A COMPARISON OF THE INTERFACIAL FRICTION FACTOR METHODS IN HORIZONTAL AND DOWNWARDLY INCLINED ANNULAR FLOW IN PIPES

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Abstract
Based on the experimental data, a comparison among many correlations and methods to calculate the interfacial friction factor in annular flow has done. These data are conducted from two different sources with same fluid through pipe: 5.08 cm diameter and 36 m length with angles of inclination 0^o, -5^o, and -20^o . The comparison reveals the performance of Tsiklauri and Lee-Bankoff correlations are so converged but the correlation of Tsiklauri is the best performance.

Introduction
The interfacial friction factor is considered an important factor in the two-phase flow. This factor is affecting on the flow of gas phase when it moves in contact to the liquid phase, therefore it reduces the velocity of the gas flow in the region of the contact surface. Any friction happens due to the roughness of the surface as in the wood, materials, etc. The interfacial friction also occurs due to the roughness of the liquid face surface which is called generally the waves which are recognizing the smooth and wave surfaces. This wavy case could be noticed clearly in stratified flow, in annular flow these waves can be observed more clearly namely by taking cross section to the pipe of flow as shown in figure (1). Due to the importance of this factor, many investigators have developed correlations to predict it empirically or semi- empirically as: Kowalski (1987), Laurinat et al. (1985), Crowley & Rothe (1986), Lee & Bankoff (1983), Tsiklauri *et al.* (1979), Eck (1973) and recently Xiao *et al.* (1990). All these correlations are developed empirically used experimental tests and the accuracy of any method is related with the volume of tests and how many empirical relations included.

Measured Friction Factor:
The momentum equation of any two-phase flow is derived from the nature of flow and all part or term in it could be evaluated using the facilities and the geometrical configuration and both depend on the holdup of the liquid directly or indirectly. Therefore, the available tests provide the value of the liquid holdup. Now the values of the interfacial friction factors could be calculated using the existed experimental information.

Firstly, the momentum equation must be derived as follows:

* for the gas core stream:

$$-A_g\left(\frac{dP}{dL}\right)-\tau_i s_i - A_g \rho_g \sin\varphi = 0 \quad \text{------------------------------------- (1)}$$

* for the liquid film stream:

$$-A_L\left(\frac{dP}{dL}\right)+\tau_i s_i - \tau_{wL} s_L - A_L \rho_L \sin\varphi = 0 \quad \text{--------------------------------- (2)}$$

If the pressure gradient $\left(\frac{dP}{dL}\right)$ is proposed the same in each phase (as Taitel-Dukler, 1976), then from the equations (1) & (2):

$$\tau_{wL}\frac{s_L}{A_L}-\tau_i s_i\left(\frac{1}{A_L}+\frac{1}{A_g}\right)+\left(\rho_L-\rho_g\right)g\sin\varphi=0 \qquad (3)$$

The equation (3) is called the momentum equation of the annular flow pattern and φ is the inclination angle of the pipe flow.

At last, the interfacial shear stress could be calculated from equation (3) and the friction factor is consequently calculated from the following equation:

$$f_i=\frac{2\tau_i}{\rho_g V_g^{\,2}} \qquad (4)$$

The Used Methods

This study adopted seven methods to calculate the interfacial friction factor in annular flow pattern. Some of them, really, had been developed for separated flow and it is used in calculation of this factor in stratified flow, and because of the annular flow is considered separated flow, these correlations used in the calculations in this study. These methods are:

1. Eck (1973) correlation:

He proposed the following correlation:

$$fi=\frac{0.0625}{\left(\dfrac{2.3\,S_g}{3.715\,d}+\dfrac{15}{Re_g}\right)^2} \qquad (5)$$

2. Tsiklauri *et al.* (1979) correlation:

They recommended the following correlation for the interfacial friction factor:

$$f_i=0.0055+2.6\times10^{-5}\,Re_L \qquad \text{where: } Re_L=\frac{\rho_L Q_L}{\mu_L\left(s_L+s_i\right)} \qquad (6)$$

3. Lee and Bankoff (1983) correlation:

$$fi=0.012+5.179\times10^{-7}\times\left(Re_g-Re_g^{*}\right) \qquad \text{if} \quad Re_g\le Re_g^{*} \qquad (7)$$

$$fi=0.012+2.694\times10^{-7}\times\left(Re_g-Re_g^{*}\right)\left(\frac{Re_L}{1000}\right)^{1.534} \qquad \text{if} \quad Re_g>Re_g^{*} \qquad (8)$$

Where: $Re_g^{*}=1.837\times10^{5}\,Re_L^{\,-0.184}$

4. Laurinat *et al.* (1984) correlation:

This correlation was:

$$\frac{f_i}{f_{wg}}=\left[2+\frac{2.5\times10^{-5}\,Re_{sL}}{d}\right]\left(1-H_L\right)^{5/2} \qquad (9)$$

5. Crowley and Rothe (1986) correlation:

They recommended use the correlation of Laurinat above and proposed the following intervals:

$$\frac{f_i}{f_{wg}}=1 \qquad \text{if} \qquad \frac{f_i}{f_{wg}}<1 \qquad (10)$$

$$\frac{f_i}{f_{wg}} = (1 + 75H_L) \qquad \text{if} \qquad \frac{f_i}{f_{wg}} > (1 + 75H_L) \quad \text{----------------------(11)}$$

6 .Kowalski (1987) correlation:

This correlation was developed using experimental data. It was found that the interfacial friction factor is affect with the liquid holdup, the gas and the liquid Reynolds numbers:

$$f_i = 7.5 \times 10^{-5} H_L^{-0.25} Re_g^{-0.3} Re_L^{0.83} \quad \text{-------------------------------------(12)}$$

$$\text{Where:} \quad Re_g = \frac{\rho_g v_g d}{\mu_g} \quad \text{and} \quad Re_L = \frac{\rho_L v_L d}{\mu_L} \quad \text{---------------------------(13)}$$

7. Xiao *et al.* (1990) correlation:

They proposed a new correlation based on the experimental study. Their correlation is dependent on four dimensionless groups developed by Duns & Ros (1962). Their proposal was:

$$fi = 0.053 N_{gv}^{0.23} N_Lv^{0.202} N_d^{-0.46} N_L^{0.076} \quad \text{---------------------------------(14)}$$

where:

$$N_{gv} = v_g \sqrt[4]{\frac{\rho_L}{g\sigma}} \quad N_{Lv} = v_L \sqrt[4]{\frac{\rho_L}{g\sigma}} \quad N_d = d\sqrt{\frac{\rho_L g}{\sigma}} \quad N_L = \mu_L \sqrt[4]{\frac{g}{\rho_L \sigma^3}}$$

The table (1) displays these methods and their symbols.

Table (1): The used methods

	Symbol	The method
1	E	Eck (1973)
2	Tsi	Tsiklauri et al. (1979)
3	LB	Lee and Bankoff (1983)
4	Lau	Laurnat et al. (1985)
5	CR	Crowley and Rothe (1986)
7	Kow	Kowalski (1987)
6	X	Xiao et al. (1990)

The Fluid Properties

The experimental tests achieved in two-phase flow test section with the air as gas phase and the kerosene as liquid phase, both fluids properties are obtained using the facilities correlations as in the following equations:

$$\rho_L = 832.34 - 0.8333Tav$$

$$\rho_g = Pav/[0.287(273 + Tav)]$$

$$\mu_L = 0.001\exp(0.0664 - 0.0207Tav)$$

$$\mu_g = 0.00001(17044 + 0.00613\,Tav - 0.0000314\,Tav^2)$$

$$\sigma = 27.6 - 0.09Tav$$

The Experimental Tests

No experimental apparatus has done in the present work, but the all tests are conducted from tests published in the literature from two different sources as explained in table (2).

Table (2): The Data

	The Source	No of tests	Inclination Angle
1	Abdul-Majeed	22	0^o
2	Mukherjee-Brill	77	$0^o,-5^o,-20^o$

Table (3): The Flow Conditions

	The Property	The Units	Minimum	Maximum
1	Superficial gas velocity	m / sec	8.047	48.908
2	Superficial liquid velocity	m / sec	0.0305	2.231
3	Average Pressure	KPa	183	608
4	Average Temperature	^oC	12.8	48.6
5	Liquid Holdup	dimensionless	0.001	0.28

The statistical Tools

The comparison to investigate the best performance has done among the available correlations using the F_{PR} which is used previously by (Ansari 1994), consequently used by (Abdul-Majeed 1997-2001), Ahmed S. Naji (2001-2003). This factor depends on both error and percent error.

$$F_{PR} = \frac{|E_1| - |E_{1min}|}{|E_{1max}| - |E_{1min}|} + \frac{E_2 - E_{2min}}{E_{2max} - E_{2min}} + \frac{E_3 - E_{3min}}{E_{3max} - E_{3min}} + \frac{|E_4| - |E_{4min}|}{|E_{4max}| - |E_{4min}|} + \frac{E_5 - E_{5min}}{E_{5max} - E_{5min}} + \frac{E_6 - E_{6min}}{E_{6max} - E_{6min}} \quad \text{----------------------(15)}$$

where:

1. Average Error:

$$E_1 = \frac{1}{n}\sum_{i=1}^{n} e_i \quad \text{---------------------- (16)}$$

2. Absolute Average Error:

$$E_2 = \frac{1}{n}\sum_{i=1}^{n} |e_i| \quad \text{---------------------- (17)}$$

3. Standard Deviation of Error:

$$E_3 = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (e_i - E_1)^2} \quad \text{---------------------- (18)}$$

4. Average Percent Error:

$$E_4 = \frac{1}{n}\sum_{i=1}^{n} pe_i \quad \text{---------------------- (19)}$$

5. Absolute Average Percent Error:

$$E_5 = \frac{1}{n}\sum_{i=1}^{n}\left|pe_i\right| \quad \text{---------- (20)}$$

6. Standard Deviation of Percent Error:

$$E_6 = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(pe_i - E_4\right)^2}$$

where:

$e_i = f_{i\,cal} - f_{i\,meas}$

$pe_i = \left[e_i / f_{i\,meas}\right] \times 100\%$

This factor is bounded between [0, 6], the best performance must be approach to (0).

The Results and Discussion

The available methods are programmed and by using the data from the displayed sources in table (2) the measured and the calculated interfacial friction factors are obtained, the comparison among them for each method has done. This comparison consisted of two ways: one of them is the statistical tools (E_1, E_2, E_3, E_4, E_5, E_6 &F_{PR}) as given in table (3) and the other is the graphs of the best performance methods only as in fig(2) to fig (4).The statistical results reveal that

1. The accuracy of all methods are not good due to they are empirical methods.
2. If the method has semi-empirical equation included, then its performance be better than they haven't same equation as it is noticed in Lee-Bankoff and Xiao et al. correlations when the semi-empirical correlation of Lee-Bankoff get better results than that full empirical correlation of Xiao et al.
3. Some correlations has stable behavior in spite of the inclination angle change and this stability may leads to the best performance such as Tsiklauri et al. correlation
4. The investigations of Kowalski and Crowley-Rothe correlations are converged due to these methods are near to depend on gas core in their predictions.
5. The semi-empirical correlation as cited above is the best performance as occurred in Lee-Bankoff and Tsiklauri et al. correlations

Table (3): Relative Performance Factor (F_{PR}) for the Whole Data

	The Method	E_1	E_2	E_3	E_4 %	E_5 %	E_6 %	F_{PR}
1	**E**	-1.187	1.187	4.81	-147	154	443	3.12
2	**Tsi**	**-1.088**	**1.088**	**4.75**	**-194**	**269**	**1293**	**1.67**
3	**LB**	**-1.094**	**1.104**	**4.73**	**-244**	**287**	**1482**	**1.72**
4	**Lau**	-0.999	1.029	4.73	-557	806	5054	2.56
5	**CR**	-1.187	1.187	4.82	-98.95	98.95	14.03	3.00
6	**Kow**	-1.187	1.187	4.81	-98.95	98.95	14.025	2.89
7	**X**	-1.118	1.138	4.81	-677	908	5654	5.21

The Conclusions

From table (3) for F_{PR} and by observing the figures below, the following notes may be revealed:

1. None of the seven methods gives the real prediction for the whole tests and all gave underestimating results.

2. The correlation of Tsiklauri et al. gave the best performance and this leads to the thinking of the interfacial is affecting with the dynamic of the liquid film more than that by the gas core.
3. The worst accuracy gives by the correlation of Xiao et al. due to it is a full empirical method.

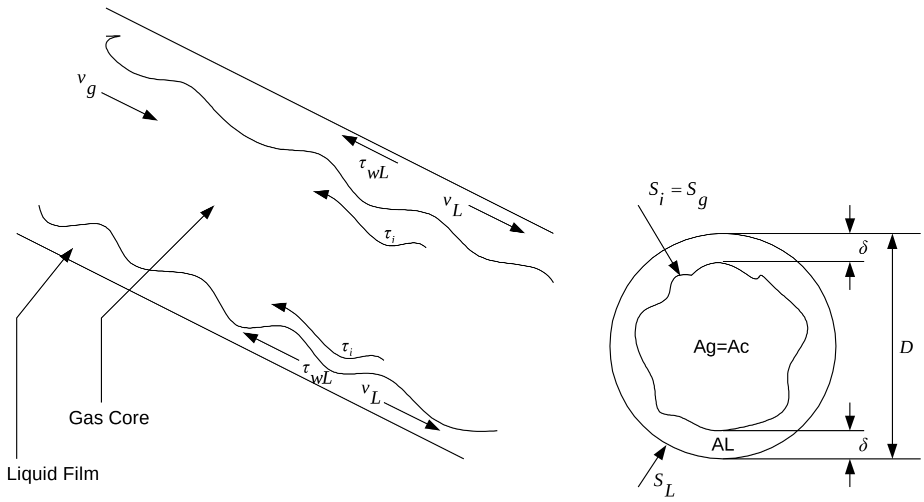

Fig (1): Annular Flow Pattern

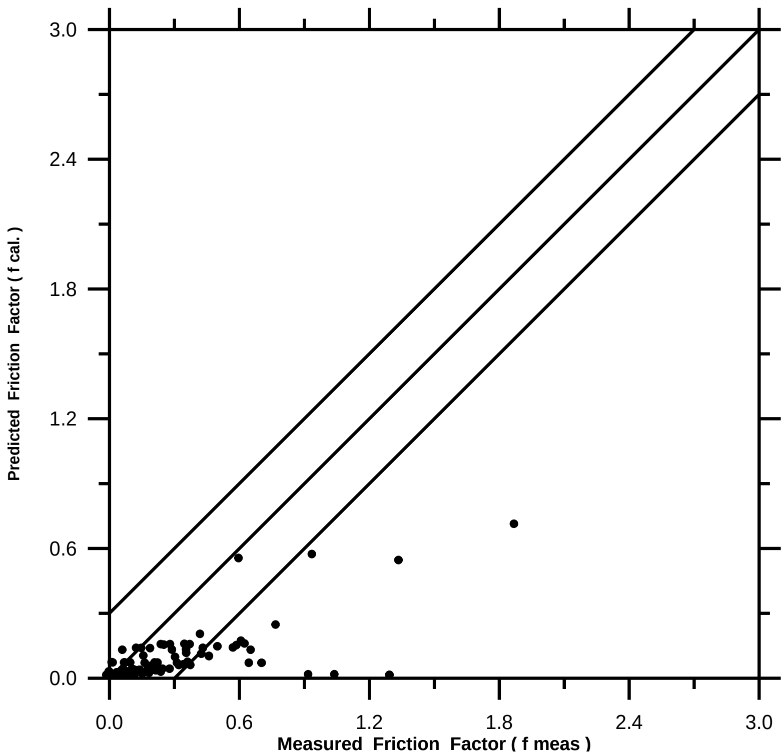

Fig (2): Tsiklauri Correlation

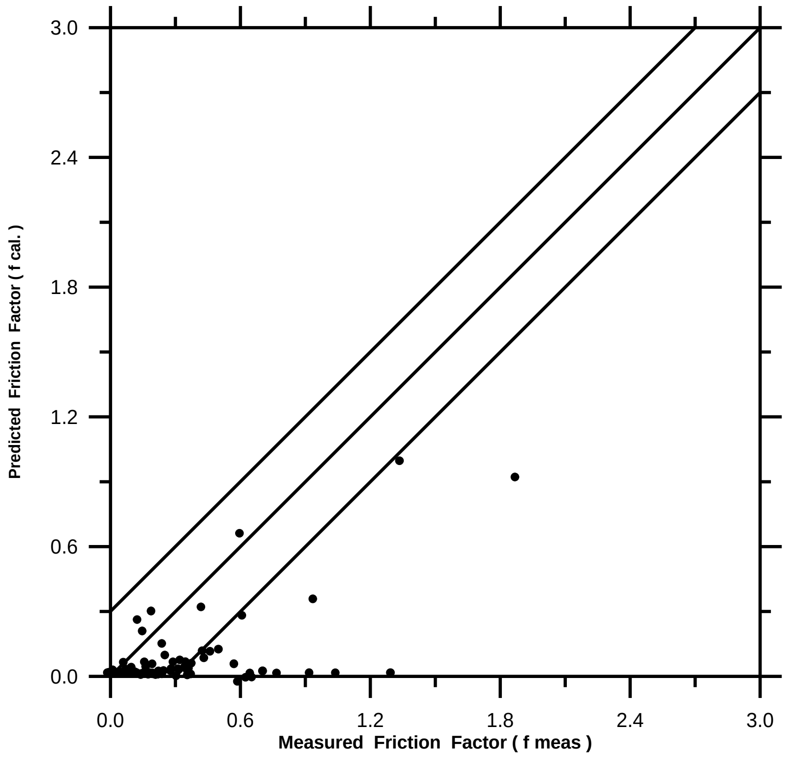

Fig (3): Lee & Bankoff Correlation

Nomenclatures:

The Symbol	The specification	The Units
A	Cross Section Area	m^2
A_g	Gas Core Cross Section	m^2
A_L	Liquid Film Cross Section	m^2
F_i	Interfacial friction factor	Less
F_{wL}	Liquid-Wall Friction Factor	Less
P_{av}	Average Pressure	N/m^2
T_{av}	Average Temperature	^oC
S_i	Interfacial Perimeter	m
S_L	Liquid Film Perimeter	m
V_g	Gas Core Velocity	m/s
V_L	Liquid Film Velocity	m/s

The Groups:

The Symbol	The Specification	The Units
N_{vg}	Gas velocity number	Less
N_{Lv}	Liquid velocity number	Less
N_L	Liquid viscosity number	Less
N_d	Diameter number	Less
Re_g	Gas Reynolds number	Less
Re_g*	Modified gas Reynolds number	Less
Re_L	Liquid Reynolds Number	Less
Re_{sL}	Superficial liquid Reynolds Number	Less

Greek Symbols:

The Symbol	The specification	The Units
δ	Liquid Film Thickness	m
τ_i	Interfacial Shear Stress	N/m^2
τ_L	Liquid-Wall Shear Stress	N/m^2
μ_L	Liquid Viscosity	N.s/m
μ_g	Gas Viscosity	N.s/m
ρ_L	Liquid Density	N/m^3
ρ_g	Gas Density	N/m^3
σ	Surface Tension	N/m

References:

1. Abdul-Majeed, G. H.: "Liquid Holdup in Horizontal Two-Phase Flow", JPSE, 15,PP.271-280,1996.
2. Ahmed S. Naji and Al-Kayiem, H. H.: "Study of Two-Phase Flow in Horizontal and Inclined Pipes", M. Sc. Dissertation, Mech. Eng. Dept., Coll. of Eng., Al-Mustansiria University,2001.
3. Alves, I. N., Caetano, E. F., Minami, K. and Shoham, O.:" Modeling Annular Flow Behavior for Gas Wells", ASME J, Chicago, No. 2, 1988.
4. Brill, J. P. and Beggs, H. D.: "Study of Two-Phase Flow in Pipes", fifth Edition, The University of Tulsa, U. S. A., 1986.
5. Crowley, C. J. and Rothe, P. H.:"State of Art Report on Multiphase Methods for Gas and Oil Pipelines", AGA Pipelines Research Committee Project PR-172-609, Dec., 1986.
6. Kowalski, J. E.:"Wall and Interfacial Shear Stresses in Separated Flow in a Horizontal Pipe", AIChE J.33, No. 2, 274-281, 1987.
7. Laurinat, J. E., Hanratty, T. J. and Dallman, J. C.: "Pressure Drop and Film Height Measurements for Annular Gas-Liquid Flow", Int. J. Multiphase Flow 10, No. 3, 341-356, 1984.
8. Lee, S. C. and Bankoff, S. G.:" Stability of Steam-Water Countercurrent Flow in an Inclined Channel:Flooding", J. of Heat Transfer 105, 713-718, 1983.
9. Mukherjee, H.: "An Experimental Study of Inclined Two-Phase Flow", Ph. D. Dissertation, the University of Tulsa, 1979.
10. Oliemans, R. V. A., Pots, B. F. and Trope, N. :" Modeling of annular Dispersed Two-Phase Flow in Vertical Pipes", Int. J. Multiphase Flow 12, No. 5, 711-732, 1986.
11. Smith, T. N. and Taitel, R. W.: "Interfacial Shear Stress and Momentum Transfer in Horizontal Gas-Liquid Flow", Chem. Eng. Sci., 21, 63-75, 1966.
12. Taitel, Y. and Dukler, A. E.: "A Model for Predicting Flow Regimes Transitions in Horizontal and near Horizontal Gas-Liquid Flow", AIChE J.22, No.1, 47-55, 1976.
13. Tsiklauri, G. V., Besfamiliny, P. V. and Baryshev, Y. V:" Experimental Study of Hydrodynamic Processes for Wavy Water Film in a Cocurrent Air Flow", Two-Phase Momentum, Heat and Mass Transfer, Vol. 1, 357-372, Hemisphere, New York, 1979.
14. Wallis, G. B.: "One Dimensional Two-Phase Flow", McGraw Hill, 1969.
15. Xiao, J. J., Shoham, O. and Brill, J. P.: " A Comprehensive Mechanistic Model for Two-Phase Flow in Pipes", 65th Ann. Tech. Conf., Soc. Pet. Eng., New Orleans, LA, Pap. SPE 20631, PP.14, 1990.

الخلاصة

تم في هذا البحث مقارنة طرق حساب معامل الاحتكاك ألتداخلي للجريان الاسطواني باستخدام بيانات عملية مستحصلة من مصدرين مختلفين ولنفس الموائع الجارية خلال أنبوب بقطر 5.08 سم وطول 36 م وذو زوايا انحدار مختلفة: 0^o و 5^o- و20^o- وتمت المقارنة باستخدام معامل الأداء F_{PR} ، وكانت النتيجة هي ان طريقتي تسكا لوري وطريقة لي– بانكوف متقاربتين جدا بالأداء الجيد لكن طريقة تسكا لوري كانت الأفضل.