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Frictional Pressure Drop for Gas-Liquid Flow in Horizontal Pipelines

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INTRODUCTION

Since frictional pressure drop for two-phase, gas-liquid flow is an important parameter for the design of pipelines and evaporators, numerous investigations on this topic can be found in the literature. Although it is still not possible to theoretically predict the mechanisms occuring in two-phase flow, a considerable number of empirical correlations for the prediction of frictional pressure drop exist. For conditions outside the range of the original data from which these correlations were derived, however, deviations of several 100% between predicted and measured values may be found, as shown by Müller-Steinhagen and Steiner (1983).

Consequently, data banks, which contain measurements with a number of liquid-gas combinations for various flow conditions and pipe diameters, have been assembled. Correlations fitted to these data banks, however, often have the disadvantage of containing a large number of empirical constants and of being inconvenient to use. Examples herefore are the correlation suggested by Storek and Brauer (1980), which contains 24 empirical constants and the correlation developed by Bandel (1973), which can only be solved with a computer.

In what follows, a particularly simple correlation for the prediction of frictional two-phase pressure drop is developed which gives satisfactory agreement with measured data.

The predictions of this correlation and of 14 correlations suggested by other authors, is compared with measured data in order to find out, which correlations are suitable for the predictions of frictional pressure drop.

DESCRIPTION OF THE NEW CORRELATION

Figure 1 shows the frictional pressure drop as a function of the flow quality. Due to the increasing interaction between gas and liquid phase, the frictional pressure drop increases with increasing flow quality, passes through a maximum for $\dot{x}$ = 0.85 and then falls to the frictional pressure drop for single-phase gas flow for $\dot{x}$ = 1. Measurements show that the frictional pressure drop for a flow quality of 0.5 is nearly always identical to the single phase gas pressure drop ($\dot{x}$ = 1). This observation was used as the basis of the new correlation.

Using the pressure drop of the respective single phase flow

$$(dp/dL)_{f,l} = \zeta_l \frac{\dot{m}}{2\rho_l d} = A \quad (1)$$

$$(dp/dL)_{f,g} = \zeta_g \frac{\dot{m}}{2\rho_g d} = B \quad (2)$$

for $Re_l, Re_g \leqslant 1187$: (3)

$$\zeta_l = \frac{64}{Re_l} \qquad \zeta_g = \frac{64}{Re_g}$$

for $Re_l, Re_g > 1187$: (4)

$$\zeta_l = \frac{0.3164}{\sqrt[4]{Re_l}} \qquad \zeta_g = \frac{0.3164}{\sqrt[4]{Re_g}}$$

$$\text{and} \quad Re_l = \frac{\dot{m}d}{\eta_l} \qquad Re_g = \frac{\dot{m}d}{\eta_g} \quad (5)$$

an equation for the roughly linear increase of the pressure drop with increasing quality for $\dot{x}$ <0.7 can be written:

$$G = A + 2\,(B - A)\,\dot{x} \quad (6)$$

To cover the full range of flow quality $0<\dot{x}<1$, a superimposition of equations (2) and (6) was used.

$$(dp/dL)_{f,tp} = G\,(1 - \dot{x})^{1/C} + B\,\dot{x}^{C} \quad (7)$$

A value of C = 3 was found by curve fitting measured data.

In addition to its simplicity, eq. (7) has the advantage of being easily integrated if the flow quality increases along the tube length. Since eg. (7) only applies for the prediction of frictional pressure drop, the static pressure change has to be added if the flow direction is not horizontal, as does the acceleration pressure drop if evaporation occurs.

The application of eq. (7) should be restricted to flow conditions where

$$Re_l = \frac{\dot{m}d}{\eta_l} > 100 \quad (8)$$

For lower mass velocities and for viscous liquids, the frictional pressure drop for $\dot{x}$=0.5 may differ considerably from the value for $\dot{x}$ = 1. Furthermore, eq. (7) can be used only as long as the frictional pressure drop of the gas flow is higher than the frictional pressure drop of the liquid flow (B>A). For certain oil/gas flow rates, this condition may not be fulfilled. Nevertheless, it should be noted that not only eq. (7) but all the correlations investigated in this

The simple correlation suggested earlier in this paper includes the frictional pressure drop for single phase liquid or gas flow ($\dot{x} = 0$ or $\dot{x} = 1$) and can be applied over the full range of flow quality, $0 < x < 1$.

To allow quantitative assessment of the correlations investigated, values predicted using the above correlations were compared to the measurements in the data bank.

A total of 9313 data set could be used for comparison with correlations 5, 6, 7, 8, 9, 12, 13, 15, only 9256 data could be used for correlations 2, 3, 4, 10, 11, 14 and only 8541 for correlation 1, because of the restrictions mentioned before.

As characteristic values for the performance of the respective correlations, the average relative error

$$RE = \frac{1}{n}\sum^{n}\left|\frac{(dp/dL)_{meas} - (dp/dL)_{pred}}{(dp/dL)_{meas}}\right| \quad (9)$$

and the average absolute error

$$AE = \frac{1}{n}\sum^{n}\left|(dp/dL)_{meas} - (dp/dL)_{pred}\right| \quad (10)$$

were used as well as the percentage of predicted values within ±10%, ±20% and ±30% to the measured data. In addition, the comparison between measured and predicted trends should be used for a final judgement concerning the reliability of correlations. This is especially necessary since the compostion of the data bank is not homogeneous.

Table 3 gives values of RE and AE for the various correlations. Since no systematic deviations were found for different flow directions, Table 3 is based on all data mentioned above.

Obviously, the correlation by Bandel (no.1) gives the best agreement between predicted and measured values. Considering the scatter of data, reasonable accuracy is also obtained using the correlations suggested by Gronnerud (no.9), Reza Chavez (No. 13), Storek-Brauer (no.14) as well as using the correlation suggested in this paper. The correlation by Reza-Chavez is particularly useful for flow of air-water and air-water (cmc). Although results obtained with correlations nos.6 and 7 are quite respectable, application of these equations should be limited to lower flow qualities since the homogeneous model generally fails for high quality. Values predicted by the well-known Lockhart-Martinelli model were usually higher than the measured values.

Recently, the correlations by Friedel (no.8) and by Storek and Brauer (no.14) have been particularly recommended. With respect to the average absolute error and the percentage of data within a certain error range, Friedel's correlation has reasonable results. The average relative error, however, is clearly higher than for a number of other correlations. This result is mainly caused by the poor accuracy for lower flow quality (low frictional pressure drop) where this correlation considerably overpredicts the pressure drop.

In addition, the correlation can fail totally for fluids with a high viscosity ratio η_l/η_g. The performance of the correlation suggested by Storek and Brauer is clearly superior. Nevertheless, it should be mentioned that it may fail for high mass flow rates and flow qualities, where predicted values may exceed the measured data considerably. The simple correlation suggested in this paper gives reasonable results for all flow conditions. Predicted values generally lie between those predicted by the above two correlations.

Table 3 Comparison between predicted and measured values of frictional pressure drop.

No. Author	RE (%)	AE (N/m^3)	RE<10% (%)	RE<20% (%)	RE<30% (%)
1 Bandel	32.6	5347.1	25.8	44.7	59.9
2 Bankoff	11525.8	139561.5	7.5	12.6	16.4
3 Chawla	8697.6	696831.7	5.5	10.5	15.3
4 Chawla-Bankoff	142.3	47471.3	18.1	32.6	40.9
5 Chisholm-Baroczy	340.0	5579.6	16.5	28.9	38.2
6 Cicchitti	65.7	4531.7	15.8	30.0	42.0
7 Dukler	37.0	4916.6	14.7	29.0	43.9
8 Friedel	111.6	5015.0	18.1	32.6	44.6
9 Gronnerud	44.6	10808.0	16.0	31.4	46.5
10 Kesper-Moussalli	69.9	6920.6	12.5	22.3	29.9
11 Lockhart-Martinelli	62.8	14244.2	21.0	38.0	52.4
12 Lombardi-Pedrocchi	152.3	4910.4	14.2	22.2	29.5
13 Reza-Chavez	35.5	5490.5	18.1	37.4	54.6
14 Storek-Brauer	36.5	7859.0	22.2	41.9	58.7
15 Eq. (7)	41.9	5481.4	17.3	34.5	49.5

CONCLUSIONS

The simple correlation suggested in this paper, as well as 14 correlations from the literature, have been checked against an extensive data bank with measurements of frictional pressure drop in pipes. Best agreement between predicted and measured values was obtained with the correlation by Bandel (1973) which, however, is quite lengthy and complicated to use. The correlation suggested in this paper is more convenient, and still predicts the frictional pressure drop with reasonable accuracy. It includes single phase liquid and gas pressure drop and predicts correctly the influence of flow parameters.

Nevertheless, it has to be concluded from the above investigation that the prediction of frictional pressure drop for two-phase flow in pipes is far from being satisfactory. Average deviations of more than ± 30% between predicted and measured values still have to be accepted.

Symbols

A	N/m^3	single phase liquid pressure drop
AE	N/m^3	absolute error
B	N/m^3	single phase gas pressure drop
C	-	constant
d	m	tube diameter
g	m/s^2	acceleration due to gravity
L	m	length
$\dot{m}$	kg/m^2s	mass velocity
p	bar	pressure
p_c	bar	critical pressure
p_r	-	reduced pressure ($=p/p_c$)
Re	-	Reynolds number
RE	%	average relative error
$\dot{x}$	-	flow quality ($=\dot{m}_g/(\dot{m}_g + \dot{m}_l)$)
ρ	kg/m^3	density
η	kg/ms	viscosity
σ	N/m	surface tension
ζ	-	friction factor

Indices

f	frictional
g	gas
l	liquid
meas	measured
pred	predicted
tp	two phase

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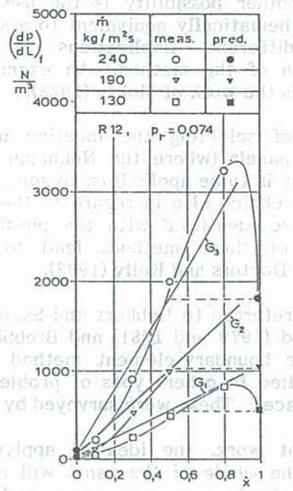

Fig. 1

Influence of flow quality on frictional pressure drop of R12.

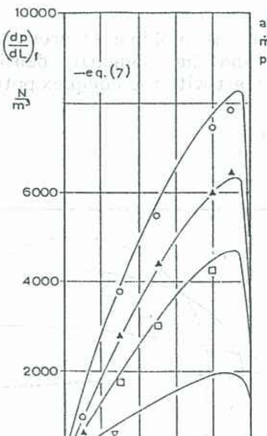

Fig. 2

Measured and predicted frictional pressure drop for flow of water and air as a function of flow quality.

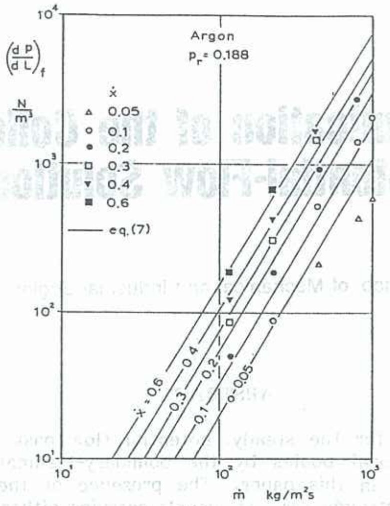

Fig. 3

Measured and predicted frictional pressure drop of argon as a function of mass velocity.

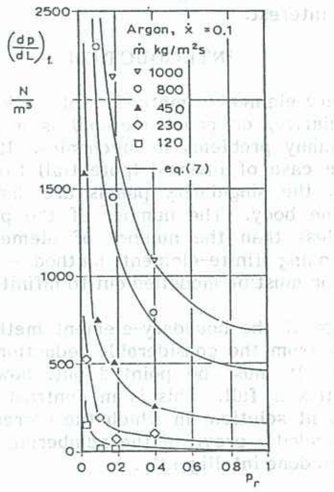

Fig. 4

Measured and predicted frictional pressure drop of argon as a function of reduced pressure.

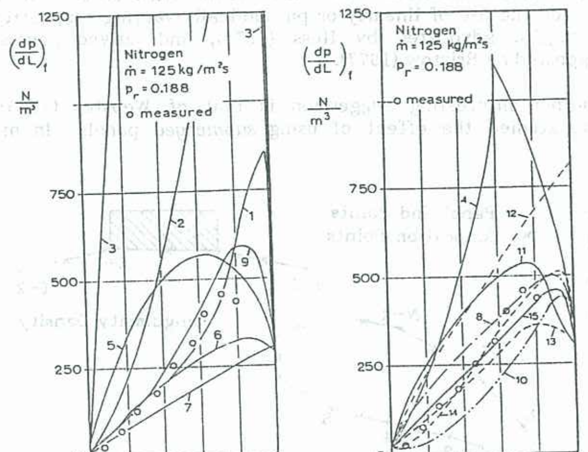

Fig. 5

Influence of flow quality on frictional pressure drop of nitrogen, calculated according to various correlations.