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soient ajustés aux conditions changeantes (par exemple: systèmes de conduites et de robinetteries interchangeables et vissables) des techniques d'essai et du génie chimique.

L'exigence économique selon laquelle il faut utiliser pour maints procédes chimiques un appareillage standardisé tout en prenant en considération une sécurité suffisante est aujourd'hui réalisable.

Dans la cadre de la description de différentes installations particuliérement intéressantes, les auteurs présentent le „know-how" technique relatif à des installations chimiques.

Improved friction pressure drop correlations for horizontal and vertical two phase pipe flow

Verbesserte Reibungsdruckabfallbeziehungen für horizontale und vertikale Gas-Dampf-Flüssigkeits-Rohrströmung

Relations améliorées pour la chute de pression par frottement des courants horizontaux et verticaux de gaz-vapeur-liquide dans les conduits

By L. Friedel [1])

Dedicated to Professor Dr.-Ing. F. Mayinger on the occasion of the 10th anniversary of the foundation of the Institut für Verfahrenstechnik der Universität Hannover

Introduction

Recent assessments of the predictive accuracy of various friction pressure drop correlations revealed a demand for more reliability, since the better methods either tend to extreme overpredictions or fail to accurately reproduce the data under certain conditions [1, 2]. This applies first of all to horizontal and vertical upflow in straight unheated tubes with circular cross section. In addition, there are up to now no widely accepted correlations for vertical downflow, since a comparatively extensive compilation of data doesn't exist for this flow direction and no systematic statistic comparisons of different correlations have been performed [3, 4]. Finally, no authentic statement on friction pressure drop in noncircular flow geometries is available.

However, for engineering design calculations in a number of applications, a trusty method of evaluation of the friction pressure drop in these situation is required. Experimental and theoretical investigations therefore were carried out to produce more accurate correlations for horizontal and vertical up- and downflow in circular and other simple pipe flow geometries.

Experimental work

The experimental efforts involved the compilation of extensive experimental friction pressure drop [2]) data and the setting up of a new data bank, whereby emphasis was placed on recently published systematical measurements. To date it embodies approximately 25 000 friction pressure drop results of various single and two component mixtures taken during unheated horizontal and vertical up- and downflow in straight tubes with circular, rectangular and annular cross sections under widely varied test conditions. The data bank and the culling procedures are described elsewhere [5]. A survey on the variables — range of parameters, fluid systems, flow geometries and data points — is given in table 1, whereby a distinction is only made between single and two component systems and the flow directions. The experimental results obtained during water, R 12, air-water and air-oil flow in circular tubes predominate, while the ranges of some of the flow parameters are more widely varied with the two component mixtures, e.g. density and viscosity ratio. Indeed, the distribution of the data points within the limits given in table 1 is extremely nonuniform, the arithmetic mean should roughly indicate this without any more details being required.

Theoretical investigation

It is very unlikely that any unique and generally satisfying solution is possible for the three flow directions, since in a wide range of flow parameters the slip behaviour of the phases and the momentum exchange between the phases respectively differ significantly in up- and downflow. The deliberations in the

Table 1: Parameters of the friction pressure drop data
Tafel 1: Parameter der Reibungsdruckdaten
Tableau 1: Paramètre des données de pression par friction

Variables	horizontal flow single component	horizontal flow two component	vertical upflow single component	vertical upflow two component	vertical downflow single component	vertical downflow two component
mass flow rate [kg/m² s]	4500-7 (674) [1])	10330-2 (885)	4800-34 (1430)	8410-20 (610)	8200-580 (2835)	2540-32 (350)
density ratio	49070-4 (1541)	1200-8 (428)	24770-2 (133)	1020-6 (428)	82-20 (29)	960-130 (770)
pressure [bar]	178-0,02 (20)	64-1 (10)	212-0,1 (33)	171-1 (7)	72-20 (55)	7-1 (11)
mass quality	≦ 1 (0,35)	≦ 1 (0,26)	≦ 1 (0,31)	≦ 1 (0,31)	≦ 0,88 (0,35)	≦ 0,85 (0,31)
(hydr.) diameter [10^{-3} m]	200-4 (27)	154-1 (49)	200-3 (12)	260-10 (25)	10-5 (7)	51-25 (42)
viscosity ratio	46-2 (17)	33620-13 (444)	40-1 (10)	89320-6 (456)	8-4 (5)	6195-38 (343)
surface tension [10^{-3} N/m]	92-2 (36)	76-20 (53)	140-0,2 (7)	110-15 (69)	40-20 (25)	73-28 (70)
two phase system	H_2O, R 113, R 22, R 12, R 11, N_2, NH_3, Ne, 1Na99K, 8Na92K	air-water, air-oil, CH_4-water, CH_4-oil	H_2O, R 12, NH_3, Na, 1Na99K	air-water, air-oil, air-alcohol, NaK-N_2, N_2-water	H_2O	air-water, air-oil
flow geometry and data points	1921	8367	6581	6555	68	1245
circular tube	1886	8166	5421	6195	68	1191
rectangular tube	35	201	394	26	—	54
annular tube	—	—	766	334	—	—

[1]) Arithmetic mean of the respective parameter range

[1]) Dr.-Ing. Lutz Friedel, Hoechst AG/Verfahrenstechnik, Frankfurt am Main
[2]) The definition of the two phase friction pressure drop is based on a momentum balance

first instance were aimed therefore towards the development of specific relationships for each flow direction. In these cases, mass flow rate, mass flow or volumetric flow quality, (hydraulic) diameter, possibly also diameter ratio for annular and aspect ratio for rectangular cross sections, pipe length, gravitational acceleration and fluid properties of both phases (density, viscosity and surface tension) play a conclusive role in two phase friction pressure drop and are to be considered as primary macroscopic parameters. Further independent but secondary variables are flow pattern, the power of which in horizontal flow might be more marked than in vertical conduits, and relative pipe wall roughness. The influence of the former on pressure drop is not yet quantitable, if at all, and probably in most engineering applications negligible, while the latter continues to be the subject of controversy.

The significance of the primary parameters with the exception of the gravitational acceleration on pressure gradient is statistically confirmed through a multiple regression analysis of the stored data while the relative pipe wall roughness in circular tubes remained insignificant and was ignored in the following. The reasons for this may be attributed to a generally lesser influence in two phase flow [6], an uncontrolled variation of the initial smoothness and roughness during the experiments, which cause a comparatively inconsistent scatter of the data and too few systematic results in pipes with relatively high natural roughness during flow conditions in the range of single phase liquid Reynolds numbers in excess of 10^5. Only beyond this threshold is it to be expected that the influence of the increased friction significantly stands out against the inevitable scatter of the data taken in pipes intentionally designated as hydraulically smooth.

Other contributing microscopic factors on friction pressure drop are for instance inlet and test section length, wetting of the pipe walls, electrolytic properties and purity of the fluids, coalescence behaviour of the gas phase, minimum value of the ratio of bubble diameter to pipe diameter and degree of saturation of the liquid with gas. However, their influence on pressure drop generally is not quantitable or declared in the literature and must therefore be discarded.

In accordance with the results of the regression analysis all the primary parameters were included in the new correlations. The concentration into dimensionless ratios and numbers followed experience with previous investigations [7, 8, 9, 10] yielding a two phase friction multiplier as function of density and viscosity ratio, mass flow quality, Reynolds, Froude and Weber number. With respect to the definition of the latter numbers, the density and viscosity of the gas or liquid phase or of two phase fluid properties may be employed. The optimisation of the correlations revealed that the use of the single phase liquid or two phase properties, according to

$$1/\varrho_{2\,ph} = x^*/\varrho_G + (1 - x^*)/\varrho_l \text{ and } 1/\eta_{2\,ph} = x^*/\eta_G + (1 - x^*)/\eta_l,$$

practically gives equivalent accurate overall results. Indeed, these correlations only based on liquid properties exhibit lower relative standard deviations, reproducing the data slightly better in the range of low two phase friction multipliers. Regarding the distribution of the data considered, this corresponds with low mass flow qualities and with a region where quite correctly the influence of the liquid phase on two phase behaviour predominates. Those relationships in connection with two phase fluid properties predict more precisely beyond this range, giving slightly lower absolute standard deviations with the same data. The latter assignment of the properties to the dimensionless numbers is prefered due to a better balance of the predictive accuracy. For the sake of completeness and ease of derivation of scaling factors the other (equivalent) correlations are included in the Appendix.

The combination of the characteristic numbers to a dimensionless power correlation was attempted in a way whereby in every case it complies with the theoretical limits of single phase

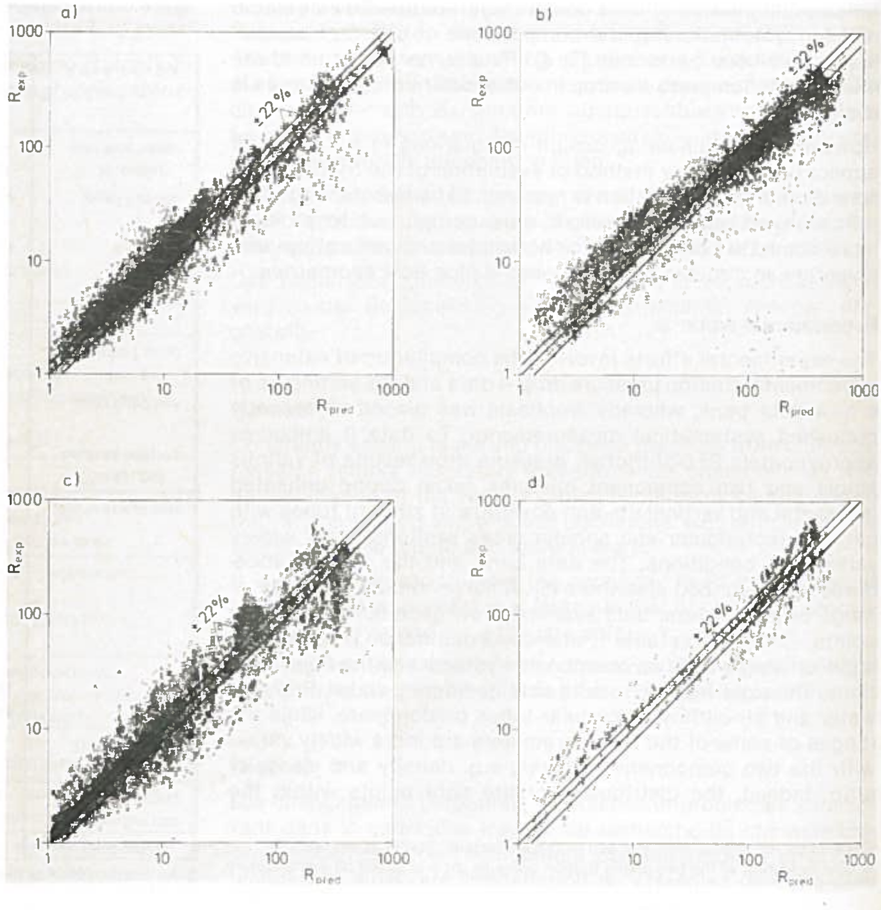

Fig. 1:
Predictive accuracy of Chisholm correlation
a) single component horizontal and vertical upflow
b) two component vertical upflow
c) two component horizontal flow
d) single and two component downflow

Bild 1:
Aussagegenauigkeit der Chisholmschen Korrelation
a) waagerechte und senkrechte Einstoffströmung nach oben
b) senkrechte Zweistoffströmung nach oben
c) waagerechte Zweistoffströmung
d) Ein- und Zweistoffströmung nach unten

Fig. 1:
Précision de la corrélation de Chisholm
a) flux à un composant horizontal et vertical ascendant
b) flux à deux composants vertical ascendant
c) flux à deux composants horizontal
d) flux à un et à deux composants ascendant

liquid and gas flow, when quality vanishes or tends toward unity. Furthermore the multiplier arrives at unity when critical pressure in single component mixtures is attained. However, no universal statements about friction are possible with the correlations put forward, when intentionally the fluid properties in two component mixtures harmonize, since quality doesn't simultaneously disappear or lose its meaning, or when so called homogeneous flow occurs. This fictitious condition mainly is attributed to the flow of mixtures with sufficiently high but not necessarily critical mass flow rates, at very low and high mass flow qualities and/or in small tubes, the (hydraulic) diameter of which appreciable exceeds the maximum bubble diameter. Beyond this it is treated as a reference condition, though the evaluation of the accompanying pressure drop is not clear. This is due to the fact that a variety of equivalent but in parts physically meaningless averaging procedures for density and viscosity are encountered, leading to quite different and partly inconsistent results, thus making this model questionable.

Apparently every intelligent optimisation of a relationship always leads to a better reproduction of the used data than any other correlation not derived from these. Thereupon the risk exists that after the addition of a substantial amount of new data the relationship just optimised fails to correctly predict, when exposed to them, since there has been no possibility to test it by extrapolation to other data. In view of this and of computer time savings, the correlations hereafter are based solely on about a third of the total available data. In the case of horizontal and vertical upflow they only rely on single component data, while in downflow conditions measurements with single and two component mixtures were considered.

After allowance for all the above conditions the new dimensionless power relationships for friction pressure drop in unheated straight tubes with circular, rectangular and annular cross section were developed, for horizontal and vertical upflow to

$$R = A + 3{,}21x^{*\,0{,}78}\left(1 - x^*\right)^{0{,}224}\left(\frac{\varrho_l}{\varrho_G}\right)^{0{,}91}\left(\frac{\eta_G}{\eta_l}\right)^{0{,}19}\left(1 - \frac{\eta_G}{\eta_l}\right)^{0{,}7} \Big/ \left(Fr_{2ph}^{0{,}0454}\; We_{2ph}^{0{,}035}\right)$$

and for vertical downflow to

$$R = A + 48{,}6x^{*0{,}8}\left(1 - x^*\right)^{0{,}29}\left(\frac{\varrho_l}{\varrho_G}\right)^{0{,}90}\left(\frac{\eta_G}{\eta_l}\right)^{0{,}73}\left(1 - \frac{\eta_G}{\eta_L}\right)^{7{,}4} \cdot Fr_{2ph}^{0{,}03} \Big/ We_{2ph}^{0{,}12}$$

with

$$A = (1 - x^*)^2 + x^{*2}(\varrho_l\,\zeta_G/\varrho_G\,\zeta_l)^{3)} \text{ and } R = (\Delta p/\Delta l)_{2ph} \Big/ (\Delta p/\Delta l)^{3)}_{1ph,l} ,$$

whereby without loss of accuracy in both situations the Reynolds number could for simplification be neglected.

The particular approach used was based on the method of least squares. In the case of horizontal and vertical upflow it yielded practically identical relations between the multiplier and the dimensionless ratios and numbers so that it was decided to lump them together. The only relatively small differences are probably associated with the measurements which were chiefly carried out in vertical and horizontal conduits with comparatively small diameters at mainly intermediate and high mass flow rates or velocities. With these flow conditions the turbulent inertia forces predominate over the gravity and shear for-

[3] Further details on the definitions of single phase friction coefficients, hydraulic diameter, dimensionless numbers etc. are included in the Appendix.

[4] Strictly speaking the CISE-correlation is an exception since it is based on an energy balance of the flow instead of the usual momentum balance. Nevertheless it has its merits and proved to be among the most accurate friction correlations [2]. The predictive accuracy of the recently proposed CISE DIF-3 correlation [17] in comparison to DIF-2 is practically identical with this data material in hand.

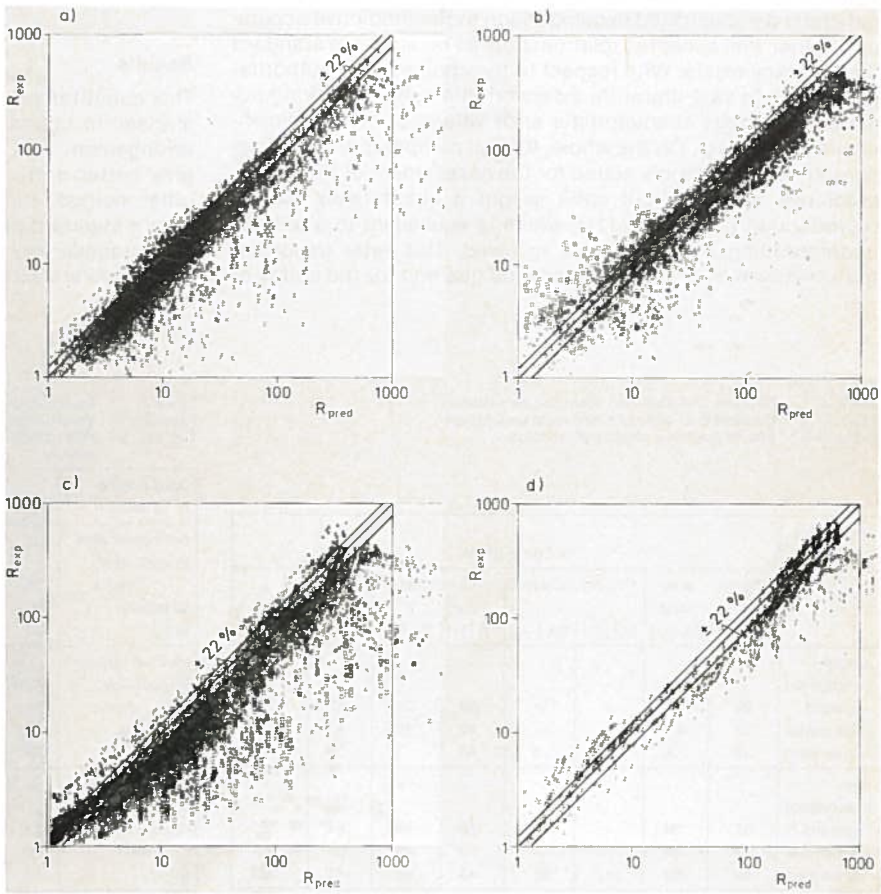

Fig. 2:
Predictive accuracy of CISE DiF-2 correlation
a) single component horizontal and vertical upflow
b) two component vertical upflow
c) two component horizontal flow
d) single and two component downflow

Bild 2:
Aussagegenauigkeit der Korrelation CISE DIF-2
a) waagerechte und senkrechte Einstoffströmung nach oben
b) senkrechte Zweistoffströmung nach oben
c) waagerechte Zweistoffströmung
d) Ein- und Zweistoffströmung nach unten

Fig. 2:
Précision de la corrélation CISE DiF-2
a) flux à un composant horizontal et vertical ascendant
b) flux à deux composants vertical ascendant
c) flux à deux composants horizontal
d) flux à un et deux composants ascendant

Table 2: System parameters and boundaries
Tafel 2: Systemparameter und -grenzen
Tableau 2: Paramètre et limites du système

Correlation	System parameters						Borders	
	x^*	ϱ_l/ϱ_G	m^*	η_l/η_G	d	σ	$\Delta p_{1ph,l}$	$\Delta p_{1ph,G}$
Chisholm	x	x	(x)[1]	x	—	—	x	(x)[2]
CISE	x	(x)[1]	x	x	x	x	x	(x)[2]
Friedel	x	x	x	x	x	x	x	x

[1]) Only included in certain parameter ranges
[2]) Only approximately attained

ces and hence the contributions of different phase configurations to the pressure drop due to deviating pipe orientations and distinctive flow cross sections are either nonpresent or vanish within the scatter of the data.

When comparing the constants and the power of the independent variables rather than of the dimensionless groups in the two correlations, the only significant difference is made up by the coefficients. It has an increased value for downflow conditions causing a comparatively higher pressure drop ratio at identical flow conditions. Actually this qualitative result corresponds to the greater void fractions or smaller slip ratios encountered in this flow direction. Indeed, the influence of mass flow rate, diameter, quality and fluid properties on pressure drop doesn't differ by much.

With increasing mass flow quality and the remaining variables fixed, the two phase friction pressure drop and two phase friction multiplier exhibit at about 70 to 80 % a more or less distinct maximum depending mainly on density ratio (pressure) and mass flow rate. This characteristic feature also is fulfilled in a limited manner by the correlations put forward, indicating also in this way a qualitative correct understanding of the data.

Characterization of the predictive accuracy

The efficiency of a newly proposed semiempirical correlation is generally demonstrated in comparison to the predictive accuracy of other well accepted relationships as no absolute standard for accuracy exists. With respect to the choice of the authoritative criteria a vast literature exists on this subject offering numerous different characteristic error values or similar dimensionless numbers. On the whole, if at all comparable and representative, they are only suited for the assessment of the overall predictive accuracy, but can't weight a qualitatively correct reproduction of the data [11], which is equivalent to a reliable understanding of the physics involved. This later important feature however, is the condition sine qua non for the ability of the correlation to an at least moderate extrapolation to flow situations within and outside the parameter ranges of the employed data.

In this investigation, the predictive accuracy of the correlations is evaluated on the basis of the up to now unusual combination of relative and absolute standard deviation around a theoretical arithmetic mean of zero, since these seem to be the best generally valid and convenient measure of the overall reproduction of the data with an average minimum relative and absolute error. The formation of the standard deviations is supplementarily explained by the distribution functions of the relative and absolute deviations, giving the number of data points predicted within given error limits. In this way it can be approximately judged whether the summation of many small and some extremely high errors or of a more balanced distribution has made up the standard deviations. The former partitioning herewith gives a first hint of a comparatively qualitative incorrect reproduction. Finally, an inspection of the plots of experimental versus two phase friction multiplier completes the assessment, inevitably introducing at the same time a subjective evaluation. However, an objective and quantitative measure doesn't seem to exist.

With respect to the extreme parameter ranges of the data in hand and to the distribution of the measurements over the total quality region, a fair comparison and assessment of the predictive accuracy of the correlations is only successful, if all relationships incorporate the primary parameters on the whole or at least identical system variables and furthermore the theoretical borders of single phase liquid and gas flow. Regarding the parameters of the proposed relationships, this former condition cannot even be met by the most accepted or best relationships available (table 2). The Chisholm [12] correlation never considers the influence of diameter and surface tension, while the power of mass flow rate and density ratio on pressure drop are only included in the relationships of Chisholm and CISE (DiF-2) [13] respectively within certain parameter borders. This drawback may in part be the source of the latter shortcoming of the rival correlations when predicting certain data.

Results

The quantitative results of the statistical analysis are summarised in tables 3 through 7. First of all it follows from the arrangement that in all situations the proposed correlations give better and more balanced overall predictions than the other methods including at the same time low relative and absolute standard deviations. The differences are in some specific instances very dramatic, particularly the absolute standard deviations are exceedingly high with the CISE correlation. In ge-

Table 3: Relative and absolute standard deviations
Tafel 3: Relative und absolute Normalabweichungen
Tableau 3: Écarts normaux relatifs et absolus

Fluid systems	Correlations							
	Friedel upw. horiz.		Friedel downw.		Chisholm		DiF-2	
	S_R [%]	S_A [—]	S_R [%]	S_A [—]	S_R [%]	S_A [—]	S_R [%]	S_A [—]
single component								
upward	26	16	—	—	39	21	27	46
horizontal	32	41	—	—	40	65	47	2405
downward	25	3	17	3	46	3	18	3
two component								
upward	52	39	—	—	176	40	61	185
horizontal	43	34	—	—	59	65	51	969
downward	54	102	40	86	48	95	41	225

Table 4: Distribution function of relative deviations for single component data
Tafel 4: Verteilungsfunktion von relativen Abweichungen für Einstoffdaten
Tableau 4: Répartition des fréquences d'écarts relatifs pour mélanges à un composant

Data points in % within	Relative deviations in % ± 10	± 20	± 30	± 40	± 50	± 60	± 70	± 80	± 90	± 100
horizontal flow										
Friedel upw. horiz.	38	67	83	92	95	97	98	99	99	100
Chisholm	32	55	72	82	88	92	94	96	96	97
DiF-2	33	60	78	88	93	96	98	99	99	100
vertical upflow										
Friedel upw. horiz.	24	46	66	81	90	94	97	98	99	100
Chisholm	19	35	52	77	79	87	93	96	99	99
DiF-2	20	39	51	60	69	77	83	88	93	100
vertical down flow										
Friedel downw.	32	80	94	100						
Chisholm	12	25	43	56	71	91	97	97	97	97
DiF-2	40	85	94	97	99	100				

neral, all correlations predict pressure drop comparatively more accurate during single component flow than with two component mixtures. Indeed, in single component systems upward and downward flow data are relatively more precisely reproduced, while the predictive accuracy is better during horizontal two component flow. This peculiar trend only coincides with the number of data considered, when the single component downward measurements are disregarded, suggesting the general need for requisition of as much data as possible.

The distribution functions in tables 4 through 7 reveal that a comparatively better allotment of the relative and absolute errors or deviations results from the new correlations, in particular the high relative and absolute errors governing the standard deviations are encountered to a lesser extent, indicating a better overall qualitative reproduction and comprehension of the data.

The inspection of figure 1 through 3, displaying graphs of measured versus predicted two phase friction multiplier, illustrates the differences and improvements. Herewith the degree of correlation of the data by each relationship is assumed to be characterised by the proximity of the data points to the 45° line. Additionally the limits of a relative error of 22 % have been indicated to aid in making qualitative comparisons between the correlations. Evidently the more precise reproduction by the advocated correlations on the basis of the standard deviations also conforms with a better understanding of the measurements. Particularly over the full range the data generally are more evenly reproduced and tiny conservative predictions are associated only with some high two phase multipliers. However, there remains an irreducible scatter within the predictions of some two component data. Careful examination of these data on the basis of over twenty pressure drop correlations confirmed that these must be attributed to unavoidable incorrect data as a whole or to measurements incorporating partially inconsistent tendencies of only some variables on pressure drop,

Table 5: Distribution function of relative deviations for two component data
Tafel 5: Verteilungsfunktion von relativen Abweichungen für Zweistoffdaten
Tableau 5: Répartition des fréquences et écarts relatifs pour mélanges à deux composants

Data points in % within	Relative deviations in % ± 10	± 20	± 30	± 40	± 50	± 60	± 70	± 80	± 90	± 100
horizontal flow										
Friedel upw. horiz.	21	39	55	68	78	85	89	93	96	99
Chisholm	24	41	55	65	73	81	86	90	92	93
DiF-2	12	23	35	48	61	72	82	88	95	99
vertical upflow										
Friedel upw. horiz.	15	32	51	66	75	81	85	88	91	93¹)
Chisholm	29	47	60	69	74	78	80	83	85	87
DiF-2	14	30	53	70	81	88	92	95	97	98¹)
vertical downflow										
Friedel downw.	18	36	50	63	78	87	94	97	99	99
Chisholm	22	39	51	62	74	85	91	94	96	96
DiF-2	17	33	52	69	79	87	92	96	98	98

¹) The DiF-2 correlation in comparison to Friedel predicts higher errors beyond this error range, these altogether yield greater relative standard deviations.

especially of diameter, surface tension and mass flow rate, whereas there is no question of flow pattern being the source of this considerable spread [14].

It should be stressed that the optimisation of the correlations was only effected with about a third of the respective available data, but they successfully perform when extrapolated. In particular the correlation for horizontal and vertical upflow, based only on single component data, shows in two component systems an exceptionally good centering of the predictions (mean percentage error < 3 %), augmenting in this way the confidence to the approach used and to the ability of the correlations when extrapolating.

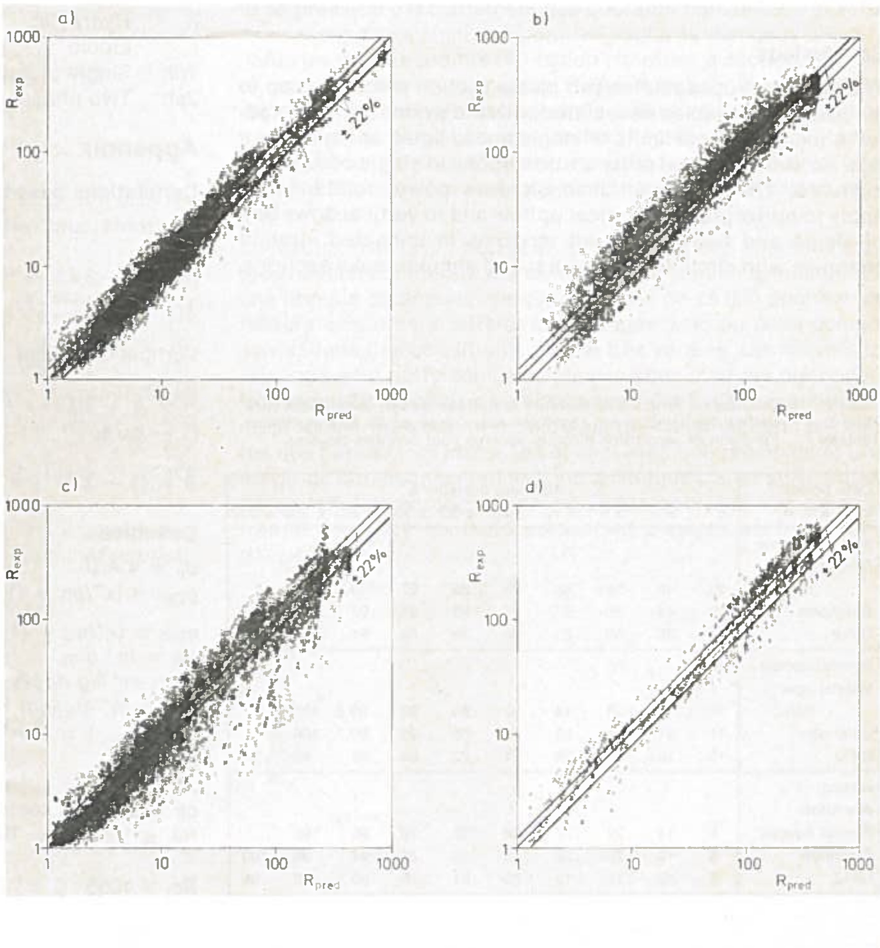

Fig. 3:
Predictive accuracy of Friedel correlations
a) single component horizontal and vertical upflow
b) two component vertical upflow
c) two component horizontal flow
d) single and two component downflow

Bild 3:
Aussagegenauigkeit der Friedelschen Korrelationen
a) waagerechte und senkrechte Einstoffströmung
b) senkrechte Zweistoffströmung
c) waagerechte Zweistoffströmung
d) Ein- und Zweistoffströmung nach unten

Fig. 3:
Précision de la corrélation de Friedel
a) flux à un composant horizontal de Friedel
b) flux à deux composants vertical
c) flux à deux composants horizontal
d) flux à un et deux composants ascendants

Table 6: Distribution function of absolute deviations for single component data
Tafel 6: Verteilungsfunktion von absoluten Abweichungen für Einstoffdaten
Tableau 6: Répartition des fréquences d'écarts absolus pour mélanges à un composant

Data points in % within	± 1	± 2	± 5	± 10	± 20	± 50	± 100	± 200	± 350	± 500
horizontal flow										
Friedel upw. horiz.	18	35	50	62	77	90	96	99	100	
Chisholm	15	29	45	56	67	82	91	98	99	100
DIF-2	13	25	41	51	62	76	85	89	90	92
vertical upflow										
Friedel upw. horiz.	35	67	80	95	97	99	100			
Chisholm	31	62	82	93	97	98	99	100		
DIF-2	33	64	86	92	95	96	97	99	99	100
vertical downflow										
Friedel downw.	49	77	93	99	100					
Chisholm	14	27	96	100						
DIF-2	36	75	91	99	100					

The proposed correlations with practically the same accuracy apply to the evaluation of pressure drop in conduits with different flow cross sections. They produce under identical operation conditions equal multipliers, when the hydraulic diameters coincide and the two phase friction pressure drop are related to the single phase liquid friction pressure drop according to the particular flow geometry. This conformity may be a sign that the contribution of the wall surfaces or wall friction respectively to the total momentum exchange or friction pressure drop at least in the first instance is covered by the concept of two phase friction multiplier. The prediction of friction pressure drop in pipes with complex flow cross sections, as in tube bundle heat exchangers or in rod bundle geometries, within the range of application therefore should be possible, whereby an accuracy sufficient for technical purposes is maintained.

Conclusions

The approach used relates two phase friction pressure drop to all essential variables associated with the system and incorporates the theoretical limits of single phase liquid and gas/vapor flow as well as critical pressure conditions in single component mixtures. The proposed dimensionless power relationships apply to horizontal and vertical upflow and to vertical downflow of single and two component mixtures in unheated straight channels with circular, rectangular and annular cross sections.

Table 7: Distribution function of absolute deviations for two component data
Tafel 7: Verteilungsfunktion von absoluten Abweichungen für Zweistoffdaten
Tableau 7: Fonction de répartition d'écarts absolus pour données binaires

Data points in % within	± 1	± 2	± 5	± 10	± 20	± 50	± 100	± 200	± 350	± 500
horizontal flow										
Friedel upw. horiz.	23	43	56	66	75	88	97	100		
Chisholm	23	44	58	67	75	85	91	97	98	100
DIF-2	12	25	39	51	63	76	85	91	94	96
vertical upflow										
Friedel upw. horiz.	10	18	31	44	62	88	96	99,8	100	
Chisholm	11	21	36	53	72	88	96	99,7	100	
DIF-2	10	18	29	39	51	72	84	92	96	98
vertical downflow										
Friedel downw.	8	14	22	27	36	56	79	96	100	
Chisholm	6	13	23	32	40	56	76	94	96	100
DIF-2	6	10	15	19	28	51	75	90	93	96

The superior predictive accuracy and reliability are demonstrated in comparison to other commonly accepted and recommended methods using various characteristic error criteria and a new data bank, which at present embodies about 25 000 friction pressure drop measurements of several single and two component mixtures taken under widely varied test conditions. The correlations now allow a reproduction of the experimental results within the investigated range with an acceptable accuracy and certainty, which suffices for technical purposes. Moderate and adequate extrapolations beyond the scope of the data used and to conduits with other flow geometries therefore are anticipated.

Nomenclature

A	Cross flow area
d	(Hydraulic) diameter
f	Degree of freedom
Fr	Froude number
g	Gravitational acceleration
Δl	Pipe length incremental
m^*	Total mass flow rate
n	Number of data points
Δp	Friction pressure drop
R	Two phase friction multiplier
Re	Reynolds number
s/w	Aspect ratio
U	Wetted perimeter
We	Weber number
x^*	Mass flow quality
ζ	Single phase friction coefficient
η	Dynamic viscosity
ϱ	Density
σ	Surface tension

Indices

a	Outer
i	Inner
G	Gas
h	Hydraulic
l	Liquid
1ph	Single phase
2ph	Two phase

Appendix

Correlations based on single phase liquid properties

Horizontal and vertical upflow

$$R = A + 3{,}43 \cdot x^{*0{,}685} (1 - x^*)^{0{,}24} (\varrho_l/\varrho_G)^{0{,}8} (\eta_G/\eta_l)^{0{,}22} (1 - \eta_G/\eta_l)^{0{,}89} \cdot Fr_l^{-0{,}047} \cdot We_l^{-0{,}0334}$$

Vertical downflow

$$R = A + 38{,}5 \cdot x^{*0{,}76} (1 - x^*)^{0{,}314} (\varrho_l/\varrho_G)^{0{,}86} (\eta_G/\eta_l)^{0{,}73} (1 - \eta_G/\eta_l)^{6{,}84} \cdot Fr_l^{-0{,}0001} \cdot We_l^{-0{,}087}$$

$$A = (1 - x^*)^2 + x^{*2} (\varrho_l \zeta_G/(\varrho_G \zeta_l))$$

Definitions

$$d_h = 4\,A/U$$
$$\varrho_{2ph} = (x^*/\varrho_G + (1 - x^*)/\varrho_l)^{-1},\; x^* = m^*_G/(m^*_G + m^*_l)$$
$$\eta_{2ph} = (x^*/\eta_G + (1 - x^*)/\eta_l)^{-1}$$
$$Re = m^*\, d/\eta_l$$
$$Fr = m^{*2}/(g\, d_h\, \varrho^2)$$
$$We = m^{*2} d_h/(\varrho\sigma)\quad We = m^{*2} d_h/(\varrho\sigma)$$
$$(\Delta p/\Delta_l)_{1ph,\, l} = \zeta_l\, m^{*2}/(2\, d_h\, \varrho_l)$$
$$j = G, l$$

circular cross sections:

$$Re_j \leqq 1055 : \zeta_j = 64/Re_j$$

$$Re_j > 1055 : \zeta_j = \{ 0{,}86859 \ln [Re_j/1{,}964 \ln Re_j - 3{,}8215] \}^{-2}$$

rectangular cross sections [15]:

$$Re^*_j = \psi Re_j,\ \psi = 2/3 + 11/24 \cdot s/w\,(2 - s/w),\ s \leqq w$$

$$\left.\begin{array}{l} Re^*_j \leqq 1055 \\ Re^*_j > 1055 \end{array}\right\} \zeta \text{ as above with } Re^*_j \text{ instead } Re_j$$

annular cross sections [16]:

$$Re_j \leqq 1055 : \zeta_j = 64/Re_j$$
$$Re_j > 1055 : \zeta_j = (2\,\lg_{10}(Re_j \sqrt{\zeta_j}) - E)^{-2}$$

d_i/d_a	0	0,05	0,3	0,6	1,0
E	0,8	0,932	0,961	0,968	0,97

Relative error or deviation:

$$x_i = (R_{i\,exp} - R_{i\,pred})/R_{i\,pred}$$

Absolute error:

$$z_i = R_{i\,exp} - R_{i\,pred}$$

Relative standard deviation:

$$s_R = \sqrt{\sum_{i=1}^{n} x_i^2/(n - f - 1)}$$

Absolute standard deviation:

$$s_A = \sqrt{\sum_{i=1}^{n} z_i^2/(n - f - 1)}$$

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Summary

New dimensionless friction pressure drop correlations are advocated both for horizontal and vertical upflow and for vertical downflow in unheated straight channels with circular, rectangular and annular cross sections. They incorporate all essentialvariables of the two phase flow as parameters and include the theoretical boundaries of single phase liquid and gas-vapor flow and of critical pressure conditions in single component mixtures.

The predictive accuracy and the improvements are demonstrated in comparison to rival methods using various characteristic error criteria and a new data bank, which at present embodies about 25 000 friction pressure drop measurements of various single and two component mixtures taken under widely varied test condititons. The proposed correlations are evidently better than other commonly accepted and recommended methods. They now allow a reproduction of the experimental results within the investigated range with an acceptable accuracy and reliability, which suffices for technical purposes. It is anticipated that moderate and adequate extrapolations beyond the scope of the data used and to conduits with other flow geometries are possible.

Zusammenfassung

Es werden neue dimensionslose Reibungsdruckabfallbeziehungen für die horizontale und vertikal aufwärtsgerichtete sowie für die vertikal abwärtsgerichtete Strömung in unbeheizten geraden Rohren mit kreisrunden, rechteckigen und kreisringförmigen Strömungsquerschnitten vorgestellt. Sie beinhalten alle wesentlichen Einflußgrößen der Zweiphasenströmung als Parameter und schließen die theoretischen Grenzfälle einer reinen Flüssigkeits- und einer reinen Gas-Dampf-Strömung sowie einer Einkomponenten-Zweiphasenströmung bei kritischem Druck ein.

Die Vorhersagegenauigkeit und die erzielten Verbesserungen werden im Vergleich zu anderen Beziehungen dargestellt anhand einer Datenbank mit insgesamt über 25 000 Meßdaten von verschiedenen Ein- und Zweikomponentengemischen in sehr weiten Versuchsbedingungen. Die neuen Beziehungen sind merklich genauer als andere häufig verwendete und empfohlene Methoden. Sie gestatten nunmehr eine Vorausberechnung innerhalb der angegebenen Parametergrenzen mit einer für technische Zwecke ausreichenden Genauigkeit und Zuverlässigkeit. Maßvolle Extrapolationen auf andere Parameterbereiche und auf Rohre mit anderen Strömungsquerschnitten werden daher möglich sein.

Résumé

On présente de nouvelles relations sans dimension pour la chute de pression par frottement des courants horizontaux et verticaux ascendants ainsi que pour les courants verticaux descendants dans des conduits droits non chauffés, à section circulaire, rectangulaire ou annulaire. Elles comprennent toutes les principales grandeurs des courants à deux phases en tant que paramètres ainsi que les cas limites théoriques d'un courant à phase unique liquide ou gaz/vapeur et d'un courant à deux phases et composant unique, aux conditions d'une pression critique.

La précision de la prédiction et les améliorations obtenues sont prouvées en comparant à d'autres relations et en se basant sur une banque de donnés comprenant plus de 25 000 données de mesure concernant différents mélanges à un ou deux composants, dans des conditions d'essai très variées. Les nouvelles-relations sont nettement plus précises que d'autres méthodes-fréquemment appliquées et recommandées. Elles permettent de procéder maintenant à un calcul prèvisionnel dans les limites des paramètres indiquées et ceci avec une précision et une certitude qui, pour les utilisations techniques, sont suffisantes. De ce fait, les extrapolations modérées pour d'autres paramètres et pour des conduits présentant d'autres sections sond possible.