COMPARISON ANALYSIS OF CORRELATIONS FOR INTERFACIAL FRICTION FACTOR APPLIED IN GAS-LIQUID ANNULAR FLOW IN VERTICAL PIPES

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ABSTRACT

Gas-liquid flows in pipes can occur in the form of an annular pattern in which the liquid flows as a thin film at pipe wall and the gas flows as a core in pipe center. This flow pattern is often encountered at boiling and condensation processes, for example, in industries of steam generation, cooling or petroleum. In annular flow, the interfacial friction factor is one of the important closing parameters for the definition of the interfacial shear stress and consequently the pressure gradient. In the literature, several correlations are found to estimate the interfacial friction factor. The main objective of this work is to carry out a comparative analysis of some these correlations against experimental data also obtained from the literature. The features and limitations of each correlation were observed, as well as the accuracy of each in relation to experimental data. The results obtained demonstrate that correlations analyzed, present relatively satisfactory results, despite the different characteristics of the correlations, however, it is necessary to carry out more extensive analyses involving others correlations and sets of experimental data.

Keywords: two-phase flow, annular flow, interfacial friction factor, modeling, correlations

NOMENCLATURE

A	Cross-sectional area, m^2
Bo	Bond number
C_f	Friction factor
D	Diameter, m
E_D	Droplets entrainment fraction
G	Gravitational acceleration, m/s^2
H	Thickness, m
J	Superficial velocity, m/s
L	Length, m
Mo	Morton number
N_U	Dimensionless velocity
P	Pressure, Pa
Q	Volumetric flow rate, m^3/s
Re	Reynolds number
S	Perimeter, m
T	Temperature, °C
U	Absolute velocity, m/s
V	Relative velocity, m/s
z	Axial coordinate, m

Greek symbols

δ	Dimensionless thickness
ε	Absolute roughness, m
μ	Dynamic viscosity, kg/(m.s)
v	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Gas-liquid surface tension, N/m
τ	Shear stress, N/m^2
ϕ	Phase fraction

Subscripts

D	Droplets
G	Gas
I	Gas-liquid interface
k	Represent a phase
L	Liquid

Abbreviations

ARM	Apparent roughness model
calc.	Calculated
meas.	Measured
Ref.	Reference
RMS	Root mean square

INTRODUCTION

Multiphase flows are those in which more than one phase or component flows simultaneously in a duct, the simplest being two-phase (for example, the gas-liquid flow), and has been extensively studied to gain a better understanding of their characteristics and applications (Ribatski and Thome, 2005; Lad et al., 2011; Aziz et al., 2012). According to Pauchon et al. (1993), the gas-liquid flows can be generally classified, according to the spatial distribution of the phases, into three primary patterns: dispersed, separated e intermittent. The stratified and annular flows are sub-classifications of the separated flow and occur when two fluids streams flow separated by a well-defined interface as a result of the forces developed in the flow.

The annular flow is often encountered in various industrial applications: condensers, boilers, reactors, cooling towers and oil production. For example, the core-annular flow is the water-lubricated transport of heavy oil used in the field of high viscous oil transportation (Ghosh et al., 2009).

The annular flow occurs when a liquid film flows at pipe wall and a gaseous core flows in pipe center, which in turn carries liquid droplets. The liquid film can be presented in three ways: smooth, in transition or rough (Pedras, 1993). The gaseous core, flowing in contact with a liquid film undergoes an interfacial friction force due to the difference in velocities and physical properties. This interfacial friction, in a similar way to the wall friction, also can be defined in terms of a friction factor.

It is possible to find in literature a reasonable number of correlations to estimate the interfacial friction factor. These correlations are obtained based on the physical phenomena involved, as well as from the experimental data analysis (Naji, 2011). Many correlations have a limited application range and generally exhibit satisfactory accuracy only under similar conditions to those considered in their proposition.

Taitel and Dukler (1976) proposed a simple definition of interfacial friction factor as being equivalent to the wall friction factor of the gas, considering stratified and annular patterns. But the interfacial shear stress was defined in terms of the gas density, relative velocity, and their interfacial friction factor definition.

Later a correlation for interfacial friction factor was developed by Cheremisinoff and Davis (1979) obtained from data of stratified flow experiments, but it can also be used in annular flow cases, presenting relatively low uncertainties according to the author’s results. In their proposed correlation, the liquid Reynolds number is the only input parameter, whose definition is somewhat different from that often used in single phase flows.

Hewitt (1981) developed a correlation for interfacial friction factor using the apparent roughness model (ARM) described by Wallis (1969). This correlation uses the wall friction factor of liquid (single phase) for calculation of the interfacial friction factor in the annular and stratified flow cases. Also, using the ARM, Bharathan and Wallis (1983) developed a correlation for interfacial friction factor as a function of the dimensionless thickness of liquid film both in the annular and stratified flows.

The gas-liquid interfacial friction also was related to the gas phase wall friction by Crowley et al. (1986), as it had already done by other authors in the literature. However, they proposed their own closure relationships, considering the liquid film thickness as a determining factor for gas-oil annular flow development.

After, Hamersma and Hart (1987) proposed a correlation for determination of interfacial roughness, which can be used to determine the interfacial friction factor in stratified and annular flows, through the solution of the implicit Colebrook-White equation (1939). Similarly, Baker et al. (1988) also developed a correlation for interfacial roughness determination. Based on these interfacial roughness correlations it is possible to determine the interfacial friction factor using explicit wall friction factor correlations of the gas phase, available in the literature for single phase flow cases.

Xiao et al. (1990) proposed a mechanistic model to be used in horizontal or quasi-horizontal flows. This model has the objective of determining the flow pattern, showing the relationship between the pressure drop and liquid lagging in relation to the gas, for flows in the stratified, intermittent, annular and dispersed pattern. They performed comparisons with some of the empirical models described above, obtaining greater accuracy for their model, which is applied exclusively to stratified and annular flows.

Also based on ARM, Pedras (1993) found that the liquid droplet drag is directly tied to the interfacial friction factor since the liquid droplets dispersed in the gas are formed by the detachment of liquid from the wave crests in the liquid film and these droplets acquire the gas velocity. On the other hand, the dispersed droplets also tend to deposit on the liquid film. Due to these phenomena, the gas phase transfers momentum to the liquid phase. In comparison to the flow without droplet drag, the wall shear stress tends to increase and the interfacial shear stress tends to decrease. From his experiments, he also showed that gravity can be disregarded in determining the interfacial friction factor, which depends principally on the average drift velocity and the fraction of the gas phase.

Fukano and Furukawa (1998) conducted experiments with the vertical upward annular flow, varying the liquid kinematic viscosity through the use of a water-glycerol mixture, with the promise of obtaining more precise results. Through datasets measured for the interfacial friction factor, they realized comparison of their proposed correlation together with those of some other authors in literature. Later, Naji (2011) also carried out a comparative analysis of some correlations of literature, including the one developed by the owner, and was related by him as being the correlation that presented the better results.

Nogueira et al. (2004) present an analytical analysis of the interfacial waves and mass transfer effects in the gas-liquid annular flow. They obtained a solution of a hydrodynamically and thermally developing flow model by integral transform technique and compared the numerical results against available experimental findings. They concluded that the wave effects are very important, increasing the heat transfer due to the thermal resistance decrease.

The main goal of this work is to perform a comparative analysis of some correlations available in the literature to estimate the interfacial friction factor in the gas-liquid annular flow. This analysis involves a brief literature survey on these correlations, their applications, and limitations, as well as the verification of which correlations present the best accuracy when compared against the experimental data also obtained from the literature.

METHODS

This section presents a brief annular flow description and its nomenclature, the correlations definition for interfacial friction factor, as well as the method to verify the accuracy of these correlations.

Annular Flow Characteristics

Considering an isothermal mixture formed by gas (*G*) and incompressible liquid (*L*) flowing in the steady state into a vertical pipe of internal diameter *D*, length *L*, and constant cross-sectional area *A*.

Figure 1 represents schematically the annular flow. The gaseous core flows in the pipe center with velocity U_G, higher than the liquid film velocity U_L. This liquid film of thickness H_L flows at pipe wall, exerting a wall shear stress τ_L, and in contact with the gaseous core, exerting an interfacial shear stress τ_I. The liquid fractions of film and droplets are represented by ϕ_L and ϕ_D. In turn, E_D corresponds to entrainment fraction of the droplets by the gaseous core. S_L is the pipe wetted perimeter by liquid film and S_I is the gas-liquid interface perimeter, which depends on the H_L, similar to the areas occupied by gaseous core A_G and the liquid film A_L.

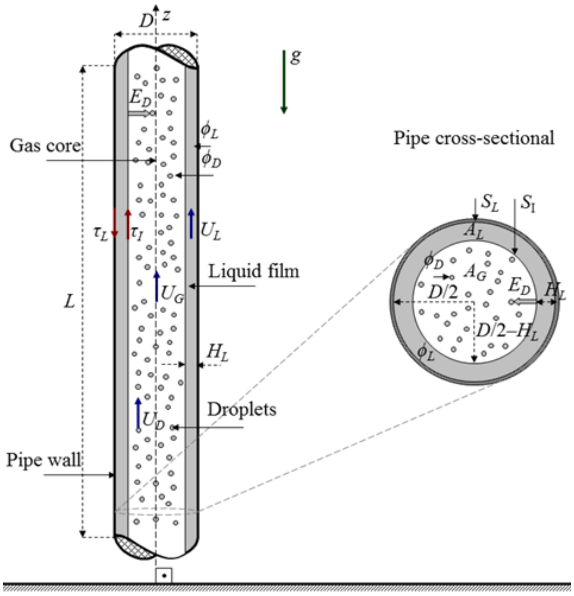

Figure 1. Schematic representation of the gas-liquid annular flow in a vertical pipe and its nomenclature; adapted from Lima (2011).

For one-dimensional fully developed annular flow in a vertical pipe, the force balances applied to the gaseous core and the liquid film result in the momentum equations:

$$-A_G\left(\frac{dp}{dz}\right)_G - \tau_I S_I - A_G\rho_G g = 0 \qquad (1)$$

$$-A_L\left(\frac{dp}{dz}\right)_L + \tau_I S_I - \tau_L S_L - A_L\rho_L g = 0 \qquad (2)$$

where ρ_G and ρ_L are the densities of gas and liquid, respectively, and *g* is the gravitational acceleration. Taitel and Dukler (1976) proposed that the pressure gradient (*dp*/*dz*) is equal for the two phases, such that the combination of Eqs. (1) and (2) results in a momentum equation for annular flow, whose solution (implicit) depend on the determination of H_L:

$$\tau_L\frac{S_L}{A_L} - \tau_I S_I\left(\frac{1}{A_L}+\frac{1}{A_G}\right) + \left(\rho_L-\rho_G\right)g = 0 \qquad (3)$$

On the other hand, by eliminating the interfacial shear stress term in Eqs. (1) and (2) one may get the pressure drop relation of the annular flow:

$$-\left(\frac{dp}{dz}\right) = \frac{1}{A_G + A_L}\left[\tau_L S_L + (A_G\rho_G + A_L\rho_L)g\right] \qquad (4)$$

The wall shear stress by the liquid film, τ_L, is defined in terms of a Fanning friction factor $C_{f,L}$ according to the expression:

$$\tau_L = C_{f,L}\rho_L U_L\left|U_L\right|/2 \qquad (5)$$

The interfacial shear stress, τ_I, can also be defined by a similar expression that presented in Eq. (5), considering the relative velocity ($U_G - U_L$), the gas density ρ_G and the interfacial friction factor $C_{f,I}$.

Correlations for the Interfacial Friction Factor

Several papers can be found in the literature that present correlations for the interfacial friction factor, $C_{f,I}$. Many of these correlations tend to present reasonable accuracy provided that they are applied under appropriate conditions and within the limitations thereof. In this work, a comparative analysis is carried out considering 10 correlations for $C_{f,I}$, as presented in Tab. 1, including some those used in the analysis carried out by Naji (2011).

Table 1. Correlations for the interfacial friction factor for annular and stratified flows.

Author	$C_{f,I}$	**Ref.**
Taitel and Dukler (1976)	$C_{f,G}$	C1

Cheremisinoff and Davis (1979)	$0.008+2\times10^{-5}\,\mathrm{Re}_{J,L}$	C2
Hewitt (1981)	$C_{f,G}\left(1+24\delta_L N_\rho^{1/3}\right)$	C3
Bharathan and Wallis (1983)	$0.005+406\delta_L^{2.04}$	C4
Crowley et al. (1986)	$C_{f,G}(1+75\delta_L)$	C5
Hamersma and Hart (1987)	$\frac{1}{4}\left[\log\left(\frac{\varepsilon_H}{3.7D}+\frac{5.74}{\mathrm{Re}_{U,G}^{0.9}}\right)\right]^{-2}$	C6
Baker et al. (1988)	$\frac{1}{4}\left[\log\left(\frac{\varepsilon_B}{3.7D}+\frac{5.74}{\mathrm{Re}_{U,G}^{0.9}}\right)\right]^{-2}$	C7
Xiao et al. (1990)	$0.053\mathrm{Bo}^{-0.23}\mathrm{Mo}^{0.019}N_{U,G}^{0.23}N_{U,L}^{0.202}$	C8
Pedras (1993)	$-0.0078+52\left(1-\sqrt{\phi_G}\right)N_\rho\,\mathrm{Re}_{V,G}^{2/5}$	C9
Fukano and Furukawa (1998)	$0.425(12)^{-1.33}(1+12\delta_L)^8$	C10

The Fanning wall friction factor of the gas phase, $C_{f,G}$, adopted in correlations C1, C3, and C5, is defined by the Poiseuille's law or by the Blasius equation, depending on the phase Reynolds number $\mathrm{Re}_{U,k}$, i.e.:

$$C_{f,k}=m\,\mathrm{Re}_{U,k}^{-n} \tag{6}$$

where:

$$\begin{cases} m=16 \text{ and } n=1; & \mathrm{Re}_{U,k}\le 2000 \\ m=0.046 \text{ and } n=0.2; & \mathrm{Re}_{U,k}>2000 \end{cases} \tag{7}$$

The sub-index k is used to represent a phase (G for gas or L for liquid). The phase Reynolds number $\mathrm{Re}_{U,k}$, also adopted in correlations C2, C6, C7 and C9, is defined in terms of the absolute velocity U_k, hydraulic diameter D_k and kinematic viscosity ν_k of the phase k, according to equation:

$$\mathrm{Re}_{U,k}=U_k D_k/\nu_k \tag{8}$$

In correlation C2, $\mathrm{Re}_{J,L}$ is a Reynolds number based on the liquid superficial velocity, and also is defined by Eq. (8) but considering the liquid superficial velocity, J_L, and the pipe diameter, D. By definition, the phase superficial velocity, J_k, is defined as the phase volumetric flow rate, Q_k, divided by the pipe cross-sectional area, A.

The wall friction factor of the gas in correlation C3, $C_{f,G}$, is defined by Eq. (6) using a Reynolds number defined in terms of the gas superficial velocity, J_G, and the pipe diameter, D, similar to correlation C2. Has even $\delta_L = H_L / D$ as the dimensionless liquid film thickness, also present in correlations C4, C5 and C10, and ρ_k which corresponds to the phase density (k = G or L), also present in correlation C9.

In correlations C6 and C7, the absolute roughness of the gas-liquid interface is represented by ε_H and ε_B, whose definitions are given by equations, respectively:

$$\varepsilon_H=2.3H_F \tag{9}$$

$$\varepsilon_B=\frac{34\sigma}{\rho_G U_L^2} \tag{10}$$

where σ is the gas-liquid surface tension. These absolute roughness definitions are used to calculate the interfacial friction factor by explicit equations of the Colebrook-White kind (Correlations C6 and C7).

In correlation C8, the Bond number, the Morton number and the phase dimensionless velocity are defined respectively by equations:

$$\mathrm{Bo}=\frac{gD^2\rho_L}{\sigma} \tag{11}$$

$$\mathrm{Mo}=\frac{g\mu_L^4}{\rho_L\sigma^3} \tag{12}$$

$$N_{U,k}=U_k\left(\frac{\rho_k}{g\,\sigma}\right)^{1/4} \tag{13}$$

The density ratio, in correlations C3 and C9, is defined by equation below:

$$N_\rho=\rho_G/\rho_L \tag{14}$$

In correlation C9, ϕ_G is the gas fraction (void fraction) and $\mathrm{Re}_{V,G}$ is a gas Reynolds number based on the average drift velocity of the gas $V_{G,J}$. The definitions proposed by Pedras (1993) for ϕ_G and $V_{G,J}$ are presented in equations, respectively:

$$\frac{\phi_G}{1-\phi_G}=1.225\times10^{-3}\,\mathrm{Re}_{J,L}^{0.56}\left|\frac{J_G}{J_L}\right| \tag{15}$$

$$V_{G,J}=\left(\frac{1}{1.225\times10^{-3}\,\mathrm{Re}_{J,L}^{0.56}}-1\right)J_L \tag{16}$$

The $C_{f,I}$ correlations presented in Tab. 1 were developed by their respective authors from data obtained in several flow configurations. These various configurations may, in some cases, be presented as a limitation on the correlations accuracy and, therefore, it becomes necessary to know them.

Table 2 shows a few information about the settings adopted on the proposition of $C_{f,I}$ correlations presented in Tab. 1.

Table 2. Flow settings assumed in the correlations propositions for interfacial friction factor applied in annular and stratified cases.

Pattern	Fluids	Ref.	Angle	Parameters
Annular	Air-water	C2	90°	$\mathrm{Re}_{J,L}$
		C6	90°	ε_H; $\mathrm{Re}_{U,G}$
		C9	90°	ρ_k; ϕ_G; $\mathrm{Re}_{V,G}$
	Various	C5	-	δ_L; $C_{f,G}$
		C10	90°	δ_L
Annular and stratified	Air-water	C1	0°–90°	$C_{f,G}$
		C3	0°–45°	δ_L; ρ_k
		C4	0°–45°	δ_L
	Various	C7	-	ε_B; $\mathrm{Re}_{U,G}$
		C8	0°–45°	Bo; Mo; $N_{U,k}$

Determination of the Correlations Accuracies

The accuracy analysis of the interfacial friction factor correlations, $C_{f,I}$, presented in Tab. 1, is based on the average value of the relative and absolute deviations, ξ_{rel} and ξ_{abs}, between the value calculated with each correlation and the value measured experimentally (Pedras, 1993):

$$\xi_{rel} = \frac{1}{N}\sum_{i=1}^{N}\frac{(C_{f,I})_{i,calc.} - (C_{f,I})_{i,meas.}}{(C_{f,I})_{i,meas.}} \qquad (17)$$

$$\xi_{abs} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(C_{f,I})_{i,calc.} - (C_{f,I})_{i,meas.}}{(C_{f,I})_{i,meas.}}\right| \qquad (18)$$

For a better results comparison involving all experimental data points, the root mean square (RMS) of the deviations is used for all N experimental points obtained by Pedras (1993):

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{(C_{f,I})_{i,calc.} - (C_{f,I})_{i,meas.}}{(C_{f,I})_{i,meas.}}\right]^2} \qquad (19)$$

In this analysis, the experimental data used were obtained from the Pedras (1993) work, which performed 49 tests using a vertical pipe of 27.1 mm internal diameter and air and water as fluids, allowing the annular pattern occurrence. The characteristics range presented in these tests can be observed in Tab. 3: phase superficial velocity, J_k; pressure, p; temperature, T; pressure gradient, (dp/dz); liquid film thickness, H_F; interfacial friction factor, $C_{f,I}$.

Table 3. Ranges of the experimental conditions for the 49 tests carried out by Pedras (1993) for annular flow cases of air and water in a vertical pipe of 27.1 mm internal diameter.

Variable	Unit	Range
J_L	[m/s]	0.02333–0.07065
J_G	[m/s]	13.24–35.51
p	[Pa]	96166.9–98014.1
T	[□]	21.0–26.0
(dp/dz)	[Pa/m]	(-722.4)–(-2248.0)
H_F	[mm]	0.17–0.40
ϕ_G	[-]	0.942–0.988
$C_{f,I}$	[-]	0.01724–0.08399

RESULTS AND DISCUSSION

The results obtained from the analysis of the interfacial friction factor, $C_{f,I}$, using the correlations shown in Tab. 1, are graphically represented in Fig. 2 (correlations applicable for annular flow case) and Fig. 3 (correlations applicable annular and stratified flow cases). In all graphs, the abscissa displays the $C_{f,I}$ values obtained from the experimental measurements carried out by Pedras (1993), considering all 49 tests of vertical annular flow, and the ordinate displays the $C_{f,I}$ values calculated from each of the correlations analyzed in this study (see Tab. 1). In each graph were added tracks equivalent to ±30% deviation between the calculated and measured values.

Figure 2a presents the results obtained by correlations C2, C6 and C9 (for air-water systems) and Fig. 2b shows the results obtained by correlations C5 and C10 (for gas-liquid systems).

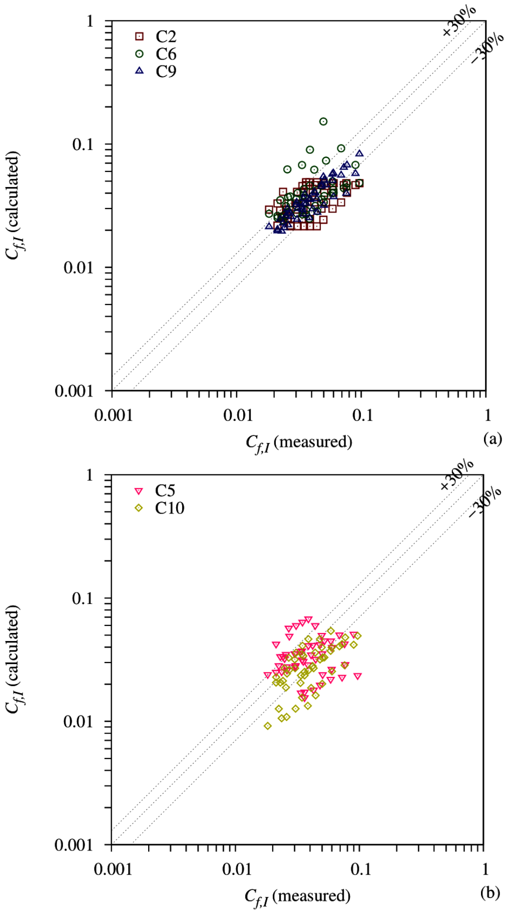

Figure 2. Analysis of the interfacial friction factor correlations applied in annular air-water flow in a vertical pipe: (a) C2, C6, and C9; (b) C5 and C10.

Correlation C9 is these that demonstrate a better precision to the $C_{f,I}$ values in relation to the measured experimentally, followed by correlations C2 and C6. Correlation C5 presents a significant number of points with deviation above +30% or below –30%, and correlation C10 presents some points with deviation below –30%.

Figure 3a presents the results obtained by correlations C3, C4 and C1 (for air-water systems) and Fig. 3b shows the results obtained by correlations C7 and C8 (for gas-liquid systems).

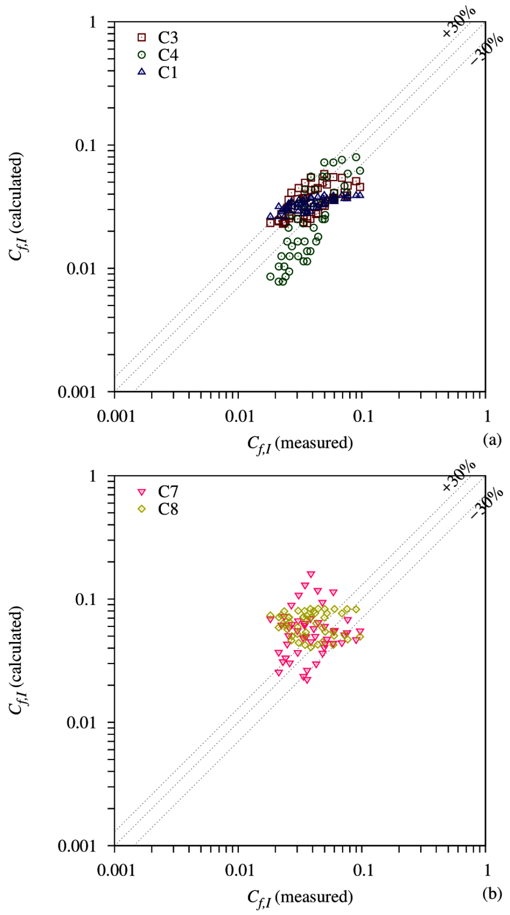

Figure 3. Analysis of the interfacial friction factor correlations applied in annular air-water flow in a vertical pipe: (a) C3, C4, and C1; (b) C7 and C8.

Correlations C3 and C1 demonstrate better results precision in the flow conditions in which $C_{f,I}$ value does not exceed 0.05. On the other hand, correlation C4 presents satisfactory results only for $C_{f,I}$ values above.

Table 4 shows the results for the average values of the relative and absolute deviations, defined by Eqs. (17) and (18), respectively, and RMS of the deviations, defined by Eq. (19), resultant between the calculated and measured values for the interfacial friction factor, $C_{f,I}$. The values obtained for relative deviations are between -31.16% and 79.89%. The values obtained for absolute deviations are between 13.21% and 87.48%. Finally, the values obtained for RMS of the deviations are between 17.21% and 113.17%. Based on this information, it is possible to verify which correlations present the smallest and largest deviations for the data set in relation to the experimental values.

Table 4. Deviations for the interfacial friction factor correlations in comparison to the values obtained experimentally by Pedras (1993).

Correlation	ξ_{rel} **/ [%]**	ξ_{abs} **/ [%]**	**RMS / [%]**
C1	-9.70	25.56	29.73
C2	-7.52	27.63	32.90
C3	-6.10	23.86	28.54
C4	-31.16	38.64	43.39
C5	-2.42	37.82	47.17
C6	11.17	34.75	51.10
C7	60.67	78.11	111.48
C8	79.89	87.48	113.17
C9	-9.15	13.21	17.21
C10	-27.41	31.48	36.99

Correlation C1, applicable for stratified and annular flows with an inclination varying from horizontal to vertical, presented satisfactory results, in the same way, that correlation C2, since it has been developed under operational conditions similar to the experimental data used in this analysis. Correlation C3 also presented satisfactory results, although it is applicable for horizontal flows, as well as correlation C4, whose results were less satisfactory. Correlation C5, developed for gas-oil flows, also showed less satisfactory results, but correlation C10 presented better results, which is a specific correlation for the vertical gas-oil annular flow. On the other hand, correlation C6 showed less satisfactory results than correlation C5, although it is based on physical concepts related to the apparent roughness model (ARM). Correlations C7 and C8 presented the worst performance among the correlations analyzed, which can be related to the experimental limitations imposed in these correlations. Finally, correlation C9 was the one that presented the most satisfactory results, followed by correlations C3 and C1. This satisfactory result for correlation C9 can be explained by the fact that this correlation was adjusted to the same experimental conditions obtained by the said author and whose experimental data were used in this analysis for comparison.

CONCLUSIONS

This work was carried out with the purpose of making a previous survey of some correlations for the determination of the interfacial friction factor in cases of gas-liquid annular flow. From this survey, comparisons of some of the correlations obtained in the literature against experimental data, also obtained in the literature, were made in order to verify the performance of these correlations.

It is of great importance to have a prior knowledge of which correlations for the interfacial friction factor have the best results for a given flow configuration since the interfacial shear stress and, consequently, the pressure gradient depends on this. This can be used to improve the results obtained by two-phase flow models or sub-models adopted in simulators, for example, the unit cell model proposed by Taitel and Barnea (1990).

The results obtained in this work demonstrate that the correlations for the interfacial friction factor analyzed, despite their different characteristics, present satisfactory results. The correlation of Pedras (1993) showed the best results, possibly due to the fact that important flow parameters such as the gas drift velocity and the liquid phase characteristics were taken into account, but also because it was adjusted based on the experimental data obtained by the author himself and this data was used in this comparative analysis.

For a better selection of correlations to the interfacial friction factor, it is necessary to carry out more extensive analyses involving other correlations available in the literature, as well as making use of other sets of experimental tests in different flow configurations. In addition, become necessary the proposition of new correlations for the interfacial friction factor, to taking into account all the phenomena involved, as well as the important parameters that influence the flow dynamics, for example, the entrainment fraction.

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