]; \alpha = \left(\frac{\rho_d}{\rho_c} \right)^{0.1} \quad (21)$$

$$U_{d-(lq-lq)} = 2.9 \left(\frac{\tilde{g} \sigma_{lq-lq} |\rho_c - \rho_d|}{\rho_c^2} \right)^{0.25} \quad (22)$$

where: \tilde{g} acceleration of gravity, σ_{lq-lq} interfacial tension.

It is here noticeable there are density differences between the continuous and dispersed phases. For gas–liquid systems it is nearly always a value bigger than zero. However, as regards a liquid–liquid system it is advisable to use a water–oil phase density differential module. Depending on the type of a liquid–liquid system, the density of the continuous liquid may be either higher or lower than that

of the dispersed liquid. This fact was taken into consideration in Eq. (22).

The drift velocity is identified with a free movement of dispersed components in an unlimited volume of the continuous phase; the movement resulting from phase density differences. Assuming so defined drift velocity in liquid formed systems of identical densities will result in its zero value. Thus, for a liquid–liquid system of about the same phase density there should apply a “simplified” equation form compatible with the *drift-flux* that was used by Fujii et al. (1991). The suggested there equations are valid for the system constituted by liquids of the same density and their form is different for O/W

$$\frac{U_{w,o}}{R_w} = 0.92U_{lq-lq} \tag{23}$$

and W/O systems

$$\frac{U_{w,o}}{R_w} = 1.51U_{lq-lq} \tag{24}$$

Jin et al. (2003) propose expressing drift velocity as a product of free gas bubble drift in liquid and a function related to the real fraction of the continuous phase. At the same time they indicate the following interrelation:

$$\frac{U_{ol,o}}{R_{ol}} = C_{ol}U_{lq-lq} + 1.53 \left(\frac{g \sigma_{lq-lq} |\rho_c - \rho_d|}{\rho_w^2} \right) R_w^\delta \tag{25}$$

They make values dispersity of oil C_{ol} and exponent δ in Eq. (25) dependent on real water fraction not giving, however, detailed forms of function expressing their values. Viewing liquid drops movement similarly to that of gas bubbles (having no generally accepted equations for liquid-in-liquid free drop movement velocity) it appears, to be justifiable only in some conditions of real processes.

4. Collection of the experimental data

The proposed equations that allow establishing the real phase fraction in a two-phase pipe flow, so far, in the bibliography were determined mainly on the basis of the results of research. A limited range of experiments resulted in a limited, often individual, applicability range of particular equations. In order to verify correctness of the proposed calculation methods related to various liquid–liquid systems and various conditions of their flows, as well as to, possibly, work out new interrelations, the author undertook his own analytical research. To carry it out, however, it was necessary to dispose of a satisfactory set

of measurement data having the biggest possible changeability of parameters characterizing a liquid two-phase system flowing in a pipe. This set of data was established on the basis of the ones found in the literature. In spite of scarce number of publications concerning this matter, the author was able to create a database comprising 276 measurement points. The collected data concerned real phase fractions of various density and viscosity constituting unstable liquid–liquid systems flowing at various velocities in horizontal pipes. Primarily, the data published by Rodriguez and Oliemans (2006), Fujii et al. (1991), Charles et al. (1961), Lovick and Angeli (2004), Pendyk (2002) and Russel et al. (1959) were used in the present work. The range of changes of the selected parameters formulated in the set of data was compiled in Table 2.

The gathered measurement data were divided into three groups. The first was related to O/W type system, the second – W/O type, the last one concerned the systems constituted by two continuous phases W + O (flow patterns *S* and *AD*). As the criterion for such a division there was used a kind of the two-phase flow pattern which is supposed to form in a pipe according to the flow patterns map presented in Fig. 2.

The graph presented in Fig. 4 shows the differences between the apparent and real dispersed fraction phase respective for the compiled set. The graph also shows lines corresponding with the constant values of the index of slip for dispersed phase. Assuming oil as a dispersed medium in W + O type systems was theoretical in its character and

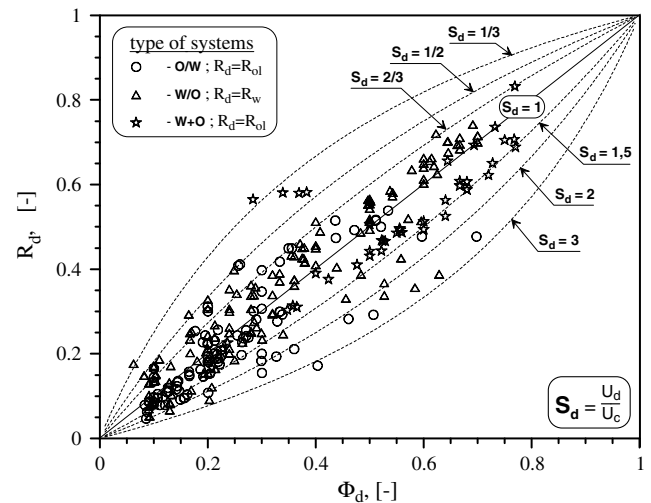


Fig. 4. Comparison of values Φ to R in the worked out set of data.

Table 2
Ranges of variability of parameters in collection set of data regarding R

Superficial mass flux of water $g_{w,o}$	Superficial mass flux of oil $g_{ol,o}$	Apparent fraction of oil Φ_{ol}	Relation of density of oil to water ρ_{ol}/ρ_w	Relation of viscosity of oil to water η_{ol}/η_w	Interfacial tension of phases σ_{ol-w}	Diameter of pipe d_p
kg/(m ² s)	kg/(m ² s)	%	–	–	mN/m	mm
14.3–2694.6	15.2–2235.6	8.3–93.8	0.783–1	6.7–76.7	20.4–45	12–83

resulted only from the necessity to determine the type of liquid the slip value was established for. From the Fig. 4 it appears that for all three types of liquid–liquid systems the index of slip can take values higher or lower than 1. Thus, the real velocity of the dispersed phase flow can be either higher or lower than of the continuous phase. It is worth adding here that a gas slip value in a gas–liquid system is always higher than one which means that the real flow velocity of the gas (usually constituting the dispersed phase) is always higher than the liquid flow velocity. As it appears from Fig. 4 this principle does not hold in the case of two-phase liquid–liquid flows. Hence there may appear some problems in attempts to use equations which are appropriate for gas–liquid systems, with respect to liquid–liquid systems.

Having quite a wide collection of experimental data we tried to verify some of the mentioned above methods of establishing the value R . The attempts to use equations appropriate for gas–liquid just failed. Regardless the type of liquid–liquid systems, the obtained on the above-based results showed discrepancy of about hundreds percent against the experimental values.

Such discrepancies are supposed to result from entirely different interrelation between physical properties of phases in both two-phase systems, and different range of flow velocity phases in a gas–liquid system from liquid–liquid system. In gas–liquid systems the dispersed phase is usually the gas, and its flow velocity is usually considerably higher than that of the dispersed phase in a liquid–liquid system. Also, it was a failure to attempt to use the Eq. (19) as its applicability range ($X_{lq-lq} < 4.27$) appeared to be considerably lower than the changeability range of the parameters in the drawn up measurement data collection.

These were the equations resulting from the *drift-flux* model (despite being valid for gas–liquid systems) that brought relatively positive outcome. The obtained test-calculation results are shown in Table 3, and the statistic parameters presented in there were defined as

$$\overline{\delta_R} = \frac{1}{n} \sum_{k=1}^n \frac{R_{d,exp,k} - R_{d,cal,k}}{R_{d,exp,k}} \cdot 100\% \quad (26)$$

and

$$|\overline{\delta_R}| = \frac{1}{n} \sum_{k=1}^n \frac{|R_{d,exp,k} - R_{d,cal,k}|}{R_{d,exp,k}} \cdot 100\% \quad (27)$$

where subscripts “exp” and “cal” denotes to experimental and calculate values.

Table 3
Accuracy of calculation R_d according to *drift-flux* model

Equations	Type of system	R_d	$\overline{\delta_R}$	$ \overline{\delta_R} $
(20–22)	O/W	R_{ol}	+12.5%	±23.4%
	W/O	R_w	+19.3%	±25.2%
	W + O	R_{ol}	+24.5%	±26.3%

The calculations were carried out separately for systems of particular type, treating the oil as a dispersed phase in O/W and W + O type systems and the water in W/O systems (analogous to of data from Fig. 4). The obtained, due to test-calculations, results justified the purposefulness of implementing the *drift-flux* model for working out a new method to calculate the real phase fraction. This method concerns a wider range of changes of parameters that characterize an unstable liquid–liquid flow in a horizontal pipe (Table 2), than the proposed in the literature so far.

5. The new method of calculating the real fraction phases

A detailed analysis of the collected measurement data revealed that it is justifiable to work out two separate equations. Each of them concerns two separate groups of liquid–liquid systems that differ from each other with the type and density interrelation between the component phases.

The first group contains all the systems where the densities of both liquids are identical or closely similar (in accordance with the analysed measurement data the difference in liquid density should not exceed 0.5%) beside the systems where, regardless of the phase density interrelations, two separate continuous phases are formed (W + O type flow patterns). For this particular group of systems it was the “simplified” form of Eq. (22) that appeared to be justifiable; here the drift velocity, connected with the density difference between the liquids, was resigned of being taken into consideration. Such a movement will not occur without density phase differences, the more so, without the dispersed phase. Correlate calculations referring to the corresponding set of experimental data resulted in the formation of the following function:

$$U_{ol} = \frac{U_{ol,o}}{R_{ol}} = 1.095 U_{lq-lq} \quad (28)$$

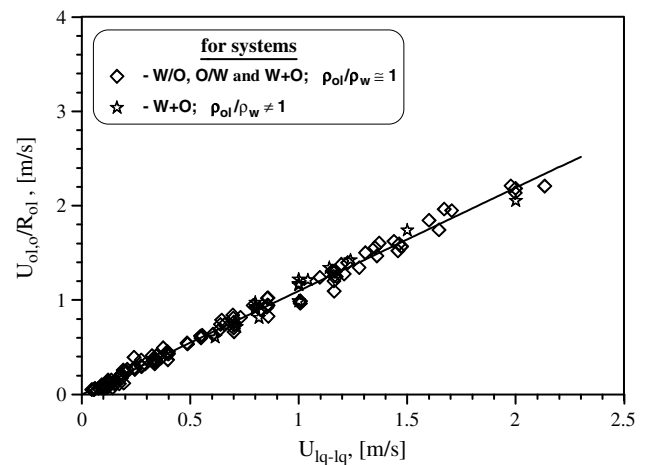


Fig. 5. Course of function (28) against the background of measurement points.

where U_{oi} , $U_{oi,o}$ denotes suitable real velocity and superficial velocity of oil.

The conformity of the interrelation (28) with the measurement data used in the correlate calculations is shown in Fig. 5. The Eq. (28) enables calculating particular phase's fraction (here: oil) in a liquid–liquid flow system. Thus, application of this equation does not require pre-determining the type of the liquid constituting either continuous or dispersed phase. It is especially important in relation to the distinguished stratifications or films flow patterns within this group, for which case both liquids preserve their continuity.

The other of the mentioned groups was the system formed by continuous and dispersed phase; however they differed from each other in their densities. The correlate calculations with the use of data related to the systems in this group resulted in working out one function:

$$U_c = \frac{U_{c,o}}{R_c} = 1.004U_{lq-lq} + 0.0248 \quad (29)$$

where U_c , $U_{c,o}$ denotes suitable real velocity and superficial velocity of continuous phase.

Its conformity with the measurement data included in the worked out set is presented in Fig. 6.

The Eq. (29) is valid for O/W and W/O type systems provided that the densities of their component phases considerably differ from each other. The explicit indication, in

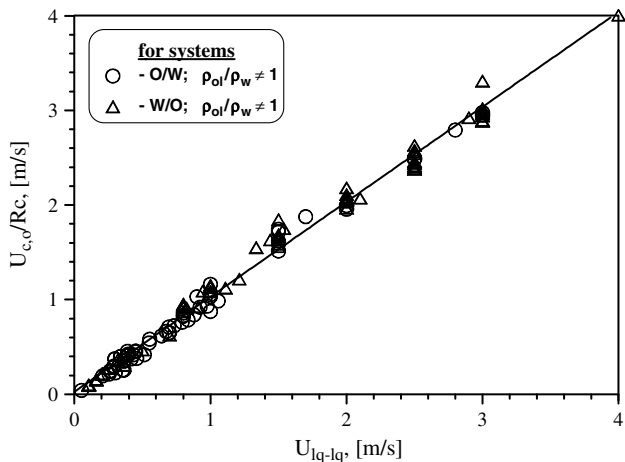


Fig. 6. Course of function (29) against the background of measurement points.

Table 4
Results of statistical estimation compatible of own calculation method real volume friction of phases with experimental data

Equation	$\frac{\rho_{oi}}{\rho_w}$	Type of system	Real fraction	$\bar{\delta}_R$	$ \bar{\delta}_R $
(28)	$\cong 1$	W/O; O/W; W + O	R_{oi}	2.2%	8.5%
	$\neq 1$	W + O			
(29)	$\neq 1$	W/O	R_{oi}	0.0%	7.3%
		O/W	R_w	5.5%	9.6%

Eq. (29), on the need to formulate the real continuous phase fraction (thereby its real velocity flow) allows to determine the fraction of this very liquid which, to a larger extent, is decisive for the course of phenomena occurring in a two-phase flow system. It is worth mentioning that while working out Eqs. (28) and (29) as well as evaluating their statistical correctness all of 276 measurement points contained in the experimental data set were taken into consideration. Hence, the data for which the Eqs. (28) and (29) led to the greatest error have not been removed from the above set. In a majority of cases, this kind of data is denoted with the term of accidental gross error in the stages of result analysis. Their applicability range corresponds with the parameters presented in Table 2. The statistical estimation of conformity of the Eqs. (28) and (29) with the measurement data is shown in Table 4.

6. Summary

To sum up, the Eqs. (28) and (29) are proposed. in order to calculate real phase fraction in an unstable two-phase flow system in a horizontal pipe. Their structure results in the avoidance of ambiguity in the determination of the kind of the liquid the volume fraction for which the phase is calculated. Practical application of the suggested interrelations requires pre-determination of the two-phase structure type, which occurs in a pipe in defined conditions of the liquid mixture flow. The type of the flow pattern ought to be determined on the basis of the flow map shown in Fig. 2. However, if the liquid–liquid system is formed by liquids of similar density, determining the system type is not necessary.

As it appears from Table 4, the accuracy of the suggested equations is high and sufficient enough to be practically applied in industry. Such an evaluation is generally justified by high dynamics of the phenomena accompanying two-phase flows, as well as the wide range of changeability of the experimental data used for the statement of the suggested equations.

Acknowledgements

This work was supported by the Grant No. 3.T10B.066.27 financed by Ministry of Science and Higher Education of Poland.

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