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AN ASSESSMENT OF VOID FRACTION CORRELATIONS FOR VERTICAL UPWARD STEAM-WATER FLOW

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60 Abstract :

An assessment of sixteen void fraction correlations have been carried out using experimental void fraction data compiled from open literature for vertical upward steam-water flow. Nearly 80% of all the data pertained to natural circulation flow.This assessment showed that best prediction is obtained by Chexal et al. (1996) correlation followed by Hughmark (1965) and the Mochizuki and Ishii (1992) correlations. The Mochizuki-Ishii correlation is found to satisfy all the three limiting conditions whereas Chexal et al. (1996) correlation satisfies all the limiting conditions at moderately high mass fluxes (greater than 140 kg/m^{2}s) while Hughmark correlation satisfies only one of the three limiting conditions. The available void fraction data in the open literature for steam-water two-phase flow lies predominantly in the low quality region. This is the reason why correlations like Hughmark which do not satisfy the upper limiting condition (i.e. at $x=1$, $\alpha=1$) perform rather well in assessments. Additional work is required for the generation of high quality (greater than 40%) void fraction data.

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CONTENTS

ABSTRACT

An assessment of sixteen void fraction correlations have been carried out using 3292 experimental void fraction data compiled from open literature for vertical upward steam-water flow. The geometry of the test section to which the data belong is either pipes, rectangular channels or annuli. Nearly 80% of all the data pertained to natural circulation flow. This assessment showed that the best prediction is obtained by Chexal et al. (1996) correlation followed by Hughmark (1965) and Mochizuki-Ishii (1992) correlations.

Void fraction correlations must satisfy the following limiting conditions:

(1) For single-phase liquid, the void fraction must be zero,

(2) For single-phase vapour, the void fraction must be unity and

(3) At critical pressure, the void fraction must be equal to the mass fraction of the vapour.

The different correlations were examined to ascertain whether they satisfy the limiting conditions. This exercise showed that the Mochizuki-Ishii correlation satisfies all the three limiting conditions whereas Chexal et al. (1996) correlation satisfies all the limiting conditions at moderately high mass fluxes (greater than 140 kg/m^2s) while Hughmark correlation satisfies only one of the three limiting conditions.

The available void fraction data in the open literature for steam-water two-phase flow lies predominantly in the low quality region. This is the reason why correlations like Hughmark which do not satisfy the upper limiting condition (i.e. at $x=1$, $\alpha=1$) perform rather well in assessments. Additional work is required for the generation of high quality (greater than 40%) void fraction data.

1. INTRODUCTION

Void fraction plays an important role in the calculation of many thermahydraulic parameters. Typical examples are two-phase pressure drop calculations, coupled neutronic-thermalhydraulic calculations for nuclear reactor core, determination of flow patterns in two-phase flows, etc. All the four components of pressure drop (viz., distributed and local friction, acceleration and elevation) directly or indirectly depend on the void fraction. For certain situations of practical interest, accurate prediction of each component rather than the total pressure drop is required. For example, steady state flow prevails in a natural circulation loop when the driving pressure differential due to buoyancy (i.e. the elevation pressure drop) balances the opposing pressure differential due to friction and acceleration. For natural circulation loops, therefore, the largest contribution to pressure drop arises from the elevation pressure drop. Also, the acceleration pressure drop can be 10-15% of the total core pressure drop. Therefore, accurate estimation of each component of pressure drop is required for the calculation of natural circulation flow rate. Hence, it is very important to have a reliable relationship for the mean void fraction. Significant deviations are observed in the predicted flow rate using different models for void fraction.

In many experiments with diabatic vertical test sections, the two-phase friction pressure gradient is obtained as shown below:

$$\left(\frac{dP}{dz}\right)_{TPF} = \left(\frac{dp}{dz}\right)_m - g\left(\frac{\alpha}{v_G} + \frac{1-\alpha}{v_L}\right) - G^2 \frac{d}{dz}\left(\frac{x^2}{\alpha} v_G + \frac{(1-x)^2}{1-\alpha} v_L\right) \quad (1)$$

where $(dp/dz)_m$ is the measured pressure drop. It is observed from the above equation that the void fraction, α, and quality, x, play an important role in deducing the frictional term from the measured static pressure drops. Usually, the acceleration and elevation drops are calculated with the help of a void fraction value, which may not be measured but calculated by a correlation.

The stability predictions of natural circulation loops are also strongly influenced by the mean void fraction model. In coupled neutronic thermalhydraulic calculations, the void fraction plays an important role in the calculation of reactor power (Saphier and Grimm (1992)). For such calculations, it is essential to use the best model for the void fraction. Hence, it is necessary to make an assessment of the void fraction correlations. Some of the commonly used void fraction correlations are described briefly in the following section.

2. VOID FRACTION CORRELATIONS

Due to its importance in thermalhydraulic calculations, several correlations are proposed by different authors. In general, the void fraction correlations can be grouped into three; viz.,

(a) slip ratio models,
(b) Kβ models and

(c) drift flux models

In addition, there are some empirical correlations, which do not fall in any of the three categories. These are grouped under miscellaneous empirical correlations. Some of the commonly used correlations in all the above categories are described below.

2.1 Slip Ratio Models

The general expression for the void fraction, α, can be written as

$$\alpha = \frac{1}{1+\frac{1-x}{x} S \frac{\rho_G}{\rho_L}} \tag{2}$$

where S is the slip ratio ($=u_G/u_L$). The slip ratio models essentially specify an empirical equation for the slip ratio, S. The void fraction can, then be calculated by the equation given above. For homogeneous flow, $u_G=u_L$ and S=1. At high pressure and high mass flow rates the void fraction approaches that of homogeneous flow, and can be calculated by setting S = 1 in the above equation. But usually, the slip ratio is more than unity for both horizontal and vertical flows. For vertical upward flows, the buoyancy also assists in maintaining S>1. The common slip ratio models are given in Appendix-1.

2.2 Kβ Models

These models calculate α by multiplying the homogeneous void fraction, β, by a constant K. Well-known models in this category are due to Armand (1947), Bankoff (1960) and Hughmark (1961) which are given in Appendix-2.

2.3 Correlations Based on the Drift flux Model

By far the largest number of correlations for void fraction reported in the literature are based on the drift flux model. The general drift flux formula for void fraction can be expressed as

$$\alpha = \frac{j_G}{C_0[j_G + j_L] + U_{GU}} \tag{3}$$

where U_{GU} is the drift velocity ($=u_G$-j, where j is the mixture superficial velocity) and for homogeneous flow $C_0 = 1$ and $U_{GU} = 0$. The various models (see Appendix-3) in this category differ only in the expressions used for C_0 and U_{GU} which are empirical in nature.

The Chexal et al (1996) correlation is applicable over a wide range of parameters and can tackle both co-current and counter-current steam-water, air-water and refrigerant two-phase flows. The 1992 version of this correlation is used in RELAP5 (The RELAP5 Development

Team (1995)) and RETRAN (Mcfadden et al. (1992)) codes. The correlation applicable for steam-water flow only is reproduced from Chexal et al. (1996) in Appendix-3.

2.4 Miscellaneous Correlations

There are a few empirical correlations which do not belong to the three categories discussed above. Some of the more common ones are given in Appendix-4.

Significant differences exist between the void fraction values obtained using different correlations. This necessitates a thorough assessment of the void fraction correlations.

3. REVIEW OF PREVIOUS ASSESSMENTS

The reported assessments of void fraction correlations are due to Dukler et al. (1964), Friedel (1980) and Diener and Friedel (1994). Dukler et al. (1964) compared three holdup (i.e. $1-\alpha$) correlations, viz., Hoogendoorn (1959), Hughmark (1965) and Lockhart-Martinelli (1949). Hughmark correlation was found to give the best agreement with data.

Friedel (1980) compared 18 different correlations for mean void fraction using a data bank having 9009 measurements of void fraction in circular and rectangular channels by 39 different authors. In his assessment no distinction was made as to whether the correlations were derived for horizontal or vertical two-phase flow. The mean void fraction correlation of Hughmark (1962) and Rouhani (I and II) (1969) were found to reproduce the experimental results considerably better than the other relationships, regardless of the fluid and flow directions. However, Rouhani equation II was found to reproduce the measured values more uniformly over the whole range of mean density. Hence, Friedel recommends Rouhani II relationship.

Diener and Friedel (1994) made an assessment of mean (cross sectional average) void fraction correlations using about 24000 data points. The data consists of single-component (mostly water & refrigerant 12) and two-component systems (mostly air-water). In this assessment, they had compiled 26 most often used and cited correlations. These correlations were then checked for the limiting conditions (i.e. zero and unity value of void fraction for single-phase liquid ($x=0$) and single-phase vapor ($x=1$)). Only 13 correlations were found to fulfill the limiting conditions and were selected for further assessment. In this assessment they have not differentiated the data on the basis of flow direction, although, in vertical upward flow the mean void fraction is expected to be lower than in case of horizontal flow under identical conditions (due to larger velocities caused by buoyancy effect). Most of the void fraction correlations reproduce the data with a rather acceptable accuracy. The three best correlations in the order of decreasing prediction accuracy are listed in Table-1 for various fluid conditions.

Table-1: Void fraction correlations recommended by Diener & Friedel (1994)

Fluid	Total number of Data points	Recommended Correlation
Water/air mixture	10991	Rouhani I, Rouhani II, HTFS-Alpha[@]
1-component mixtures	9827	HTFS-Alpha, HTFS[@], Rouhani II
2-component mixtures	14521	HTFS-Alpha, Rouhani I, Rouhani II
2-component mixtures with G > 100 kg/m^2s	11394	Rouhani II, Rouhani I, HTFS

@ - proprietary correlations belonging to HTFS.

4. ASSESSMENT PROCEDURE

An assessment of the void fraction correlations given in appendices 1 to 4 was carried out using a part of the void fraction data contained in the BARC -TPFDB (BARC-Two Phase Flow Data Bank). The data used for assessment pertains to vertical upward flow of steam water mixture in circular and rectangular channels. Table-2 shows the range of parameters applicable to the void fraction data in the data bank. The original references from which the data were compiled are shown in Table-3. The data used for the assessment was screened by deleting those data with predicted errors exceeding ± 100% by any of the four correlations (i.e., Chexal et. al, Rouhani, Mochizuki-Ishii). Number of data points deleted is about 2.7 % of the total data (3292 entries) in the original data bank. It is found that the erroneous data are not concentrated in a single data set but present in almost all the data sets used in this data bank.

Table 2: Range of parameters in the data bank

Parameter	Minimum	Maximum
Quality (%)	0.01	22
Mass-Flux (kg/m^2s)	125	2950
Hydraulic Diameter (mm)	10	38
Measured Void fraction (%)	40	90
Pressure (bar)	7	51

Table-3 : Details of steam-water void fraction data

Author (year)	Test section	Flow direction	adiabatic/ diabatic	Forced/ Natural	Fluid used	No. of Data pts.	Hydraulic-dia (mm)	Pressure range (MPa)	Mass Flux (kg/ m^2 s)	Quality range
Rouhani (1963)	P	V-U	diabatic	Forced	S-W	149	6.1	0.7-6.0	650-2050	0.0 0.38
Merchattere (1956)	RC	V-U	diabatic	natural	S-W	675	16.2	0.8-4.3	360-502	0.0 0.082
Cook et al. (1956)	RC	V-U	diabatic	natural	S-W	1077	19.9	4.2	173-457	0.0 0.141
Petrick (1962)	P	V-D	diabatic	forced	S-W	108	49.3	4.1-10.3	163-1256	0.0-0.11
Merchattere et al. (1960)	RC	V-U	diabatic	natural	S-W	292	11.3	1.12-423	490-1112	0.0-0.076
Merchattere et al. (1960)	RC	V-U	diabatic	forced	S-W	237	11.3	1.12-4.23	490-1455	0.0-0.065
Merchattere et al. (1960)	RC	V-U	diabatic	natural	S-W	567	20.3	1.12-4.23	289-744	0.0-0.076
Rouhani (1966)	A	V-U	diabatic	forced	S-W	535	13.0	1.0-5.0	650-1450	0.0-0.12

P - Pipe ; A - Annulus ; RC - rectangular channel ; RB - rod bundle ; V-U - vertical upward ;
V-D - vertical downward ; H - horizontal ; S-W - steam-water

The following correlations were assessed:

1. Chexal et. al (1996)
2. Rouhani (1969)
3. Zuber-Findlay (1965)
4. Bankoff-Jones (1962)
5. Dix (1971)
6. Homogeneous model
7. GE - Ramp (1970)
8. Nabizadeh (1977)
9. Bankoff - Malnes (1979)
10. Mochizuki-Ishii (1992)
11. Osmachkin (1970)
12. Armand (1947)
13. Bankoff (1960)
14. Thom (1964)

15. Hughmark (1965)
16. Martinelli-Nelson (1948)

The assessment was carried out by standard statistical procedure. The error (e_i), mean error ($\bar{e}$), mean of absolute error ($|\bar{e}|$), R.M.S. error (e_{rms}) and standard deviation (σ) are calculated as follows:

$$e_i = \left(\frac{\alpha_c - \alpha_m}{\alpha_m}\right) x100 \qquad (4)$$

$$\bar{e} = \frac{1}{N}\sum_{i=1}^{N} e_i \qquad (5)$$

$$|\bar{e}| = \frac{1}{N}\sum_{i=1}^{N} |e_i| \qquad (6)$$

$$e_{rms} = \left(\frac{\sum_{i=1}^{N} e_i^2}{N}\right)^{0.5} \qquad (7)$$

$$\sigma = \left(\frac{\sum_{i=1}^{N} (\bar{e} - e_i)^2}{N-1}\right)^{0.5} \qquad (8)$$

Where α_c and α_m refer to the calculated and measured values of the void fraction and N is the total number of data points.

5. RESULTS

The present assessment showed that Chexal et. al correlation performs better than other correlations. Clearly, all the statistical parameters considered above are minimum for this correlation, followed by Hughmark, Mochizuki-Ishii and Rouhani correlations (see table - 4). Previous assessments by Dukler et al. (1964) and Friedel (1980) have shown that the Hughmark correlation is the best. Assessment by Diener and Friedel (1994) have shown the Rouhani correlation to be among the best three correlations for predicting void fraction.

Table 4 : Comparison of various correlations

Correlation name	mean error, $\bar{e}$ - %	mean of absolute error, $\lvert\bar{e}\rvert$ - %	r. m. s. error e_{rms}, - %	standard deviation, σ - %
Chexal et. al	5.10	15.25	22.74	22.16
Hughmark	6.85	16.72	23.81	22.60
Mochizuki-Ishii	-5.44	18.13	24.19	23.58
Rouhani	10.76	18.42	25.97	23.64
Zuber-Findlay	11.20	19.32	26.15	23.64
Bankoff	9.08	19.21	26.58	24.98
Osmachkin	1.32	18.91	26.59	26.56
Bankoff-Jones	12.50	20.78	27.95	25.00
Thom	6.72	21.11	28.88	28.08
Nabizadeh	-21.17	24.40	30.00	21.35
Armand	21.54	27.75	34.75	27.27
GE-Ramp	27.30	32.60	39.10	28.08
Bankoff-Malnes	30.98	36.57	44.15	31.45
Dix	17.81	39.92	48.52	45.14
Homogeneous model	44.90	49.03	55.51	32.65
Martinelli - Nelson	62.52	63.24	101.78	80.32

A generic problem of all good correlations mentioned above except Mochizuki-Ishii correlation is that they overpredict the void fraction. This is clear from the mean error given in the table 4, which is positive for almost all the correlations (except Nabizadeh and Mochizuki-Ishii correlations). This is further clear from the frequency distribution given in figures 1 to 5. Only the Mochizuki-Ishii correlation shows a skewness towards the negative side (see Fig. 3) which indicates an underprediction to some extent. A comparison of the measured and predicted void fractions are given in figures 6 to 10 which show predicted void fraction, α_c to be consistently more than the measured void fraction α_m except in the case of Mochizuki-Ishii correlation. For the Mochizuki-Ishii correlation, the predictions are more or less evenly distributed around the zero line. It may be noted that while Chexal et. al and Rouhani are drift flux models, Hughmark is a $k\beta$ model and Mochizuki-Ishii correlation is a slip ratio based model.

5.1 Assessment of correlations for the limiting conditions

It may be noted that in the present data set all the void fraction data were in the range of 0 to 22% mass quality. Even with the assessments carried out earlier, it is observed that practically very few void fraction data exists for steam-water flow with quality higher than 40%. The only way to check the behaviour of the correlations outside the range of data is to assess the correlations for the limitting conditions. Void fraction correlations have to satisfy the following limiting conditions:

1. As x tends to 0, α tends to 0 (lower limiting condition)
2. As x tends to 1, α tends to 1 (upper limiting condition)
3. As P tends to $P_{critical}$; α tends to x (critical limiting condition)
4. As u_G=u_L, all correlations must reduce to the homogeneous model

The last limiting condition is not considered as it is difficult to establish the conditions at which the gas phase and liquid phase velocities are equal. To check for the compliance of the correlations with the other limiting conditions, void fractions predicted by different correlations are studied over a wide range of mass fluxes and pressures for $x = 0$ and $x = 1$. In order to allow for the round-off errors and approximations made in the computation of void fractions using various correlations, the following allowances are made to the limiting conditions. It is assumed that a correlation satisfies the limiting conditions if it satisfies the following conditions:

1. At $x = 0.000001$, α is less than 0.001 (approximation of lower limiting condition)
2. At $x = 1$, α is greater than 0.999 (approximation of upper limiting condition)
3. At $P = 218.3$ bar, Maximum deviation (see equation 9) of predicted void fraction over the entire range of mass flux, *i.e.*, 0 to 10,000 kg/m^{2}s, is less than 5 % (approximation of critical limiting condition).

The results of the observations are listed in table 5. It is observed that the homogeneous model and the slip ratio based models satisfy all the three limitting conditions for all mass fluxes. Among the top four correlations only the Mochizuki-Ishii correlation satisfies all the three limiting conditions. The Chexal et. al correlation satisfies all the three limiting conditions for G>140 kg/m^{2}s whereas Rouhani correlation satisfies all the three limiting conditions only for G>2050 kg/m^{2}s. From these considerations, Mochizuki-Ishii and the Chexal et. al correlations are recommended for use in computer codes for reactor analysis.

From the table 5, it is clear that all the slip ratio models satisfy the lower and upper limiting conditions. However all the drift flux models except the Rouhani correlation do not satisfy the upper limiting condition. Among $k\beta$ models, only Armand correlation satisfies both lower and upper limiting conditions. In general, all the correlations satisfy the lower limiting condition.

Table 5 : Limiting conditions

Correlation name	$G \leq 100.0$ kg/m^{2}s			$G > 100.0$ kg/m^{2}s		
	at $x = 0$; $\alpha = 0$	*at* $x = 1$; $\alpha = 1$	*at* $P=P_{cr}$; $\alpha = x$	*at* $x = 0$; $\alpha = 0$	*at* $x = 1$; $\alpha = 1$	*at* $P=P_{cr}$; $\alpha = x$
Chexal et. al	yes	no	yes above 10	yes	yes above 140	yes
Hughmark	yes	no	no	yes	no	no
Mochizuki-Ishii	yes	yes	yes	yes	yes	yes
Rouhani	yes	yes	no	yes	yes	yes above 2050
Zuber-Findlay	yes	no	no	yes	no	no
Bankoff	yes	no	yes	yes	no	yes
Osmachkin	yes	yes	yes	yes	yes	yes
Bankoff-Jones	yes	yes	yes	yes	yes	yes
Thom	yes	yes	no	yes	yes	no
Nabizadeh	yes	no	no	yes	no	no
Armand	yes	yes	no	yes	yes	no
GE-Ramp	yes	yes above 10	no	yes	yes	no
Bankoff-Malnes	yes	yes	no	yes	yes	no
Dix	yes	no	no	yes	no	no
Homogene--ous model	yes	yes	yes	yes	yes	yes
Martinelli-Nelson	yes	yes	no	yes	yes	no

It can also be inferred from table 5 that among drift flux correlations, only Chexal et. al correlation satisfies the critical limiting condition for a wide range of mass fluxes except for those below 10 kg/m^{2}s. Rouhani correlation satisfies this condition only for mass fluxes above 2050 kg/m^{2}s. Among $k\beta$ models, only Bankoff correlation satisfies the critical limiting condition while all the slip ratio models satisfy this condition.

To check whether the correlations satisfy the critical limiting condition, void fractions are calculated using various correlations at critical pressure and for quality ranging from 0 to

1, for a given value of mass flux. For each value of quality, deviation of the predicted void fraction from the expected value, *i.e.*, $\alpha = x$, is calculated using the following relation:

$$Deviation = \left|\frac{x-\alpha}{x}\right| \times 100 \qquad (9)$$

The maximum of these deviations, as x changes from 0 to 1 (calculations were done in steps of 0.01), is obtained for each value of mass flux. This process is repeated for mass fluxes ranging from 0 to 10,000 kg/m^{2}s. Plots of maximum deviation against mass flux made using the top four correlations are shown in figures 11 and12.

The plots in figures 11 and 12 also give us a picture of the extent to which the top four correlations satisfy the critical limiting condition at various mass fluxes. These plots indicate that Mochizuki-Ishii correlation is in excellent agreement with the third limiting condition at all mass fluxes. Chexal et. al correlation, though good at high values of mass fluxes, gives large deviations at mass fluxes smaller than 100 kg/m^{2}s. Rouhani and Hughmark corelations show large deviations at all mass fluxes.

5.2 Theoretical comparison of selected correlations

Although Chexal et. al correlation has been proved to be one of the best, it has a disadvantage in that, it is not amenable for quick computation as it involves an iterative procedure for calculation of void fraction. However, correlations like Mochizuki-Ishii, Rouhani, etc., are useful especially when quick computation is needed. Hence an attempt is made to identify various correlations closest to Chexal et. al correlation in different conditions.

5.2.1 Behaviour at high mass fluxes

Plots of void fraction vs. quality made using the best four correlations (as suggested by the present assessment) with pressures ranging from as low as 10 bar to as high as 200 bar are shown in figures 13 to 18. These plots are made for various mass fluxes falling in the natural circulation region as well as in the forced circulation region. From these figures, the following conclusions can be drawn :

1) At low pressures (around 10 bar), the Mochizuki-Ishii correlation is a better approximation to the Chexal et. al correlation than any of the others.
2) All correlations except Hughmark correlation (*i.e.*, Mochizuki-Ishii, Chexal et. al and Rouhani) tend to give very close predictions as the pressure tends to the critical value.
3) Hughmark correlation is at it's closest to other correlations only at low pressures. As the pressure increases, it drifts apart from other correlations.

4) For quality greater than 20%, the Mochizuki-Ishii correlation always gives the highest predicted value of void fractions.

5) As mass flux increases beyond 3000 kg/m^{2}s, predictions of Rouhani and Chexal et. al correlations are close to each other.

6) All correlations including Hughmark are close to each other if quality is less than 15%.

5.2.2 Behaviour at low mass fluxes

Plots of void fraction vs. quality made using the best four correlations at low mass fluxes with pressures ranging 10 bar to 200 bar are shown in figures 19 to 23. The mass flux used in these plots ranges from 5 kg/m^{2}s to 100 kg/m^{2}s. This range is especially important during the start-up of natural circulation nuclear reactors, where the flow starts from stagnant conditions. The following conclusions can be drawn from the plots:

1) At very low mass fluxes (less than 75 kg/m^{2}s), only Mochizuki-Ishii correlation satisfies the limiting conditions, while Chexal et. al and Hughmark correlations fail to meet the limiting conditions. Rouhani correlation, though leading to $\alpha = 1$ as x tends to 1.0, fails to meet the $\alpha = x$ condition at critical pressure. Instead, it gives values of α lower than x at pressures lower than critical pressure, which is physically unrealistic.

2) At higher mass fluxes (75-100 kg/m^{2}s), Rouhani correlation predicts far lower values of void fraction than the other correlations at low pressures (<10 bar). However, at higher pressures (100-200 bar), it is very close to other correlations.

3) For any given pressure, Mochizuki-Ishii correlation still gives the highest predicted value of void fraction.

6. RECOMMENDED FUTURE WORK

It may be noted that all correlations satisfy the limitting condition of α=0 at x=0 (see table-5). This is the reason why all correlations predict void fraction values close to each other at low values of x. Also, most experimental data available in the literature are for low qualities (less than 0.22 in the present assessment). That is the reason why the Hughmark and Zuber-Findlay correlations perform rather well in the present assessment eventhough these correlations do not satisfy the limitting condition at x=1. In fact, the assessment of Dukler et al. (1964), Friedel (1980) and the present assessment showed Hughmark correlation to be one of the best to predict void fraction. All these indicate that the available experimental data on steam-water mixture void fraction lies predominantly in the low quality region. The main reason for this appears to be attributable to the technique used for measuring void fraction. Generally, gamma-ray radiography is used to measure void fraction which is less sensitive to changes in void fraction at high qualities. A more sensitive technique like neutron radiography can be used to measure void fraction with better accuracy at high qualities. Further work needs to be done in this direction.

Present assessment shows that the void fraction predictions using the correlations considered here are likely to be in significant error at low mass fluxes (<250 kg/m^2). The available data in the open literature is very few in this range of mass flux to adequately quantify this error. Therefore, more experimental work is required to generate additional data for the low mass flux range.

7. CONCLUDING REMARKS

An assessment of void fraction correlations using experimental data for vertical upward flow of steam-water mixture has been carried out. As per this assessment, Chexal et al. (1996) correlation is found to perform better than all other correlations considered. Futher experimental work is necessary to generate steam-water void fraction data at high qualities (>40%) and low mass fluxes (<250 kg/m^2).

NOMENCLATURE

A	- flow area
C_0	- distribution coefficient
D	- diameter
e	- error
Fr	- Froude Number
G	- mass flux
g	- gravitational acceleration
h	- heat transfer coefficient
h_{fg}	- latent heat
j	- mixture superficial velocity
j_G	- superficial velocity of gas
j_L	- superficial velocity of liquid
N	- total number of data points
P	- pressure
Re	- Reynolds Number
S	- slip ratio
u	- velocity
v	- specific volume
v_{fg}	- v_G - v_L
W	- mass flow rate
x	- mass quality

Greek Symbols

α	- void fraction
β	- homogeneous void fraction

μ - dynamic viscosity
ρ - density
σ - surface tension

Subscripts

c - calculated
crit - critical
G - vapour
h - hydraulic
i - ith value
L - liquid
m - measured
R - relative

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Appendix-1: Slip ratio models for calculation of void fraction

Osmachkin (1970)

$$S = 1 + \frac{(0.6 + 1.5\beta^2)\left(1 - \frac{P}{P_{crit}}\right)\left(\frac{G}{\rho_L}\right)^{0.5}}{(gD_h)^{0.25}} \quad \text{(A1.1)}$$

Bankoff and Jones (1962)

$$S = \frac{1-\alpha}{K - \alpha + (1-K)\alpha^r} \quad \text{(A1.2)}$$

where K=0.71+0.00131P and r=3.33+2.61x10^{-3}P+9.67x10^{-3}P^2, P is in bar.

Bankoff and Malnes (1979)

S = (1-α)/(C-α) for α≤C-0.02 (A1.3)

and

S = 50[1.02-C+50(α-C+0.02)(1-C)] for α > C-0.02 (A1.4)

Modified Smith (Mochizuki and Ishii (1992))

$$S = K + (1+K)\left[\frac{\frac{\rho_L}{\rho_G} + K\left(\frac{1}{x} - 1\right)}{1 + K\left(\frac{1}{x} - 1\right)}\right]^{0.5} \quad \text{(A1.5)}$$

where K = 0.95 tanh(5.0x)+0.05

Appendix-2: Kβ models for the calculation of void fraction

Armand (1947)

$$K = 0.833 + 0.167x \qquad \text{(A2.1)}$$

Bankoff (1960)

$$K = 0.71 + 0.00131\,P, \quad \text{where } 4.9 \leq P \leq 206.2 \text{ bar} \qquad \text{(A2.2)}$$

Hughmark (1961)

$$K=-0.16367+0.31037Y-0.03525Y^2+0.0013667Y^3 \text{ for } Y < 10 \qquad \text{(A2.3)}$$

$$K = 0.75545+0.00358Y-0.1436.10^{-4}Y^2 \text{ for } Y \geq 10 \qquad \text{(A2.4)}$$

$$Y=Re^{1/6}\,Fr^{1/8}\,(1-\alpha)^{-1/4} \qquad \text{(A2.5)}$$

$$Re = GD/[\alpha\mu_G+(1-\alpha)\mu_L] \qquad \text{(A2.6)}$$

$$Fr = (G^2/gD)(x/\rho_G+(1-x)/\rho_L)^2 \qquad \text{(A2.7)}$$

Appendix-3: Drift flux models for the calculation of void fraction

Zuber-Findlay (1965)

$$C_0 = 1.13 \quad and \quad U_{GU} = 1.41\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25} \tag{A3.1}$$

Rouhani (1969)

$$C_0 = 1 + 0.2(1-x)\left\{\frac{gD_h\rho_L^2}{G^2}\right\}^{0.25} \tag{A3.2}$$

$$U_{GU} = 1.18(1-x)\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25} \tag{A3.3}$$

Dix (1971)

$$C_0 = \beta\left[1 + \left\{\frac{1}{\beta - 1}\right\}^b\right]; \quad b = \left\{\frac{\rho_G}{\rho_L}\right\}^{0.1} \tag{A3.4}$$

$$U_{GU} = 2.9\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25} \tag{A3.5}$$

Nabizadeh (1977)

$$C_0 = \beta\left\{1 + \frac{1}{n}Fr^{0.1}\left(\frac{\rho_G}{\rho_L}\right)^n\left(\frac{1-x}{x}\right)^{1.22n}\right\} \tag{A3.6}$$

where

$$Fr = \frac{G^2}{\rho_L^2 gD_h}; \qquad n = \sqrt{0.6\left\{\frac{\rho_L - \rho_G}{\rho_L}\right\}}; \qquad U_{GU} = 1.18\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25}.$$

GE-Ramp (1970)

$C_0 = 1.1$ for $\alpha \le 0.65$
$= 1 + 0.1(1-\alpha)/0.335$ for $\alpha > 0.65$ (A3.7)

and the drift flux velocity is given by,

$$U_{GU} = R\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25} \tag{A3.8}$$

and R = 2.9 for $\alpha \le 0.65$
= 2.9 (1−α) / 0.335 for $\alpha > 0.65$ (A3.9)

EPRI (1986)

$$C_0 = \frac{L(\alpha, P)}{K_0 + (1 - K_0)\alpha^r} \quad \text{(A3.10)}$$

$$L(\alpha, P) = \frac{1 - \exp(C_1\alpha)}{1 - \exp(-C_1)} \quad \text{(A3.11)}$$

where the constants are given by,

$$C_1 = \frac{4\,P_{crit}^2}{\left[P\left(P_{crit} - P\right)\right]}; \quad K_o = B_1 + (1 - B_1)\left(\frac{\rho_G}{\rho_L}\right)^{1/4}; \quad r = (1 + 1.57\frac{\rho_G}{\rho_L})(1 - B_1);$$

$$B_1 = \min(0.8, A_1); \quad A_1 = \frac{1}{\left[1 + \exp\left(-\mathrm{Re}/10^5\right)\right]}$$

and the drift velocity is given by

$$U_{GU} = 1.41\left\{\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^2}\right\}^{0.25} \frac{(1-\alpha)^{0.5}}{1+\alpha} \quad \text{(A3.12)}$$

Chexal et. al. (1996)

The correlation valid for steam-water flow is presented here. For refrigerant two-phase flow or Air-water two-phase flow reference may be made to the original report.

Distribution parameter (C_0)

The distribution parameter, C_0, for a two-phase mixture flowing at any angle, where the angle is measured from the vertical axis, is the weighted average of values for horizontal and vertical flow.

$$C_o = F_r C_{ov} + \left(1 - F_r\right) C_{oh} \quad \text{(A3.13)}$$

where C_{ov} and C_{oh} are the distribution parameters evaluated for vertical and horizontal flow and F_r is a flow orientation parameter defined as

for $Re_G > 0$

$$F_r = \frac{(90° - \theta)}{90°} \; for \; \left(0° \le \theta \le 90°\right) \quad \text{(A3.14a)}$$

for $Re_G < 0$

$$F_r = \begin{cases} 1 & \text{for } (\theta \le 80°) \\ \dfrac{(90° - \theta)}{10°} & \text{for } (80° < \theta < 90°) \end{cases} \quad \text{(A3.14b)}$$

where

θ = pipe orientation angle measured from the vertical axis
Re_G = $D_h W_G / (\mu_G A)$ local vapor superficial Reynolds number

Note that in all cases, the pipe orientation angle $\theta = 0°$ for a vertical pipe and $\theta = 90°$ for a horizontal pipe. The angle is always in the limits of $(0 \le \theta \le 90°)$.

Vertical flow - For vertical pipe ($\theta = 0°$), the volumetric fluxes, j_L and j_G, are taken as positive if both phases are flowing upward and negative if both phases are flowing downward. For countercurrent flow, the vapor velocity is always positive (upward) and the liquid velocity is always negative (downward). Countercurrent flow is only considered for vertical flows. The distribution parameter for vertical flow is given by

for $Re_G \ge 0$

$$C_{ov} = \frac{L}{\left[K_o + (1 - K_o)\alpha^r\right]} \quad \text{(A3.15a)}$$

for $Re_G < 0$

$$C_{ov} = \max \begin{cases} \dfrac{L}{\left[K_o + (1 - K_o)\alpha^r\right]} \\ \dfrac{V_{Gj}^o (1 - \alpha)^{0.2}}{\left(|j_L| + |j_G|\right)} \end{cases} \quad \text{(A3.15b)}$$

where V_{Gj}^o = defined later by Eq. (A3.30)
L = Chexal-Lellouche fluid parameter

Different forms of L are used with different fluids. For **steam-water** mixtures the form of L is selected to ensure proper behavior as the pressure approaches the critical pressure,

$$L = \frac{1 - \exp(-C_1 \alpha)}{1 - \exp(-C_1)} \quad \text{(A3.16)}$$

where

$$C_1 = \frac{4\, P_{crit}^2}{\left[P\,(P_{crit} - P)\right]} \quad \text{(A3.17)}$$

Other variables in the distribution parameter correlation are defined as,

$$K_o = B_1 + (1 - B_1)\left(\frac{\rho_G}{\rho_L}\right)^{1/4} \quad \text{(A3.18)}$$

$$r = \frac{(1.0 + 1.57\ \rho_G / \rho_L)}{(1 - B_1)} \quad \text{(A3.19)}$$

$$B_1 = \min(0.8, A_1) \quad \text{(A3.20)}$$

$$A_1 = \frac{1}{[1 + \exp(-\mathrm{Re}/60{,}000)]} \quad \text{(A3.21)}$$

$$\mathrm{Re} = \begin{cases} \mathrm{Re}_G \ \textit{if}\ \mathrm{Re}_G > \mathrm{Re}_L \ \textit{or}\ \mathrm{Re}_G < 0.0 \\ \mathrm{Re}_L \ \textit{if}\ \mathrm{Re}_G \le \mathrm{Re}_L \end{cases} \quad \text{(A3.22)}$$

$$\mathrm{Re}_L = \text{local liquid Reynolds number} = \frac{W_L D_h}{\mu_L A} \quad \text{(A3.23)}$$

$$\mathrm{Re}_G = \text{local vapor Reynolds number} = \frac{W_G D_h}{\mu_G A} \quad \text{(A3.24)}$$

The sign convention for all Reynolds numbers, Re, Re_L, and Re_G is the same as the sign convention for the individual flows.

Horizontal flow - For horizontal flow (θ = 90°), the void fraction correlation considers only cocurrent flows. Horizontal countercurrent flow has not yet been included in the data base. The volumetric fluxes for horizontal flow are always taken as positive; negative volumetric fluxes should not be used. The distribution parameter for horizontal flow is given by

$$C_{oh} = \left[1 + \alpha^{0.05}(1 - \alpha)^2\right] C_{ov} \quad \text{(A3.25)}$$

where C_{ov} is defined by Eq. (A3.15a) above, and is evaluated with positive vapor Reynolds numbers, using the horizontal fluid parameter, L_h, defined as follows:

$$\text{steam-water} \quad L_h = \frac{1 - \exp(-C_1\alpha)}{1 - \exp(-C_1)} \quad \text{(A3.26)}$$

All other parameters are defined as for vertical flows, with positive fluxes.

For both vertical and horizontal flows, the steam-water parameter is a function of pressure and void fraction.

<u>Drift velocity</u> *(U_{GU})*

The drift velocity, U_{GU} for cocurrent upflow and pipe orientation angles $(0° < \theta < 90°)$ is defined as

$$U_{GU} = F_r V_{gjv} + (1-F_r) V_{gjh} \quad \text{(A3.27)}$$

where V_{gjv} and V_{gjh} are the drift velocities for vertical and horizontal flow and F_r is the flow orientation parameter defined by Eqs. A3.14a and A3.14b. For cocurrent downflow, the drift velocity is defined as

$$U_{GU} = F_r V_{gjv} + (F_r-1) V_{gjh} \quad \text{(A3.28)}$$

<u>Vertical flow</u> - Like the distribution parameter, the drift velocity for a vertical pipe ($\theta = 0°$), V_{gjv}, covers cocurrent upflow and downflow and countercurrent flow. The drift velocity for vertical flow is given by

$$V_{gjv} = V_{gj}^{o} C_9 \quad \text{(A3.29)}$$

where

$$V_{gj}^{o} = 1.41 \left[\frac{(\rho_L - \rho_G)\sigma g}{\rho_L^{\ 2}} \right]^{0.25} C_2 C_3 C_4 \quad \text{(A3.30)}$$

$$\text{for } Re_G > 0 \quad C_9 = (1-\alpha)^{B_1} \quad \text{(A3.31)}$$

$$\text{for } Re_G < 0 \quad C_9 = (1-\alpha)^{0.5} \quad \text{(A3.32)}$$

Other parameters are defined as

$$\text{for } \left(\frac{\rho_L}{\rho_G}\right) \le 18 \qquad C_2 = 0.4757 \left[\ln \left(\frac{\rho_L}{\rho_G}\right) \right]^{0.7} \quad \text{(A3.33)}$$

$$\text{for } \left(\frac{\rho_L}{\rho_G}\right) > 18 \qquad C_2 = \begin{cases} 1 & \text{if } C_5 \ge 1 \\ \dfrac{1}{\left\{1 - \exp\left[\dfrac{-C_5}{(1-C_5)}\right]\right\}} & \text{if } C_5 < 1 \end{cases} \quad \text{(A3.34)}$$

$$\text{where} \qquad C_5 = \sqrt{\frac{150}{\left(\dfrac{\rho_L}{\rho_G}\right)}} \quad \text{(A3.35)}$$

$$C_4 = \begin{cases} 1 & \text{if } C_7 \geq 1 \\ \dfrac{1}{1-\exp(-C_8)} & \text{if } C_7 \leq 1 \end{cases} \tag{A3.36}$$

$$C_7 = (D_2/D_h)^{0.6} \tag{A3.37}$$

$$C_8 = \frac{C_7}{1-C_7} \tag{A3.38}$$

D_2 = Normalizing diameter, 0.09144 m (A3.39)

The parameter C3 is determined based on the direction of the gas and liquid flows. It is continuous as the two directional boundaries are crossed, but has a particularly strong derivative when coming across the j_L equals zero plane. The values of C_3 for the three types of flows (cocurrent upflow, cocurrent downflow, and countercurrent flow) are given as:

The upflow C_3 expression is as follows:

$$C_3 = \max\begin{cases} 0.5 \\ 2exp\left(-|Re_L| / 300{,}000\right) \end{cases} \tag{A3.40}$$

The original NSAC-139 countercurrent/downflow C_3 expression is as follows:

$$C_3 = 2\left(\frac{C_{10}}{2}\right)^{B_2} \tag{A3.41}$$

$$C_{10} = 2\exp\left\{\frac{|\mathrm{Re}_L|}{350{,}000}\right\}^{0.4} - 1.75\{|\mathrm{Re}_L|\}^{0.03}\exp\left\{\frac{-|\mathrm{Re}_L|}{50{,}000}\left(\frac{D_1}{D_h}\right)^2\right\} + \left(\frac{D_1}{D_h}\right)^{0.25}|\mathrm{Re}_L|^{0.001} \tag{A3.42}$$

Where

$$B_2 = \left[\frac{1}{\left(1+0.05\left(|\mathrm{Re}_L|/350{,}000\right)\right)}\right]^{0.4} \quad \text{and } D_1 = \text{Normalizing diameter} = 0.0381 \text{ m} \tag{A3.43}$$

For clarity, the revised expression for C_{10} is broken into the three constituent terms which are summed to form C_{10}.

$$C_{10}(Term\ 1) = 2\,exp\left\{\frac{|Re_L| + Y}{350{,}000}\right\}^{0.4} \tag{A3.44}$$

$$C_{10}(Term\ 2) = -1.7\left\{|Re_L|\right\}^{0.035} \exp\left\{\frac{-|Re_L|}{(35{,}000\,J_{Lrx} + 25{,}000)}\left(\frac{D_1}{D_h}\right)^2\right\} \tag{A3.45}$$

$$C_{10}(Term\ 3) = \left[0.26\,J_{Lrx} + 0.85(1.0 - J_{Lrx})\right]\left(\frac{D_1}{D_h}\right)^{0.1} |Re_L|^{0.001} \tag{A3.46}$$

Where

$$Y = \begin{cases} 8.0^{(0.5D_1/D_h)}\,Re_G\,J_{Lrx} \exp\left\{\frac{-10}{|Re_L|}\right\} & \text{in the } 2^{nd} \text{ Quadrant} \\ 0 & \text{in the } 3^{rd} \text{ Quadrant} \end{cases} \tag{A3.47}$$

and

$$J_{Lrx} = \begin{cases} \left(1 - \frac{j_L}{j_{L(ccfl)}}\right)^Z & \text{in the } 2^{nd} \text{ Quadrant} \\ 1 & \text{in the } 3^{rd} \text{ Quadrant} \end{cases} \tag{A3.48}$$

$j_{L(ccfl)}$ is the superficial liquid velocity at CCFL for vapor velocity j_G, and

$$Z = \begin{cases} 0.8 & for\ \frac{j_L}{j_{L(ccfl)}} < 0.3 \\ 0.8 - \left(\frac{j_L}{j_{L(ccfl)}} - 0.3\right) & for\ \frac{j_L}{j_{L(ccfl)}} \geq 0.3 \end{cases} \tag{A3.49}$$

The new terms Y, Z, and J_{Lrx} work together in the countercurrent quadrant to fit both the data and the CCFL line. In the 3rd quadrant, Term 1 reduces to its original form and Term 2 has only slight differences in the coefficients. The magnitude of Term 3 is small relative to the other two in the 3rd quadrant.

For countercurrent flow, a large hydraulic diameter model is included to accommodate the behavior of the large diameter blowdown tests. The large diameter model is applicable when hydraulic diameter is greater than 0.3048 m (1 ft). A transition from the normal to the large diameter model is made from D_1 (0.0381 m / 0.125 ft) to 0.3048 m.

The following equations illustrate the large diameter model:

$$C_3 = \begin{cases} 0.6 * X_T * S + C_{3N} * (1.0 - X_T) & for\ 0.3048\,m > D_h > D_1 \\ (0.6 - 0.27*(D_h - 0.3048)/0.3048) * S & for\ 0.9144\,m > D_h \geq 0.3048\,m \\ 0.06 * S & for\ D_h \geq 0.9144\,m \end{cases} \tag{A3.50}$$

Where

C_{3N} = the normal C_3 as defined by Eq (A3.41)

$$S = J_{Lrx} + \left(1.0 - J_{frx}\right) * \left(\frac{D_h}{D_1}\right)^{0.5} \text{, and}$$

$$X_T = \left(D_h - D_1\right) / \left(0.3048 - D_1\right)$$

Horizontal flow

When a drift-flux model is applied to horizontal flow, the drift velocity, V_{gj} is often set to zero. This would be reasonable if V_{gj} was purely buoyancy related. However, from its definition (Eq. A3.15), there is no reason that it should go to zero in horizontal flow. When the horizontal flow data is analyzed it becomes clear that $V_{gj} \neq 0$ is necessary for a reasonable fit with the data. For horizontal flow only cocurrent flows are considered. The drift velocity for horizontal flow, V_{gjh}, is evaluated with Eq. (A3.29), using positive values of the volumetric fluxes.

Units

The correlation is the same in either British or SI units. C_0 has no units and V_{gj} has the units of a velocity and should be consistent with the units used for the volumetric flux.

Appendix-4: Miscellaneous empirical correlations for void fraction

Thom (1964)

$\alpha = \gamma x/\{1+x(\gamma-1)\}$ (A4.1)

γ is a constant at any pressure and assumes the following values for water.

P (bar)	1.014	17.24	41.38	86.21	144.83	206.9	221.1
γ	246.0	40.0	20.0	9.8	4.95	2.15	1.0

Martinelli-Nelson (1948)

$$\alpha = \frac{C\sqrt{x}}{(1-x)+C\sqrt{x}} \qquad \text{(A4.2)}$$

where $C = (\rho_L/\rho_G)^{0.5}$

Baroczy (1966)

Baroczy has expressed in graphical form, the void fraction as a function of the Martinelli parameter, χ_{tt}, and the property index:

$$\chi_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.2} \qquad \text{(A4.3)}$$

Based on these graphs Marinelli and Pastori (1973) have obtained the following best fit equation valid only for 70 kg/cm^2

$\alpha = 0.1800285+4.2049x-11.523x^2+14.856x^3-6.7624x^4$ (A4.4)

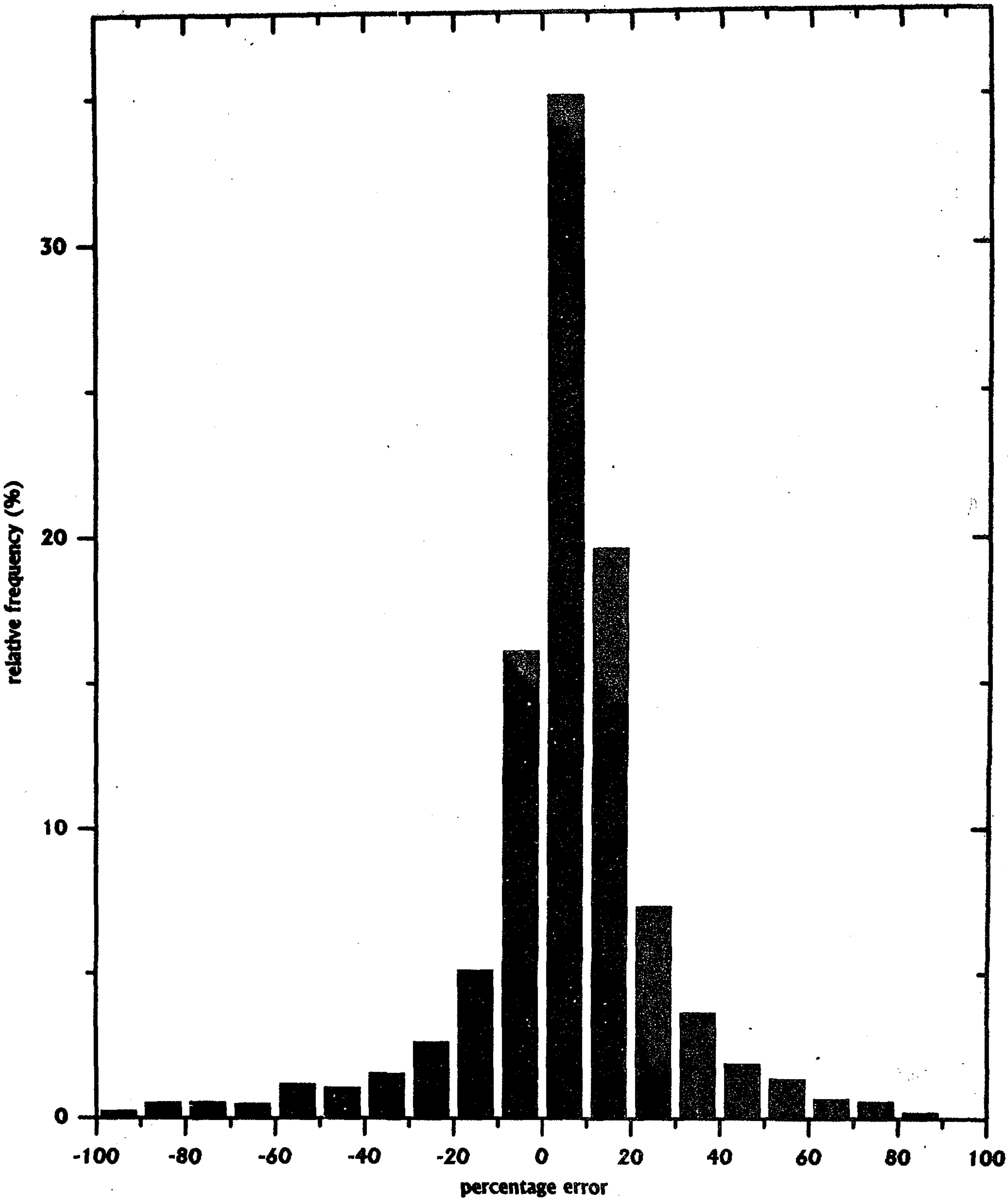

Fig. 1 Error distribution in predicted void fractions using Chexal et al. (1996) correlation

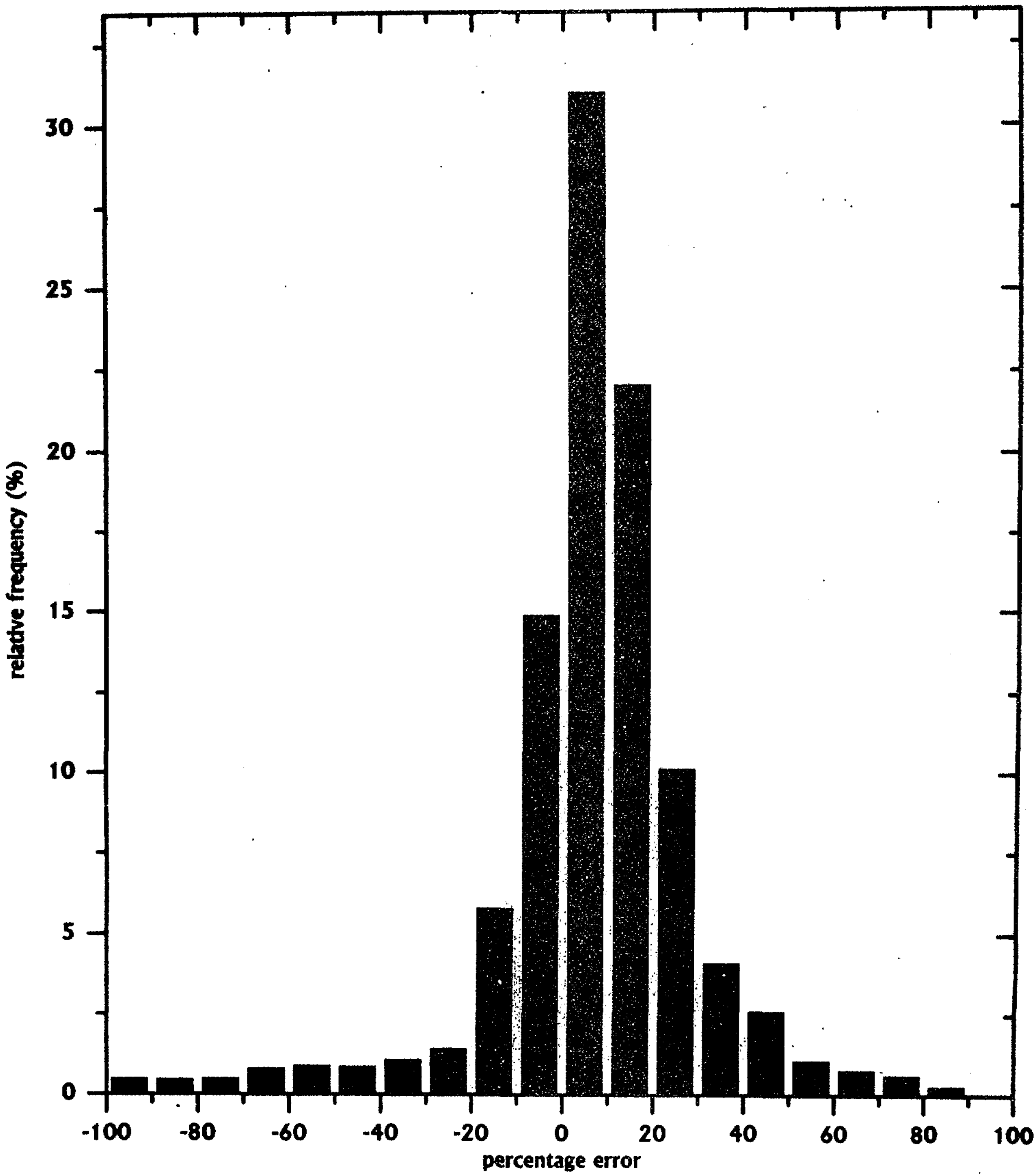

Fig. 2 Error distribution in predicted void fractions using Hughmark correlation

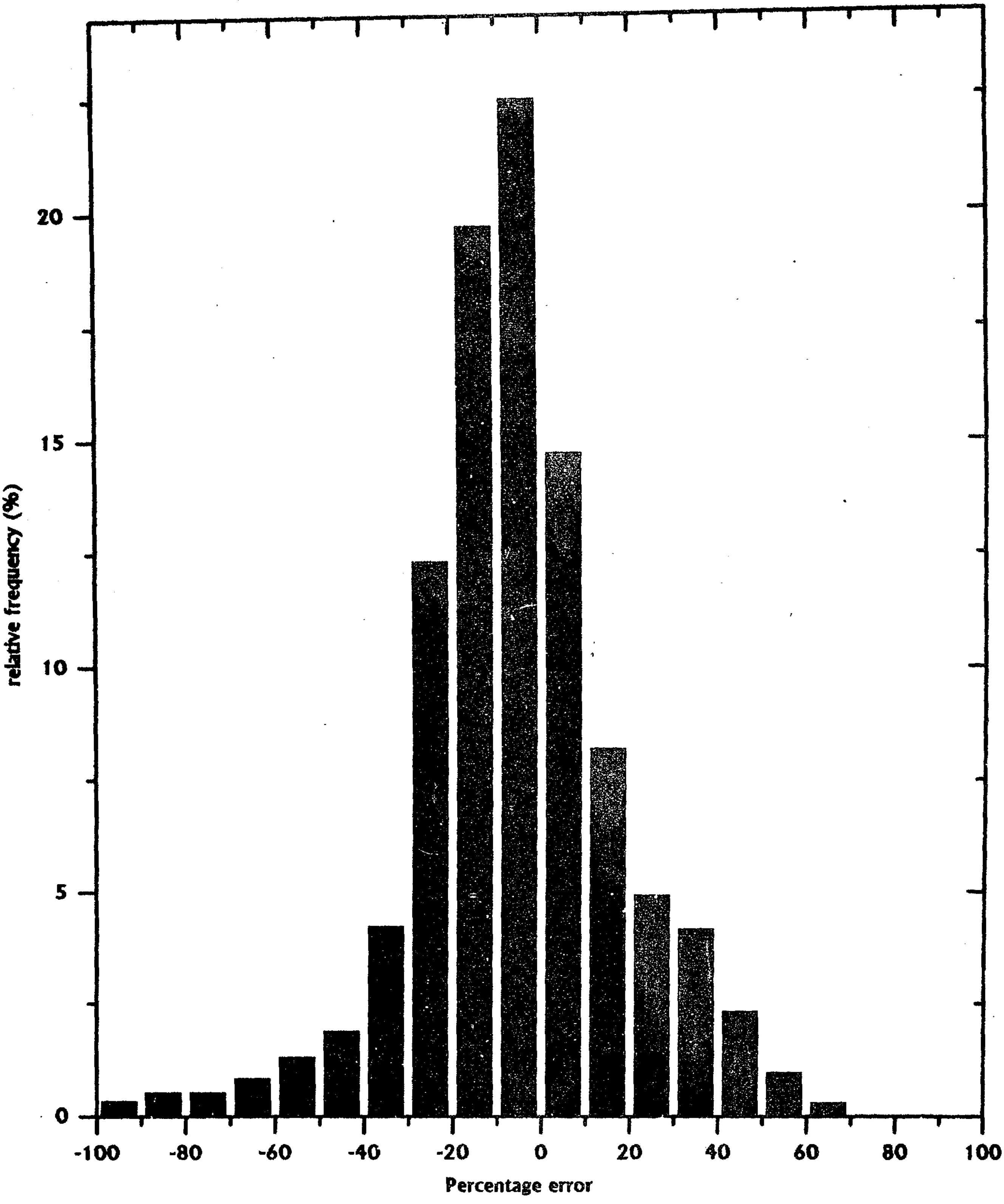

Fig. 3 Error distribution in predicted void fractions using Mochizuki-Ishii (1992) correlation

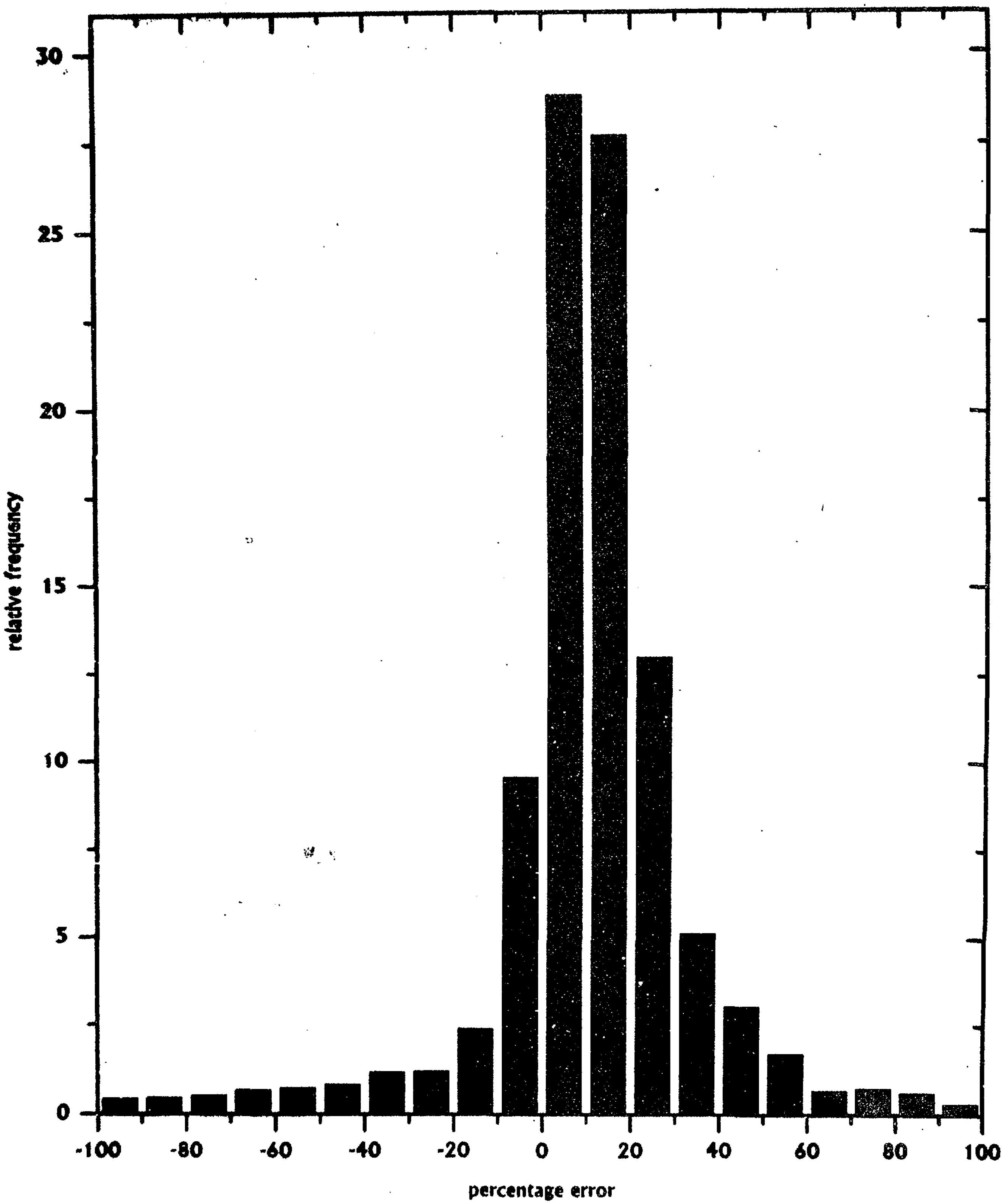

Fig. 4 Error distribution in predicted void fractions using Rouhani (1969) correlation

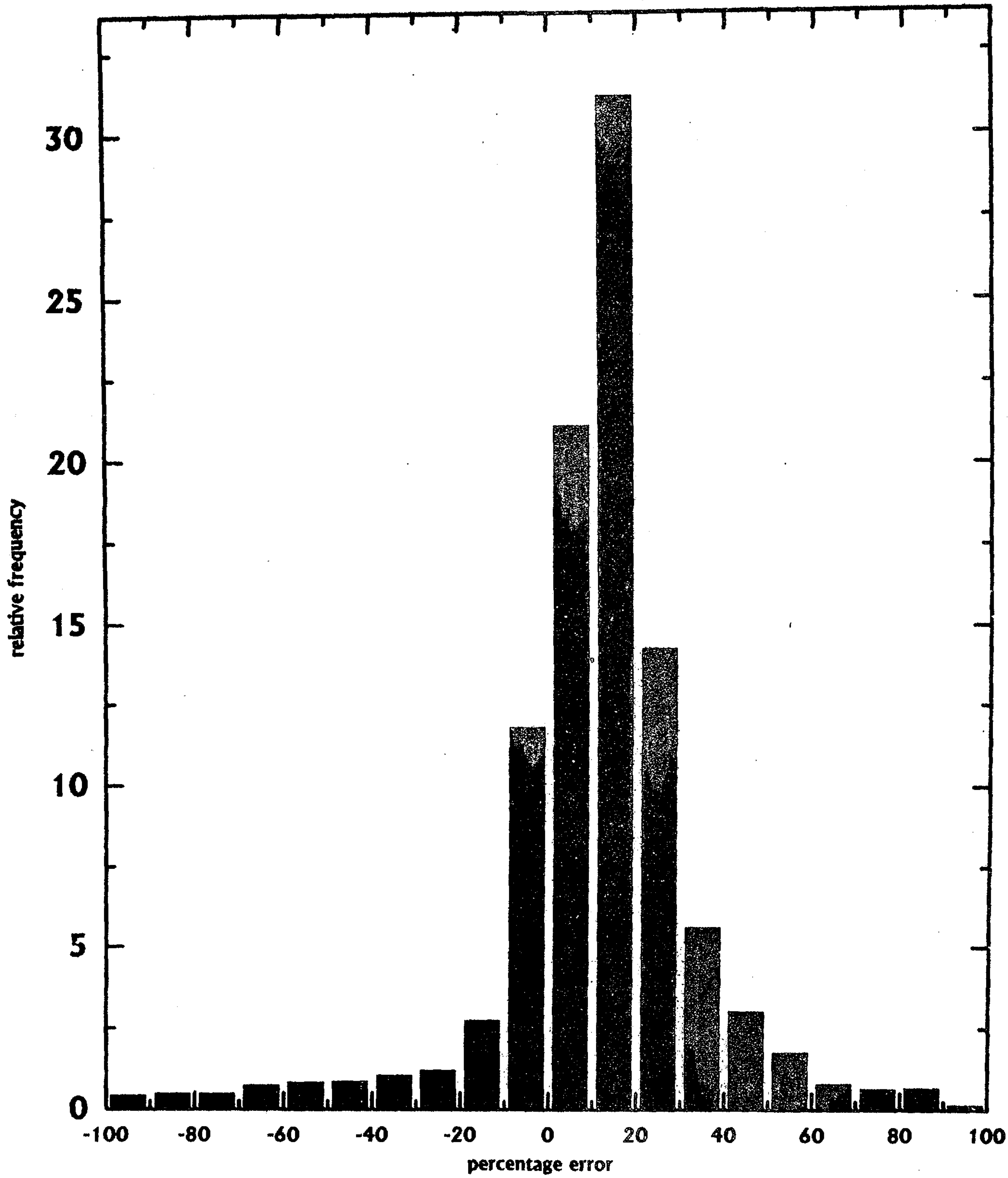

Fig. 5 Error distribution in predicted void fractions using Zuber-Findlay (1965) correlation

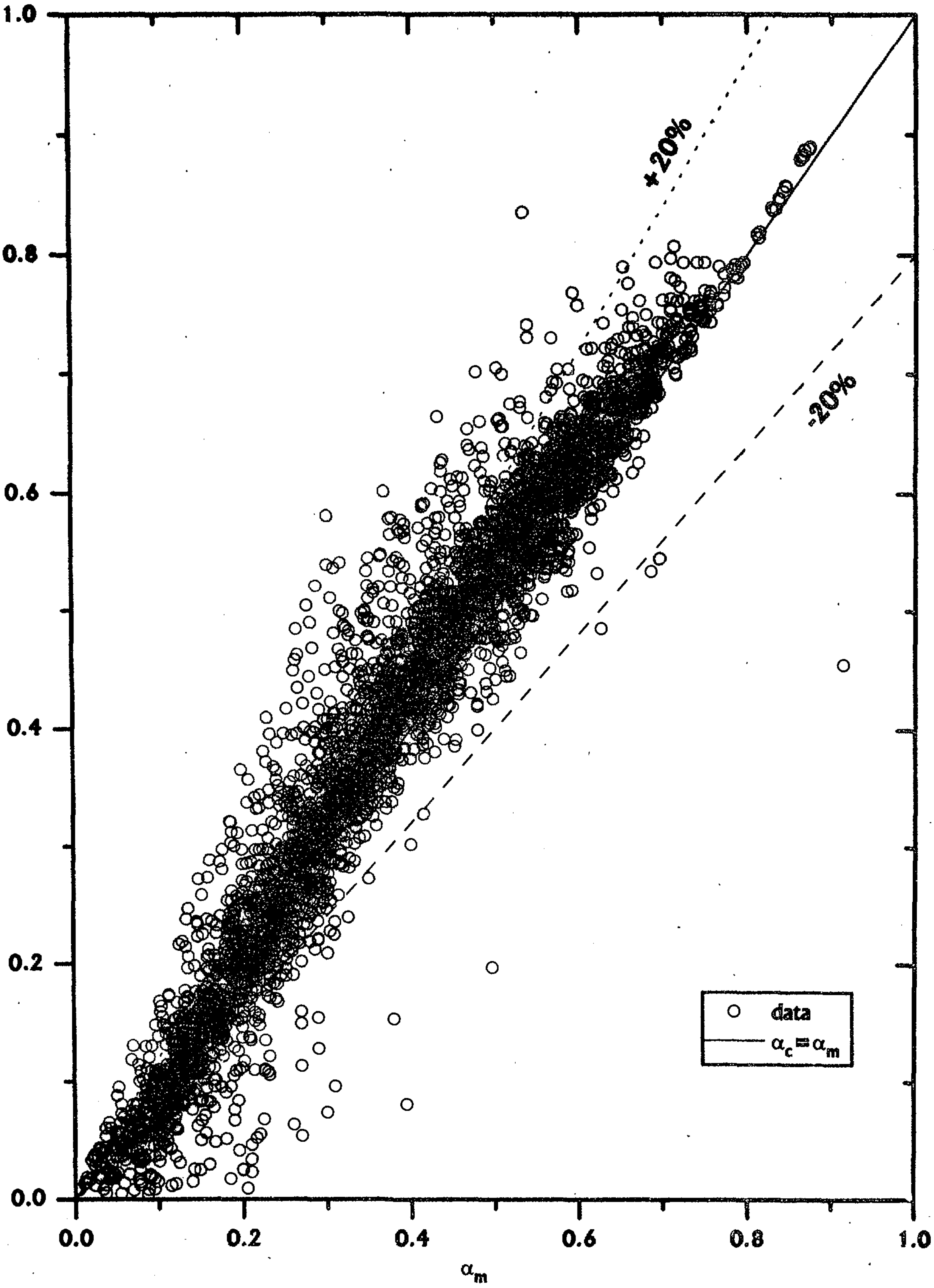

Fig. 6 Comparison of measured and predicted void fractions using Chexal et al. (1996) correlation

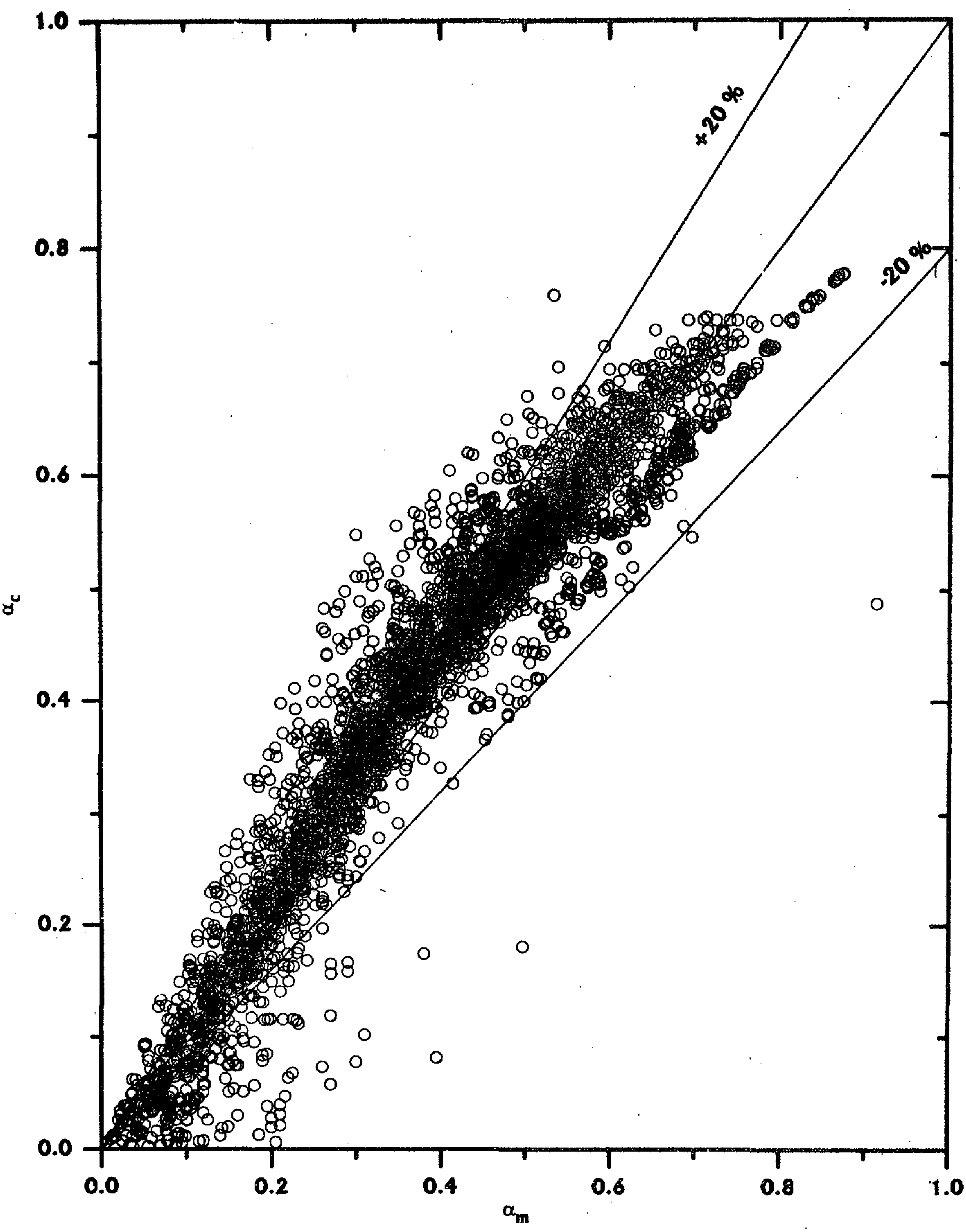

Fig. 7 Comparison of measured and predicted void fractions using Hughmark correlation

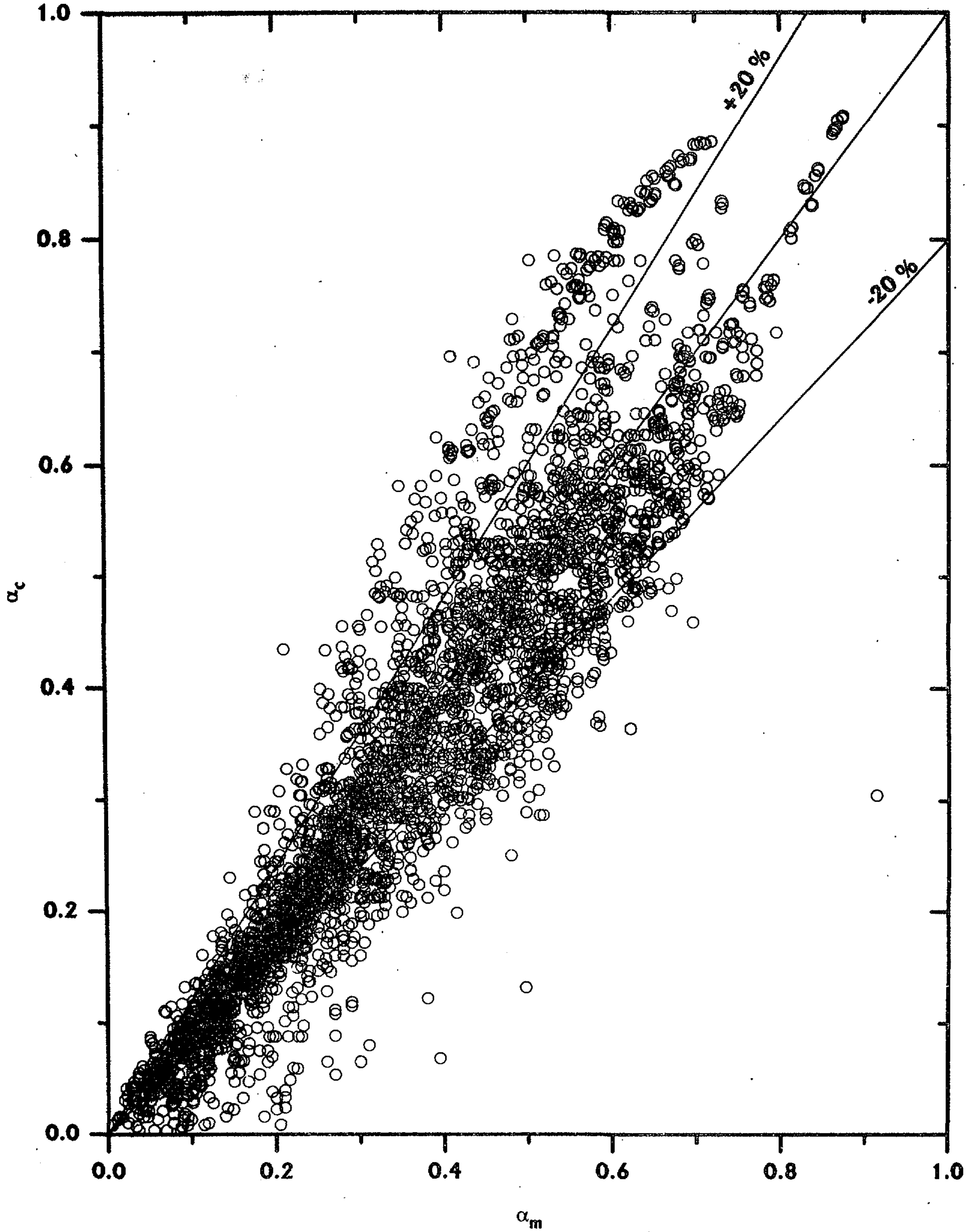

Fig. 8 Comparison of measured and predicted void fractions using Mochizuki-Ishii (1992) correlation

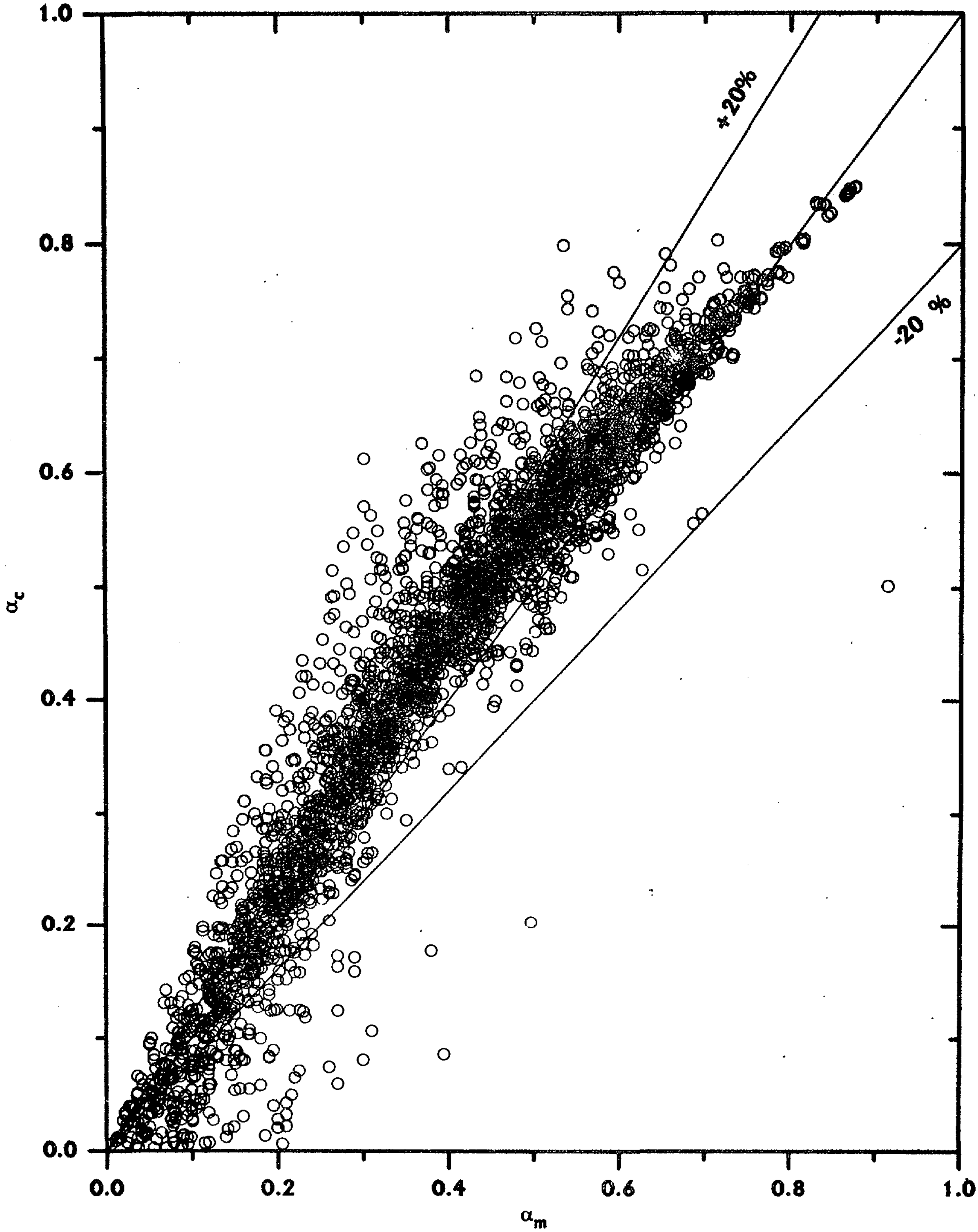

Fig. 9 Comparison of measured and predicted void fractions using Rouhani correlation

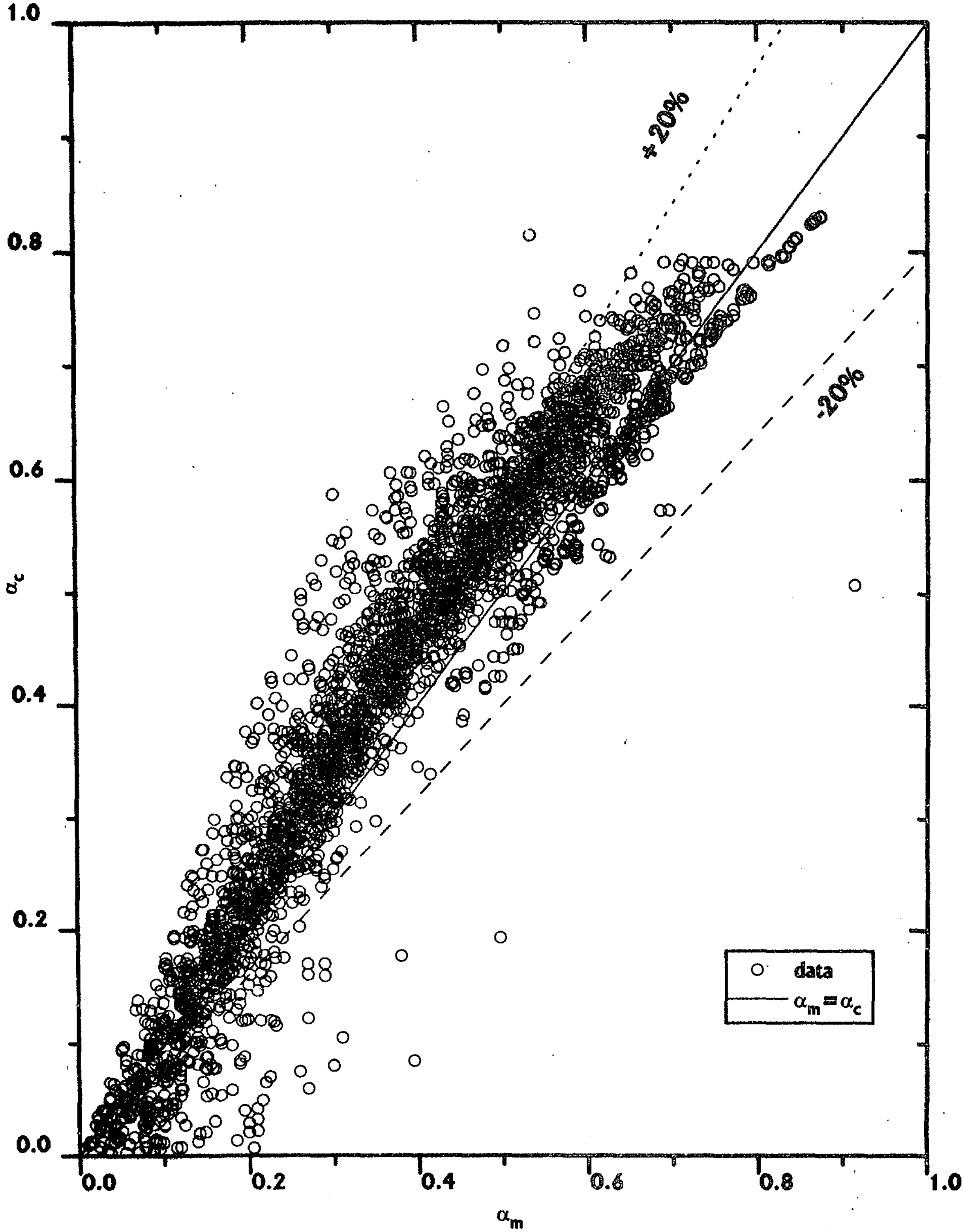

Fig. 10 Comparison of measured and predicted void fractions using Zuber-Findlay correlation

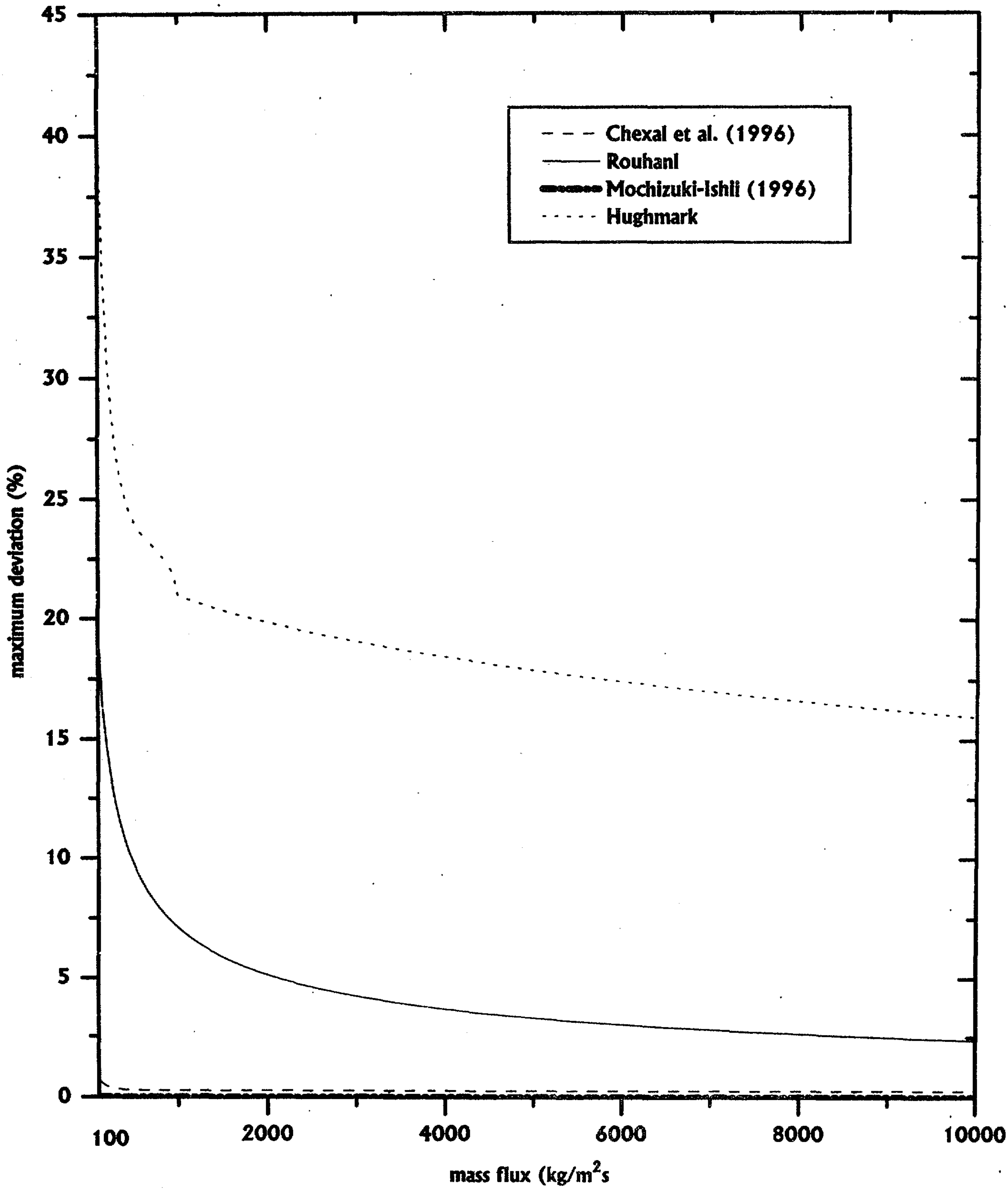

Fig. 11 Maximum deviation of predicted void fractions from expected values using various correlations at critical pressure and at varying mass flux in a 25.4 mm tube

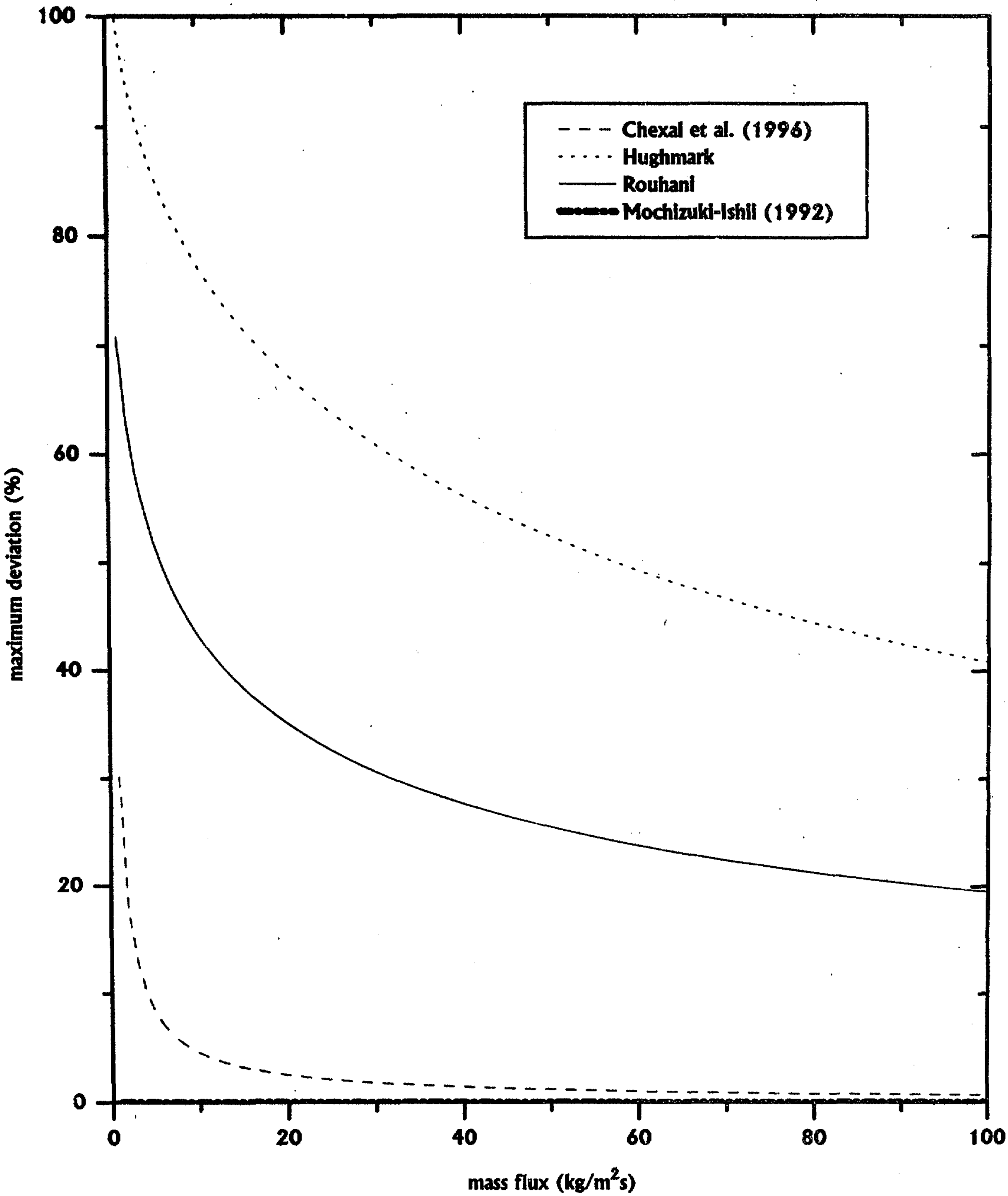

Fig. 12 Maximum deviation of predicted void fraction from expected values using various correlations at critical pressure and at varying mass flux in a 25.4 mm tube for steam-water flow

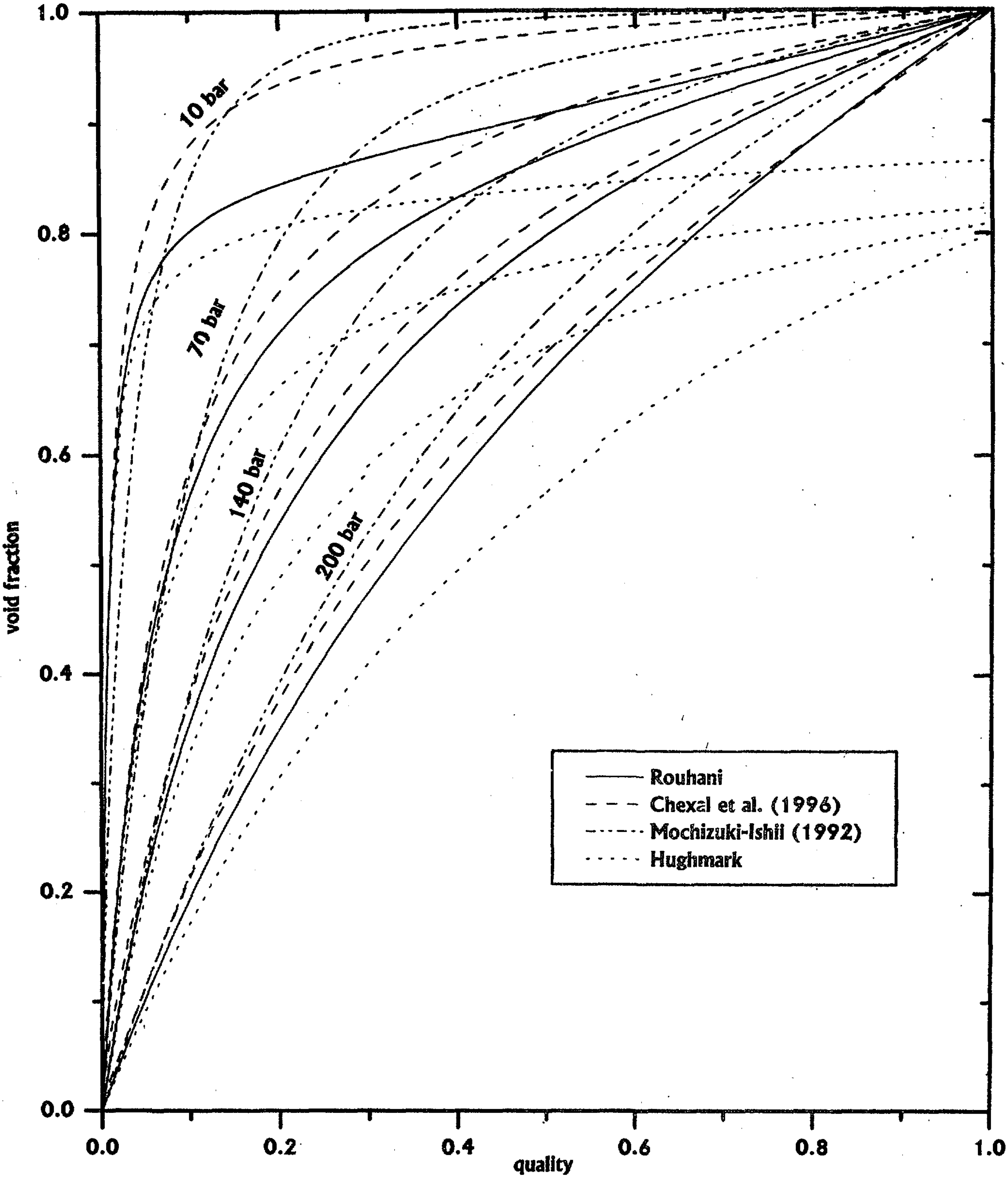

Fig. 13 Predicted void fractions using various correlations at a mass flux of 500 kgm^{-2}s^{-1} and at different pressures for steam-water flow in a 25.4 mm i.d. tube

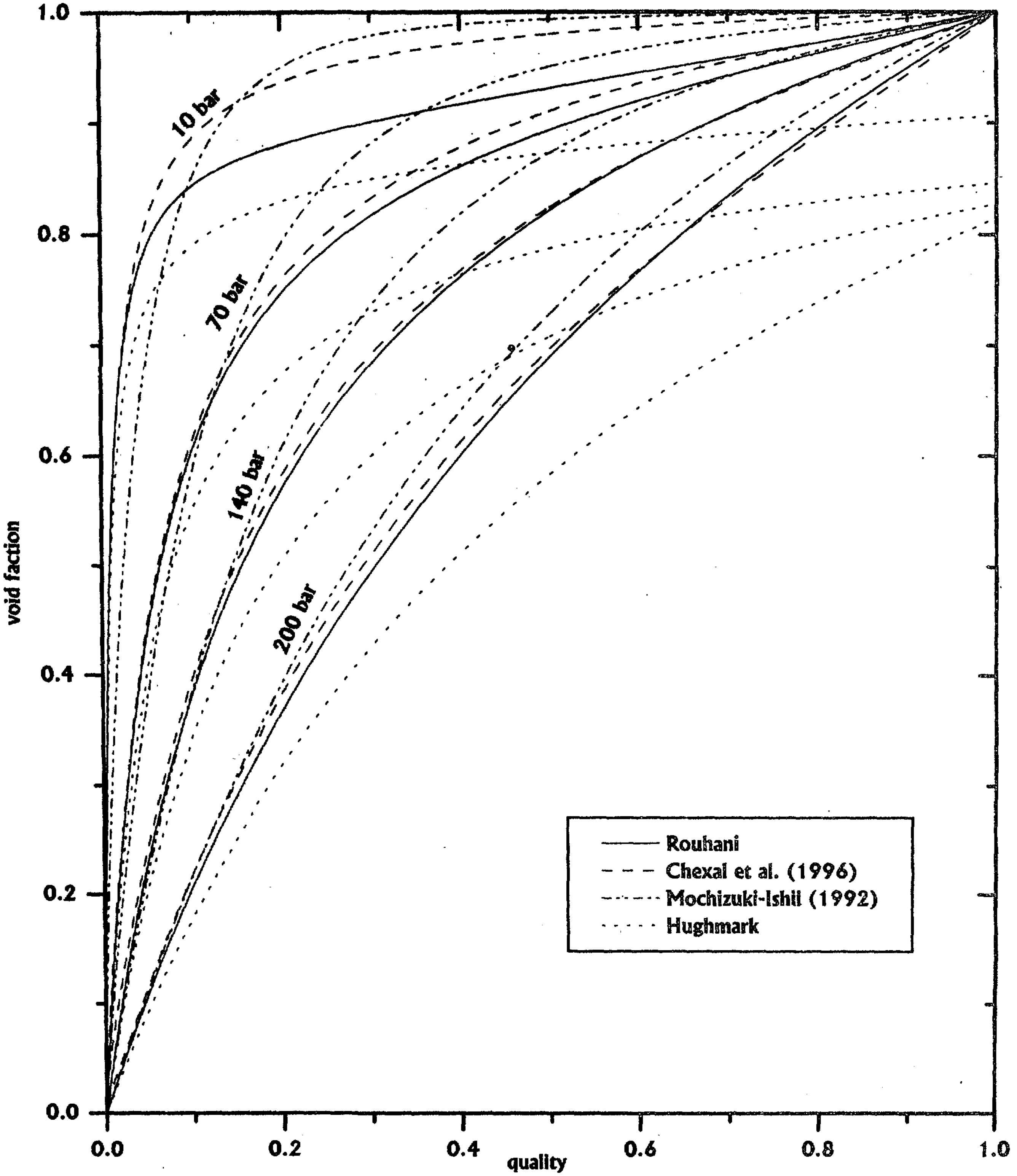

Fig. 14 Predicted void fractions using various correlations at a mass flux of 1000 $kgm^{-2}s^{-1}$ and at different pressures for steam- water flow in a 25.4mm i.d. tube

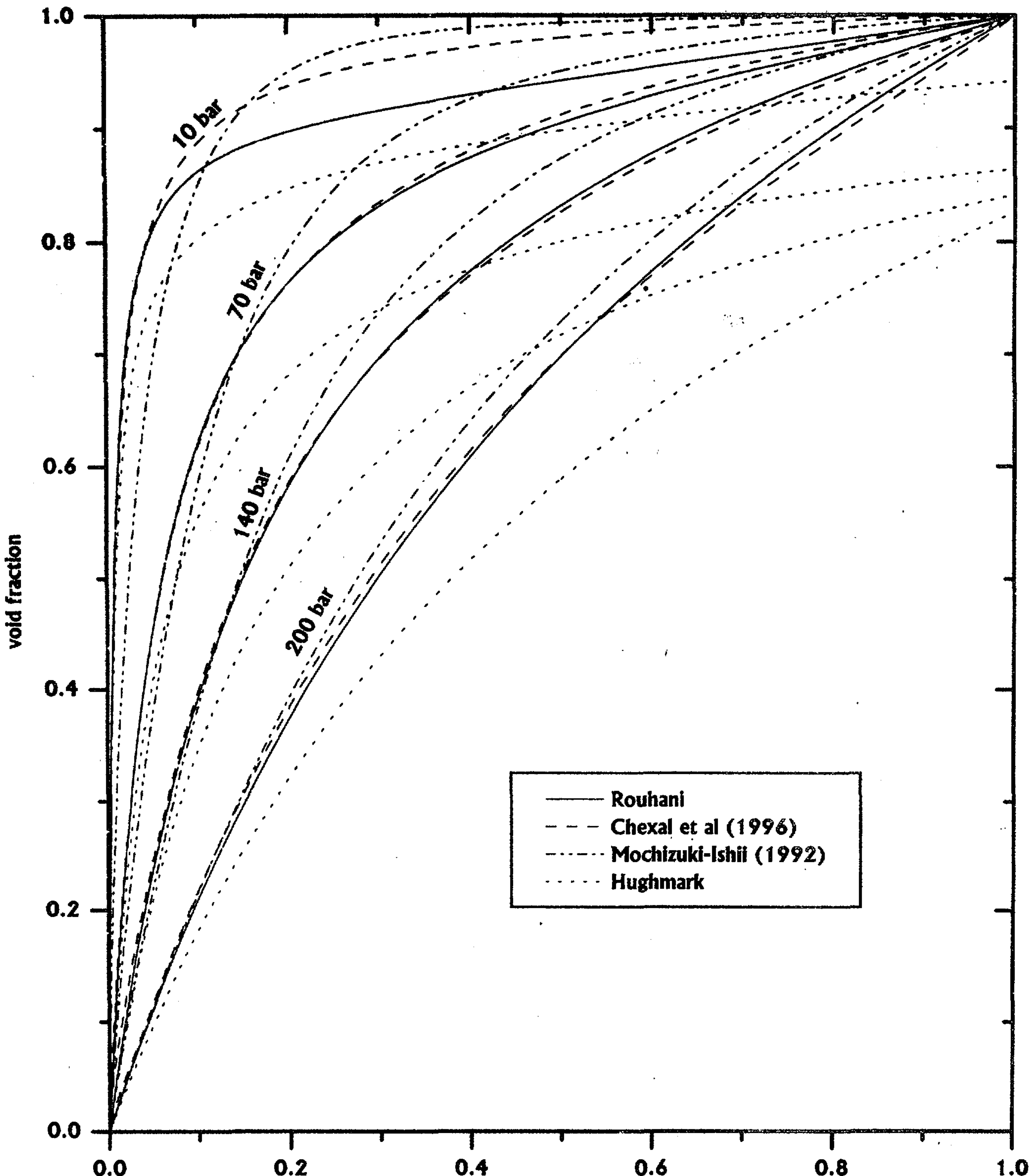

Fig.15 Predicted void fractions using various correlations at a mass flux of 1500 kgm^{-2}s^{-1} and at different pressures for steam-water flow in a 25.4mm i.d. tube

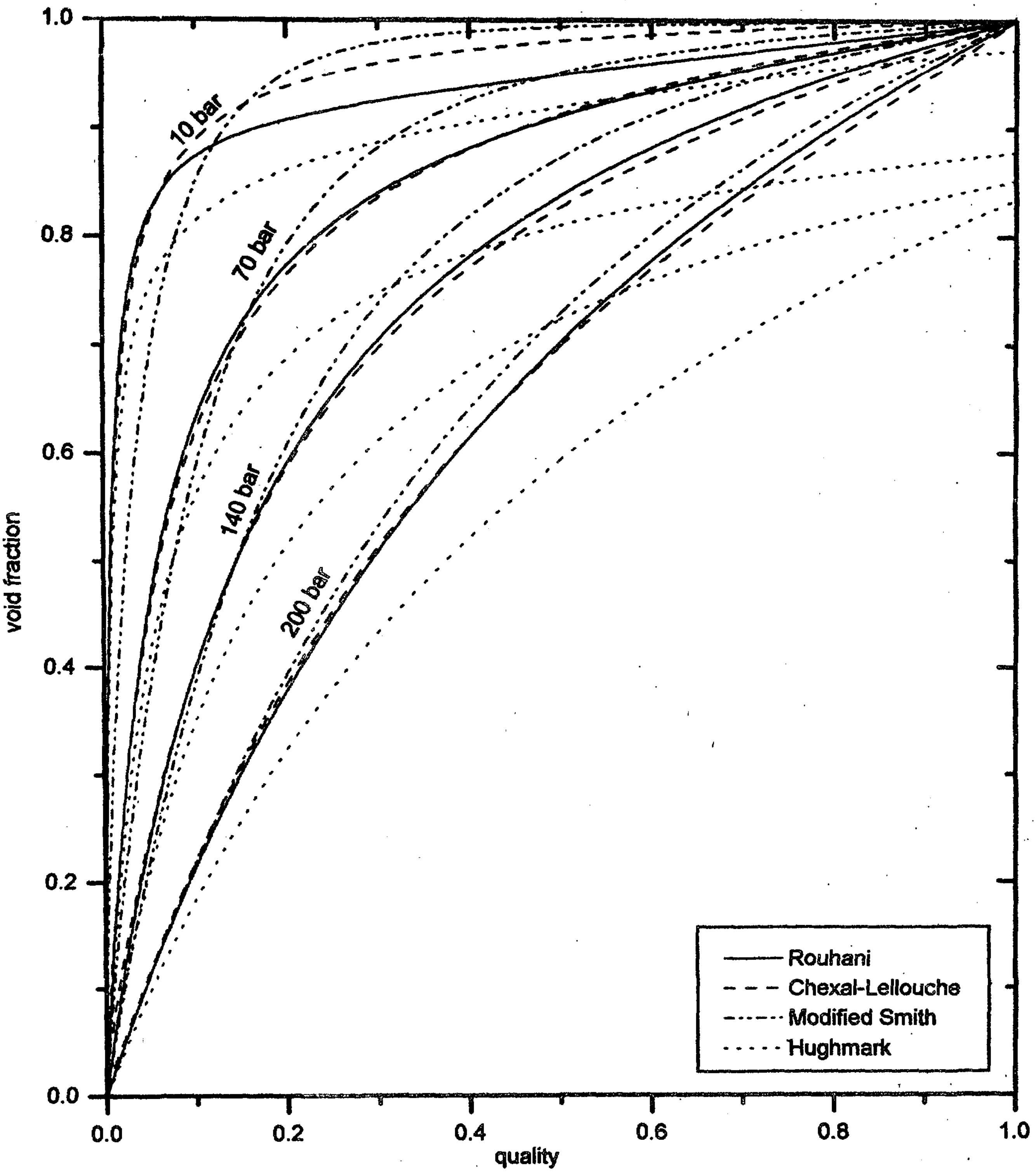

Fig. 16 Predicted void fractions using various correlations at a mass flux of 2000 $kgm^{-2}s^{-1}$ and at different pressures for steam-water flow in a 25.4mm i.d. tube

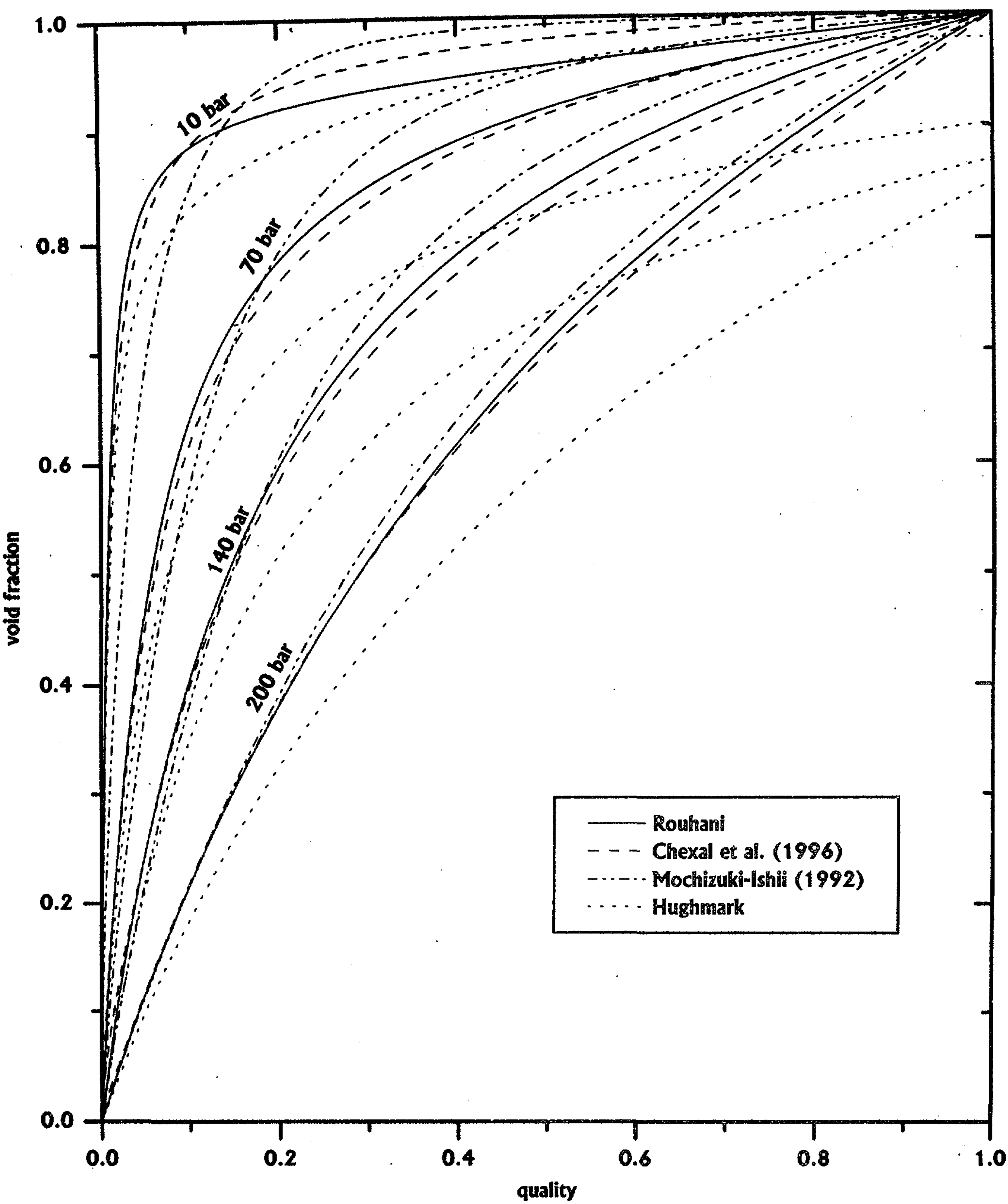

Fig. 17 Predicted void fractions using various correlations at a mass flux of 3000 kgm^{-2-1} and at different pressures for steam-water flow in a 25.4 mm i.d. tube

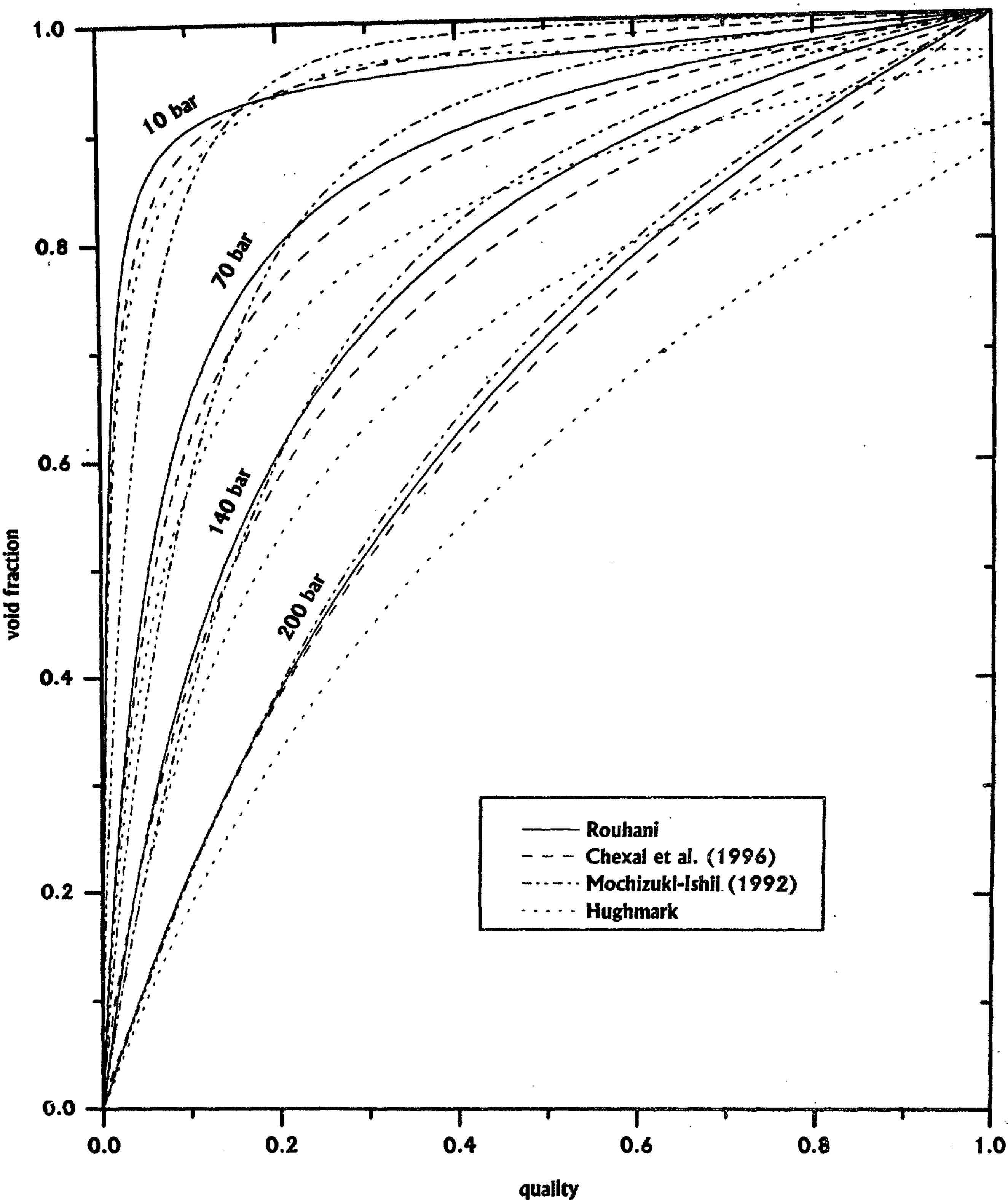

Fig. 18 Predicted void fractions using various correlations at a mass flux of 6000 $kgm^{-2}s^{-1}$ and at different pressures for steam-water flow in a 25.4mm i.d. tube

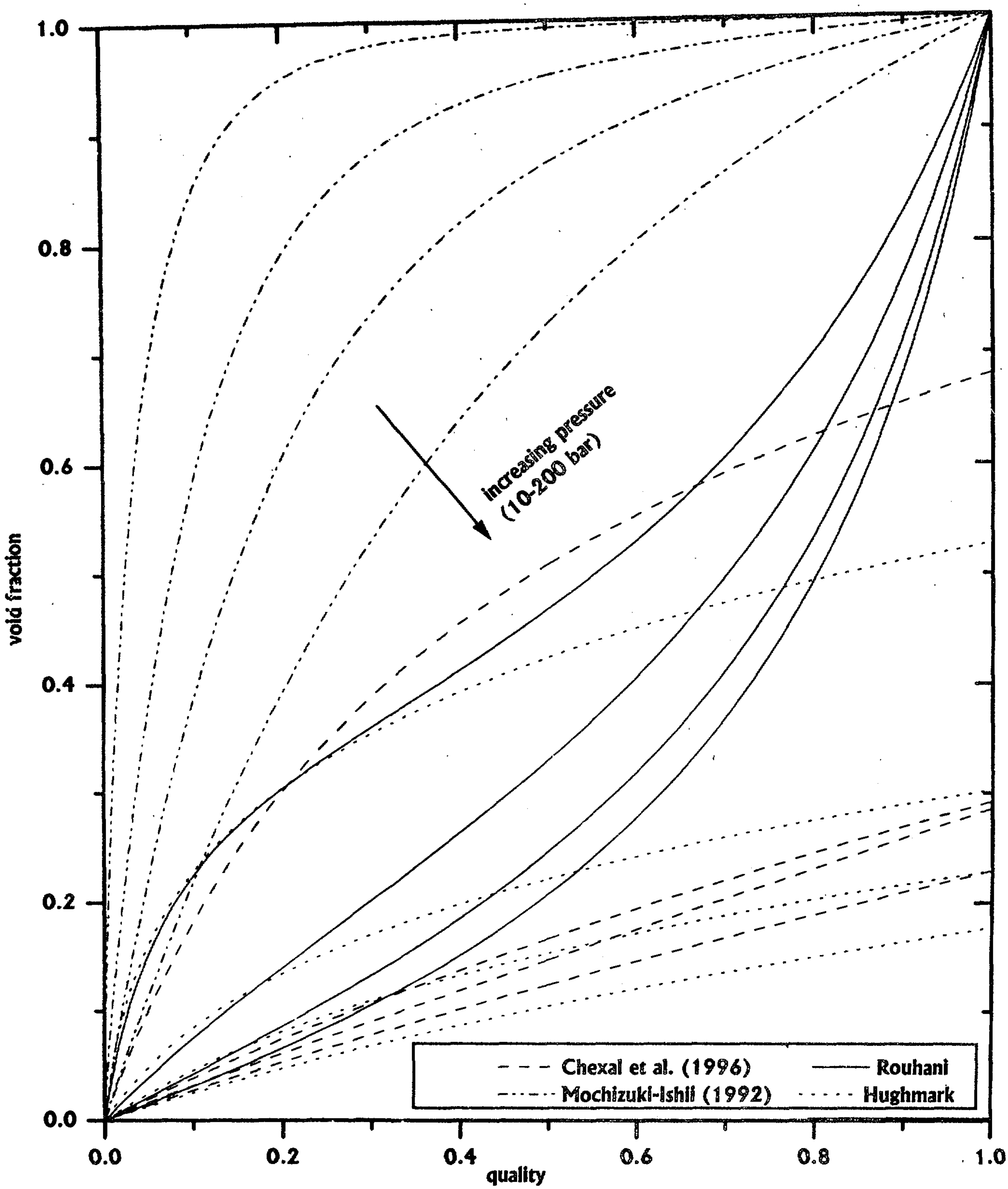

Fig. 19 Comparison of predicted void fractions using various correlations at a mass flux of 5 kgm^{-2}s^{-1} and at 10, 70, 140 and 200 bar for steam-water flow in a 25.4 mm i.d. tube

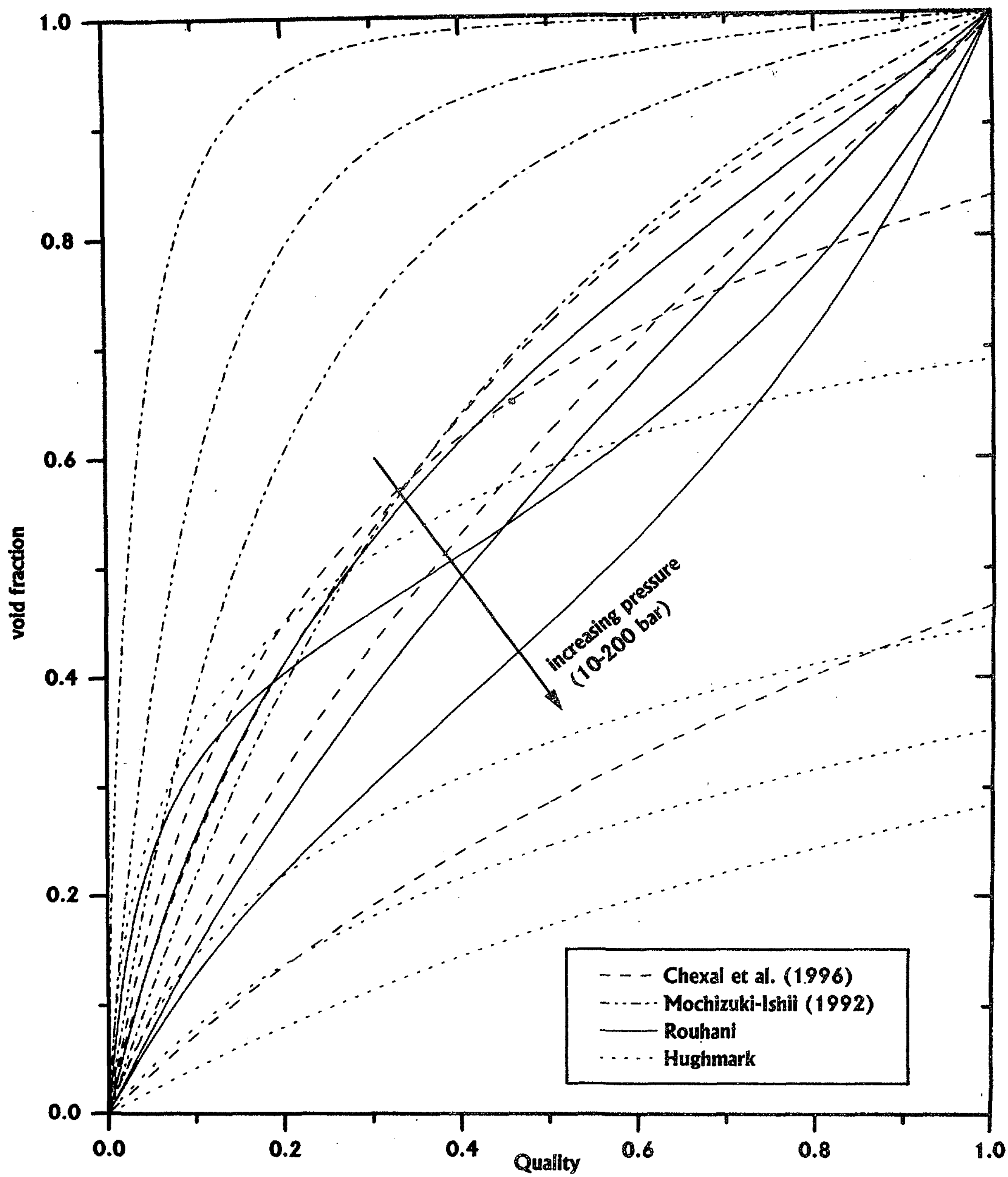

Fig. 20 Comparison of predicted void fractions using various correlations for steam-water flow at a mass flux of 10 $kgm^{-2}s^{-1}$ and at 10, 70, 140 and 200 bar in a 25.4 mm i.d. tube

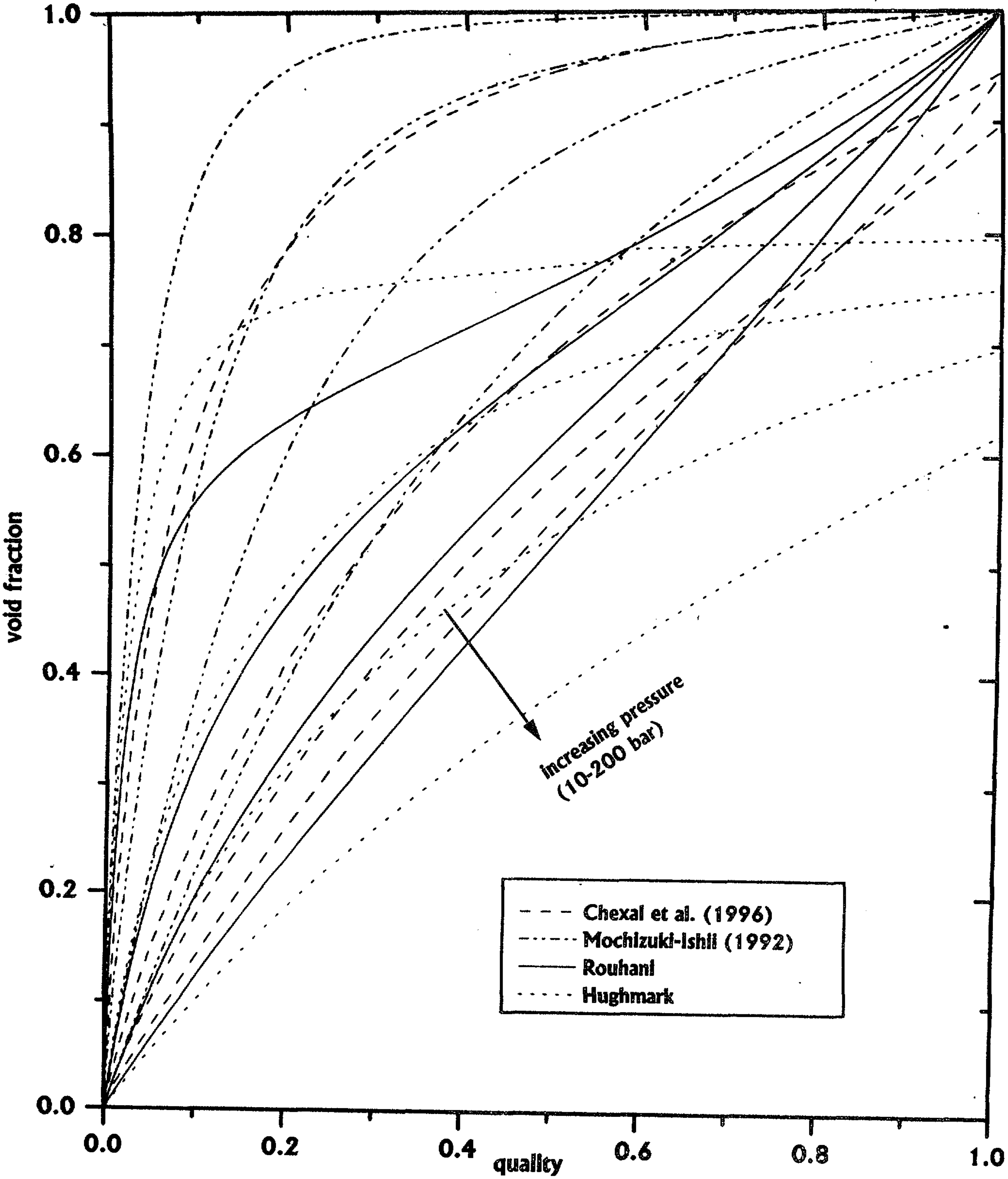

Fig. 21 Comparison of predicted void fractions using various correlations at 50 $kgm^{-2}s^{-1}$ and at 10, 70, 140 and 200 bar for steam-water flow in a 25.4 mm i.d. tube

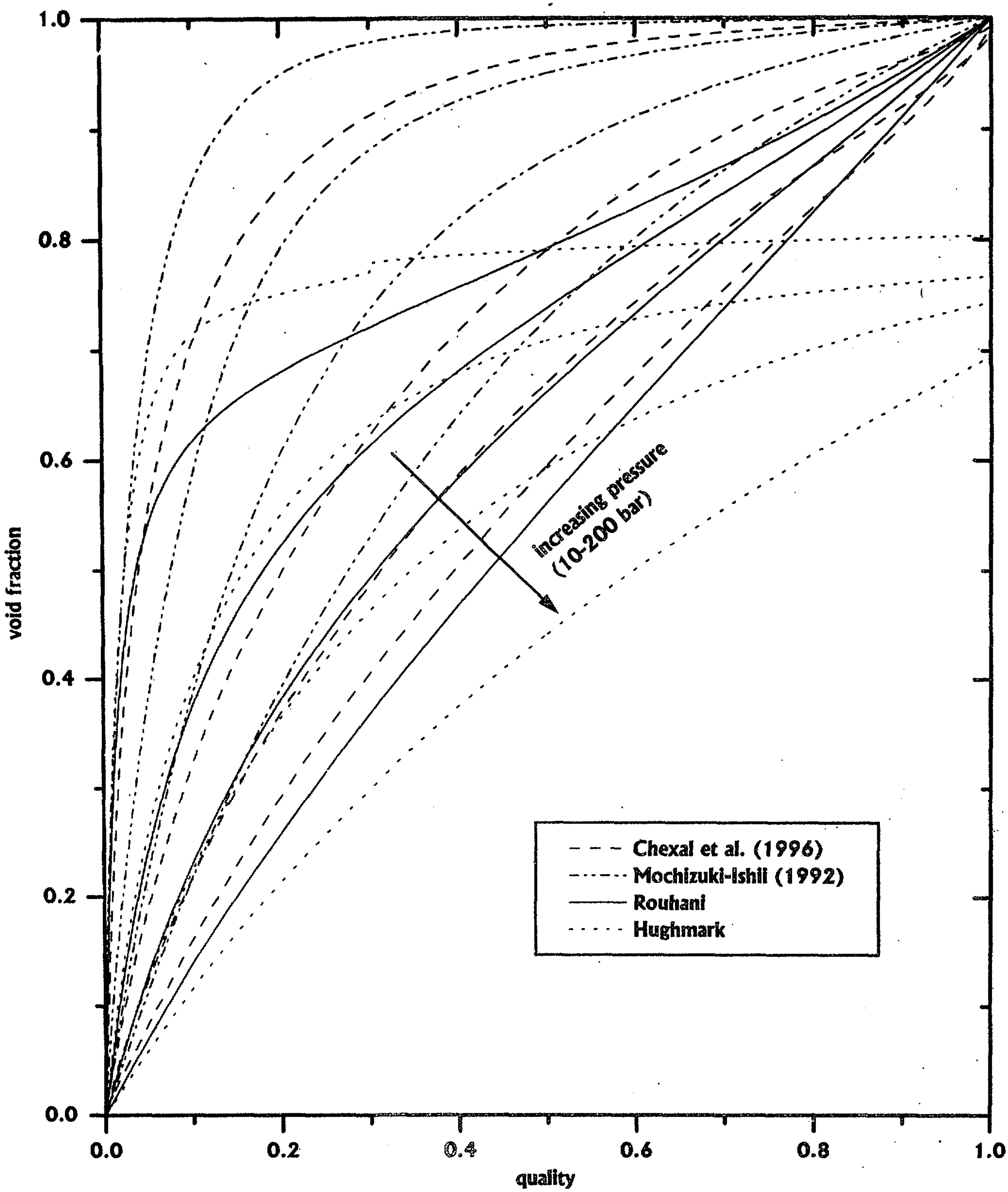

Fig. 22 Comparison of predicted void fractions using various correlations for steam-water flow at a mass flux of 75 $kgm^{-2}s^{-1}$ and at 10, 70, 140 and 200 bar in a 25.4 mm i.d. tube

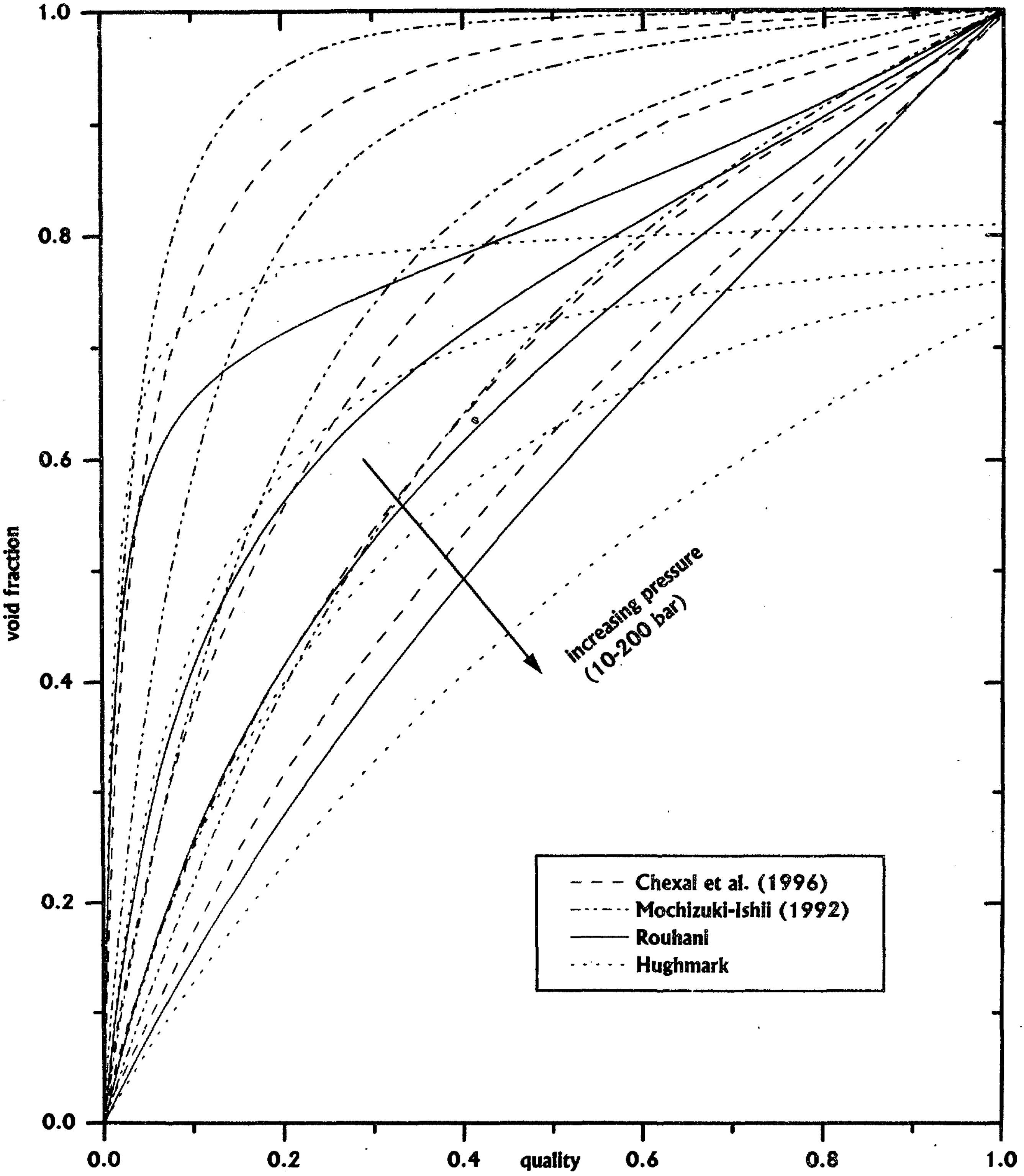

Fig. 23 Comparison of predicted void fractions using various correlations for steam-water flow at a mass flux of 100 $kgm^{-2}s^{-1}$ and at 10, 70, 140 and 200 bar in a 25.4 mm i.d. tube

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