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ABSTRACT

An extensive analysis shows that published two-phase friction data conform to a series of distinct trends. This suggests that the different characteristics are associated with different flow regimes.

Flow regime boundaries are clearly indicated when the data are plotted according to the method described. Apparent discrepancies or data scatter are resolved by recognising that more than one flow regime may sometimes exist for a given set of flow conditions.

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CONTENTS

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CONTENTS (continued)

1. INTRODUCTION

Pressure drops associated with the flow of a two-phase mixture comprise terms for the fluid head, acceleration, and two-phase friction, none of which can be said to be properly understood. However, the losses attributable to head and acceleration are usually a small part of the total, and satisfactory pressure loss calculations depend on the accuracy with which the frictional component is evaluated.

The present state of knowledge on two-phase friction is far from satisfactory. Analytic models based on single-phase theory expectedly disagree with experiment, and more refined theoretical approaches are limited by a lack of detailed knowledge of the flow structure.

Empirical or semi-empirical models differ widely in their predictions. This may be because:

(i) The pressure drop behaviour is different for different types of two-phase flow, and different correlations result from the fact that differing flow regimes occur under the same nominal operating conditions. This aspect of two-phase flow has generally been neglected in pressure loss work.

(ii) Different models may apply to very different ranges of the parameters. The dependence on a particular parameter may not be noticed if the range of experimental values of the parameter is not sufficiently wide.

(iii) An experimental rig may be such that the flow is underdeveloped in the test section, and upstream pipework may considerably influence the flow. ('Developed' flow is taken to mean flow in which entrance effects have disappeared.)

The work reported here is an examination of the characteristics of two-phase friction data.

2. TWO-PHASE PRESSURE DROP DATA

Many of the two-phase pressure drop data available are presented with too little information. One reason for this is a tendency to present data in terms of the Lockhart-Martinelli parameters (Ref. 1). This makes data difficult to analyse, and in addition:

(i) the scatter on the data becomes less apparent, as noted by various authors (e.g. Ref. 2) as well as in written discussion accompanying Reference 1, and

(ii) values of an important parameter, the mass velocity, are often omitted.

This omission is surprising since a strong mass velocity dependence was shown in data presented during the discussion which followed the original paper. It is even more surprising since, as is shown by Levy (Ref. 3), the data used by Lockhart and Martinelli to obtain the mass velocity independent correlation for their 'viscous-viscous' region contain a strong mass velocity dependence.

Many references have given pressure drop data as a secondary consideration. This is particularly so for references dealing with the heat transfer crisis. Both this limit and section pressure loss characteristics are determined by flow behaviour near the heated wall. It is surprising that test section instrumentation often consists only of burnout detectors; the crisis phenomena is more likely to be understood when corresponding data are also obtained which provide information on the flow structure and behaviour. In fact, where sufficient instrumentation is used, sudden changes in the trend of one measured quantity are generally seen to be accompanied by changes in the trend of others.

The data of Klyushnev and Tarasova (Ref. 4) and Tarasova et al. (Ref. 5) deserve some comment. Both references discuss work performed by the same group. While the experimental approach seems reasonable, the presentation of the results seems to be lax. The same data plotted in the two references show several corresponding points with differing values; in the second reference labels for round tube data and annulus data appear to be interchanged; local multipliers are unfortunately compared with curves for integrated multiplier values from Martinelli and Nelson (Ref. 20); and, in general, insufficient information is given concerning the data.

The CISE team (Centro Informazioni Studi Esperienze, Italy) used well-instrumented rigs, the experiments were performed systematically, and sufficiently extensive data are presented to permit a detailed investigation of the characteristics of the two-phase flow conditions. For these reasons, the present work predominantly concentrates on analysing the CISE data presented in References 6 to 13.

Figures 1 to 6 show data obtained from 21 different references from 10 different research groups. The data cover one and two component two-phase fluids under different conditions in a variety of test sections. It is considered that the data used are sufficiently extensive to permit generally valid conclusions to be drawn. Although a large amount of additional data has been examined, none have been found to be inconsistent with the results of this analysis.

3. DATA REDUCTION

In those cases in which values of the two-phase friction multiplier were not provided, the two-phase pressure drop data were analysed with the aid of a computer program. This reduced each experimental value to the frictional pressure gradient by subtracting calculated gravitational losses based on Jones' modification of Bankoff's slip model (Ref. 14) and acceleration losses based on the homogeneous model. In the absence of regime information these models are considered to be adequate. In any case, because of their comparatively small values, errors in the calculation of these components do not affect the accuracy of the calculated friction loss. Diabatic data were converted to local multiplier values by a technique discussed in Appendix 1.

Average values of the frictional pressure gradient along a test section were used to evaluate the two-phase friction multiplier ϕ^2_{LO}. Assuming a simple relation between the two-phase friction multiplier and quality x to be

$$\phi^2_{LO} = 1 + ax^b \qquad \ldots(1)$$

the data were plotted as log $(\phi^2_{LO} - 1)$ against log x.

4. FLOW REGIME EFFECTS

4.1 Flow Regime Boundaries

Log-log plots of $(\phi^2_{LO} - 1)$ against quality, x, result in straight lines, in agreement with the assumed relation. The lines may undergo step changes in slope and these are interpreted as being a result of a change of flow regime.

Such changes may occur in a systematic fashion. In figure 1, the data fall systematically into three distinct regions on the plot, each with its own functional form for 'a' and 'b' of equation (1). As the mass velocity dependence in the higher quality region is readily determined (Figure 2), equation (1) becomes, for the three regions of Figure 1

$$\phi^2_{LO} = 1 + 147\ x^{7/6} \qquad \text{(low quality region)}$$

$$\phi^2_{LO} = 1 + 11.5\ (x/0.059)^{b(G)} \qquad \text{(intermediate quality region)}$$

$$\phi^2_{LO} = 1 + 79\ (G/100)^{-0.59}\ x^{7/6} \qquad \text{(high quality region)}$$

The mass velocity dependent exponent b(G) of the intermediate quality region is long in form, but may be determined due to the requirement of continuity at the 'regime boundary line' between the intermediate quality and high quality regions.

The existence of a fourth region, where data presumably approach the correct unity quality value

$$\left[\frac{\rho_\ell}{\rho_g} \left(\frac{\mu_g}{\mu_\ell} \right)^{0.2} - 1 \right] .$$

is indicated by the start of a downward trend in the lowest mass velocity data of Figure 1.

Regime changes may be induced by heat transfer. An example showing this effect is given in Figure 3. Changes of slope within Figure 3a are small compared to those of Figure 1. This is not unexpected because regime change effects are inherently due to physical differences in the two phases, and since these decrease with increasing pressure, regime change effects are likely to do the same.

Figure 3b indicates a change of structure due to the influence of heat transfer. Clearly, the heat transfer induced structure change is large compared with the changes apparent in Figure 3a. For this particular test section, this characteristic held for all heat transfer conditions to near the critical heat flux, when the characteristics changed to those shown in Figure 3c.

4.2 <u>Apparent Scatter of Data</u>

When data which normally showed considerable scatter were plotted in the log (ϕ^2_{LO} - 1) : log x plane, they were often resolved, rather precisely, into distinct separate lines. Unlike the example in Figure 1, the separate lines were not confined to distinct quality ranges in the plot. It is concluded that the scatter in these data results from more than one regime being possible for a given set of flow conditions.

Examples of data scatter are shown in Figures 4 and 5. The three lines on Figure 5 (for CISE test section 153) correspond to the three regions of Figure 1 which show data obtained at a different pressure for the same test section. The apparently anomalous point in the higher quality region can clearly be associated with the regime applicable to the intermediate quality data and is not a result of erroneous experimentation. This was apparently the interpretation of the CISE group, since this point was omitted from their graphical presentation of the data (Ref. 13). It is noted that their more conventional data plots show neither the rather sharp boundary between different trends in the data nor the similarity between the low and high quality data, both of which are quite clear in the plots given in Figures 1 and 5.

Figure 1 shows another apparently anomalous point, for the 75 g cm^{-2} sec^{-1} data, where a point in the lower quality region in fact conforms to data of the intermediate quality region.

Data showing characteristics similar to the intermediate quality region of Figure 1 are tentatively interpreted as resulting from a form of annular flow.

Data with these characteristics are to some extent non-reproducible and this may be associated with a liquid film thickness having a non-unique equilibrium value. An example showing this non-reproducibility is given in Figure 5 for data from CISE test section 52 (Ref. 11). Both lines pass through the all-gas theoretical value at unit quality, as do lines of other mass velocities for this test section. Although the two sets of data are self-consistent, and both pass through the 'common point' value (see section 4.3.6), they show the extent to which non-reproducibility may occur. The burnout data obtained in the same runs show a similar apparent scatter, having generally lower burnout heat fluxes with the repeated runs. This is consistent with the interpretation that lower frictional values are associated with a thinner liquid film.

It appears that analysis of data in terms of log $(\phi^2_{LO} - 1)$ against log x is useful in interpreting scatter.

4.3 Data Analysis

As stated, two-phase friction data plotted as straight lines for a given set of parameters in the log $(\phi^2_{LO} - 1)$: log x plane. Virtually all data analysed behaved this way. The straight lines could be subdivided into groups with similar characteristics, depending predominantly on the value of 'b' in equation (1). Examples of data showing the various characteristics are given in Figure 6a to 6j. The data in these figures in general cover a sufficient region of the plots with sufficiently small scatter for there to be little doubt as to the slopes of the lines describing the data. In most cases, an alteration of the stated slope by one or two per cent results in a significant misfit of the data.

In many cases the data sets shown in Figures 6a to 6j are not complete. This is not dishonest representation but the result of being able to separate scattered data into distinct trends. The data shown demonstrate particular trends; where points of a set show different but recognisable trends (usually for different quality ranges) they have been omitted. For example, had the high quality region data shown for CISE test section 153 in Figure 5 been included in Figure 6d, the anomalous point at $x \simeq 0.64$ and data for $x \leq 0.4$ would be omitted, as these show differing characteristics.

The straight line plots indicate that data may be described by $\phi^2_{LO} = 1 + a\,x^b$. Figures 6 indicate three broad divisions of the data;

(i) 'b' is a multiple of 1/6;

(ii) $a\,x^b$ is more specifically $(\phi^2_{LO} - 1)_c \left(\frac{x}{x_c}\right)^{b(G)}$, with $[x_c, (\phi^2_{LO} - 1)_c]$ defining a common point in the log $(\phi^2_{LO} - 1)$: log x plane through which all lines for different mass velocities pass; and

(iii) 'b' is slightly less than unity.

These groupings are discussed in more detail in the following paragraphs.

4.3.1 Data characterised by $\phi^2_{LO} = 1 + a\,x^{5/6}$ (Figure 6b)

This is a particularly common characteristic and seems not to be restricted to a limited mass velocity range, geometry range, etc. The tendency for this characteristic to be associated with high flows, and the apparent independence of flow orientation suggests that it is unlikely that gravity plays any significant part in the flow behaviour corresponding to this characteristic.

The well known Martinelli-Nelson graphical correlation for high pressure steam-water flow (Ref. 20), based on data (Ref. 21) from diabatic test sections of spirally coiled tubing can be approximated by

$$\phi^2_{LO} = 1 + \frac{11}{6}\left[\frac{\rho_\ell}{\rho_g}\left(\frac{\mu_g}{\mu_\ell}\right)^{0.2} - 1\right] x^{5/6} \quad .$$

Compare this with the 28 coefficient curve fit of the Martinelli-Nelson curves in Ref. 14..

Hoogendoorn (Ref. 22) gives an expression very close to

$$\phi^2_{LO} = 1 + 230\,x^{5/6}$$

for plug, slug and froth flow in horizontal pipes (2.4, 5, 9.1 and 14 cm dia.) using air-water, air-gas oil, and air-spindle oil. This has been extended (Ref. 23) using Freon 11 liquid-vapour in horizontal 15 cm dia. pipes, to cover a wider $\frac{\rho_\ell}{\rho_g}$ range. The newer correlation, given graphically, is very close to

$$\phi^2_{LO} = 1 + \psi\left(\frac{\rho_\ell}{\rho_g}\right) x^{5/6} \quad .$$

Chenoweth and Martin (Ref. 24), using air-water, air-kerosene, air-benzine and air-diesel oil in pipes 1.2 cm to 9 cm dia. found that for low voidage conditions much of their data was described by

$$\phi^2_{LO} = (1 - \alpha)^{-0.86} \quad .$$

It is readily shown that this may be approximated by

$$\phi^2_{LO} \simeq 1 + \left[\left(\frac{\rho_\ell}{\rho_g} - 1\right) x\right]^{5/6} \quad .$$

Lester (Ref. 25) found that this correlation adequately described his own steam-water data (15.4 cm dia. horizontal pipe), Maskill-Smith's (Ref. 26) steam-water horizontal flow data (10.3 cm dia. pipe), Johnson and Abou-Sabe's (Ref. 27) water-air data (2.2 cm dia.), Alves' (Ref. 28) water-air data (2.67 cm dia.) and Reid's (Ref. 29) air-water data (10 cm and 15 cm dia. pipes).

Wallis (Ref. 30) gives, for a 2.2 cm horizontal pipe with air bubbling through a porous wall

$$\frac{\Delta P}{\Delta P_{LO}} = 1 + (490\ x')^{0.82}$$

where x' is a quantity proportional to quality.

The correlation by Baroczy (Ref. 31), given graphically, is approximated by

$$\phi^2_{LO} = 1 + \psi\left\{G, \frac{\rho_\ell}{\rho_g}\left(\frac{\mu_g}{\mu_\ell}\right)^{0.2}\right\} x^{5/6}$$

for a large region of the correlation. Liquid metal data (mercury-nitrogen data of Ref. 32 and boiling potassium data of Ref. 33) show the same quality exponent.

4.3.2 <u>Data characterised by $\phi^2_{LO} = 1 + a\ x$</u> (Figure 6c)

Only one set of data definitely showed this characteristic. This set was obtained with orifice plates just before the test section, and cannot therefore be regarded as typical. It appears that a quality exponent of unity is not normally encountered in that class of data with an exponent of a multiple of 1/6. It is possible that these data are modified into that class of data with an exponent slightly less than unity (Figure 6j).

4.3.3 <u>Data characterised by $\phi^2_{LO} = 1 + a\ x^{7/6}$</u> (Figure 6d)

The value of 'a' here may or may not be mass velocity dependent. The data shown in Figure 6d are generally independent; examples of mass velocity dependent coefficients are shown for the CISE test section 153 in the high quality regions in Figures 1 and 4.

The exponent of 7/6 appears to be quite general for test section 153. This is not the case for data from CISE test sections 68 and 500, and data shown in Figure 6d from these sections are exceptions. Nevertheless, as can be seen, these data agree well with data obtained at the same pressure from three other sources.

The Martinelli-Nelson (Ref. 20) steam-water correlation for atmospheric pressure, based on the Lockhart-Martinelli correlation, is approximated by $\phi^2_{LO} = 1 + 930\ x^{7/6}$, but no data were given to substantiate this correlation.

Jacob et al. (Ref. 36) give a correlation for the total pressure drop, ΔP, in diabatic horizontal flow of steam-water mixtures in a 0.95 cm dia. tube based on data with a mass velocity range of 54 - 175 g cm^{-2} sec^{-1} and a pressure range of 2 - 14 kg cm^{-2} as

$$\frac{\Delta P}{\Delta P_{LO}} = 1 + (1{,}410 - 520 \log P) x_{out}^{1.17}$$

(with P in psi). They found no evidence of mass velocity dependence. Because of insufficient information, the data of Reference 36 could not be reduced to a friction multiplier. However since the acceleration component should be small a similar quality exponent is expected for the friction component.

4.3.4 Data characterised by $\phi^2_{LO} = 1 + a\, x^{8/6}$ (Figure 6e)

Data showing this characteristic are not common, and all those encountered, with the exception of the Russian data in Figure 6e (the Russian data show certain anomalies - see section 2), were obtained for heat transfer conditions.

4.3.5 Data characterised by $\phi^2_{LO} = 1 + a\, x^{9/6}$ (Figure 6f)

Data in Figure 6f, with the exception of the anomalous Russian data and the four CISE points which are highly inconsistent with other CISE data, all result from horizontal flows with high voidage and low flow rates. It is reasonable to suppose that the characteristics shown in Figure 6f correspond to wave or stratified flow.

Hoogendoorn (Ref. 22) using data based on air-gas oil and air-spindle oil flow in 5, 9.1 and 14 cm dia. pipes correlated wave flow and stratified flow pressure drop by

$$\frac{\Delta P}{\frac{1}{2}\frac{\Delta z}{D}\frac{G^2}{\rho_\ell}} = c\,\frac{\rho_\ell}{\rho_g}\,x^{1.45}$$

with 'c' a function of pipe diameter and pipe roughness. Unlike the data of Isben et al. (Ref. 2) in Figure 6e, Hoogendoorn's data show no dependence on mass velocity.

4.3.6 Data characterised by $\phi^2_{LO} = 1 + (\phi^2_{LO} - 1)_c \left(\frac{x}{x_c}\right)^{b(G)}$ (Figures 6h, 6i)

Examples of this are shown in Figures 1 and 3 as well as 6h and 6i.

This type of behaviour can be subdivided into two groups depending on the value of the common point $[x_c, (\phi^2_{LO} - 1)_c]$; one group where the value of $(\phi^2_{LO} - 1)_c$ is the theoretical value of $(\phi^2_{LO} - 1)$ at unit quality, and the other where it is not. Both are shown in Figure 3, and both are interpreted as being associated with an annular flow.

Those data which have $(\phi^2_{LO} - 1)_c$ identical to the theoretical unit quality value have $x_c \geq 1$. This behaviour often appears just before burnout; the implication of this will be discussed in a future report.

Sher and Green (Ref. 40) have correlated their data with curves having similar characteristics. Their friction data are, however, subject to considerable errors resulting from having large acceleration loss contributions in the total pressure losses measured.

4.3.7 Data characterised by $\phi^2_{LO} = 1 + a\,x^b$ with $b \sim 0.94$ (Figure 6j)

The trend shown by data in Figure 6j is similar to trends shown in Figures 6a to 6g, except that 'b' is not quite a multiple of 1/6. (It has already been noted that data characterised by b = 1 are uncommon). Furthermore, a unique value of 'b' does not describe the data unless a somewhat larger discrepancy is tolerated for the curve fits of Figure 6j than occurs generally in Figures 6a to 6g.

Further examples of this characteristic are shown in Figure 3a.

Correlations with a quality exponent slightly less than one have been reported in the literature. Wallis (Ref. 30) correlated data for water flow with air injected from porous walls along the test section (simulating diabatic one-component flow) with exponents of 0.96 and 0.94 for two different diameter pipes, and Becker et al. (Refs. 45-48) correlate results from diabatic steam-water flow by

$$\phi^2_{LO} = 1 + 2400\left(\frac{x}{P}\right)^{0.96}, \quad (P \text{ in Kg cm}^{-2})$$

with no apparent influence of mass velocity or tube diameter. The graphs in References 45-48 however, show a noticeable mass velocity effect and the quality exponent is not 0.96. The equation in fact appears to be an optimised curve where mass velocity effects are neglected.

4.3.8 Characteristics not shown in Figures 6a to 6j

Only a selected set of values of n have been used in demonstrating the behaviour as $\phi^2_{LO} = 1 + a\,x^{n/6}$. Data with values of n outside the range $5 \leq n \leq 11$ have not been included since these data generally do not cover a sufficient region of the log $(\phi^2_{LO} - 1)$: log x plane for the slope to be determined with accuracy. For example, Figure 4 shows some data with a quality exponent which cannot be determined accurately but is in the vicinity of 3.5; and the non-conforming 50 g cm^{-2} sec^{-1} data of Figure 6c can, with some uncertainty, be described by a line of slope 1/6.

In addition to this, some data exist (mainly from annular sections) with an exponent of 13/12. These data show little dependence on mass velocity and heat flux.

5. DISCUSSION

As was suggested in the introduction, differences in predictions of empirical or semi-empirical equations for two-phase friction are partly due to different equations being obtained for different flow regimes.

It is surprising that differing characteristics, which might be intuitively expected, have not been noticed (even when looked for, e.g. in Ref. 13) and that statements appear in the literature suggesting that such effects are at most second order.

To the author's knowledge, only five references consider regime effects: Hoogendoorn (Ref. 22) gives separate equations for different regimes; Baker (Ref. 49) gives different correlations in terms of the Lockhart-Martinelli parameter for different regimes; two references (Refs. 50, 51) in which data are separated according to the frictional characteristics; and a further reference in which regime boundaries appear to be associated with non-developed flow (Ref. 4).

A thorough examination of the other two postulated causes for differing equations (neglect of parametric effects and entrance effects) is outside the scope of this report. There are, however, indications that parameters generally neglected can be important (Figure 3 shows the influence of heat transfer, a generally neglected parameter) and that, in certain cases entrance effects influence the frictional behaviour (an example is discussed in section 4.3.3).

6. CONCLUSION

Two-phase friction data tend to conform to one of a number of distinct and separate behaviour characteristics. These are ascribed to different two-phase flow patterns.

Data, in general, plot as straight lines on the log $(\phi_{LO}^2 - 1)$: log x plane. Regime changes are indicated by step changes in the slopes of the lines. Data scatter is often resolved into distinct lines on the plane, suggesting that the scatter is due to the fact that different flow regimes may sometimes occur for a given set of flow conditions.

The straight line plots indicated that data may be described by

$$\phi_{LO}^2 = 1 + a\,x^b$$

The separate behaviour patterns may be divided into three broad groupings:

(i) 'b' is a multiple of 1/6,

(ii) ax^b is more specifically $(\phi_{LO}^2 - 1)_c \left(\frac{x}{x_c}\right)^{b(G)}$, with $[x_c, (\phi_{LO}^2 - 1)_c]$ defining a common point on the log $(\phi_{LO}^2 - 1)$: log x plane through which all lines for different mass velocities pass, and

(iii) 'b' has a value slightly less than unity.

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APPENDIX 1

LOCAL MULTIPLIERS FROM DIABATIC FLOW FRICTIONAL PRESSURE GRADIENTS IN UNIFORMLY HEATED DUCTS

Suppose that locally, $\phi^2_{LO} = 1 + a\,x^b$ is valid over the whole test section (Negative inlet qualities are excluded from this analysis).

Then the total pressure loss due to friction is

$$\Delta P_f = \int \frac{\partial P}{\partial z}\bigg|_{f_{LO}} (1 + a\,x^b)\,dz$$

But, from a heat balance, $dz = k'dx$

$$\therefore \Delta P_f = k' \frac{\partial P}{\partial z}\bigg|_{f_{LO}} \int_{x_{in}}^{x_{out}} (1 + a\,x^b)\,dx$$

$$= k' \frac{\partial P}{\partial z}\bigg|_{f_{LO}} \left[x_{out} - x_{in} + \frac{a}{1+b}\left(x_{out}^{1+b} - x_{in}^{1+b}\right)\right]$$

But $\int dz = k'(x_{out} - x_{in})$

$$\therefore \frac{\Delta P_f}{\Delta P_{f_{LO}}} = 1 + \frac{a}{1+b}\,\frac{x_{out}^{1+b} - x_{in}^{1+b}}{x_{out} - x_{in}} \simeq 1 + a\left(\frac{x_{out} + x_{in}}{2}\right)^b$$

$$= 1 + a\,x_{av}^b = \phi^2_{LO}(x_{av})$$

The approximation is exact for b = 0 or b = 1, and is reasonable for all values of b encountered, particularly if the quality increment over the test section is small.

Hence, for uniformly heated ducts, $\frac{\Delta P_f}{\Delta P_{f_{LO}}}$ is regarded as being equivalent to the value of the local multiplier at the quality of the test section midpoint.

NOTATION

a, b	coefficients in assumed form of ϕ^2_{LO}
D	diameter
f	friction factor
G	mass velocity
k', k"	constants
n	integer
P	pressure
x	quality $\left(\dfrac{G_g}{G_g + G_\ell}\right)$
z	axial direction, length
α	voidage
μ	viscosity
ρ	density
ϕ^2_{LO}	two-phase frictional multiplier $\left.\dfrac{\partial P}{\partial z}\right\|_f \Big/ \left.\dfrac{\partial P}{\partial z}\right\|_{f_{LO}}$

SUBSCRIPTS

c	'common' (see Figures 6h, 6i)
f	frictional component
g	gas phase
ℓ	liquid phase
LO	value which would exist if the flow were liquid flowing with the mixture mass velocity
<--->	average value of quantity over flow cross section

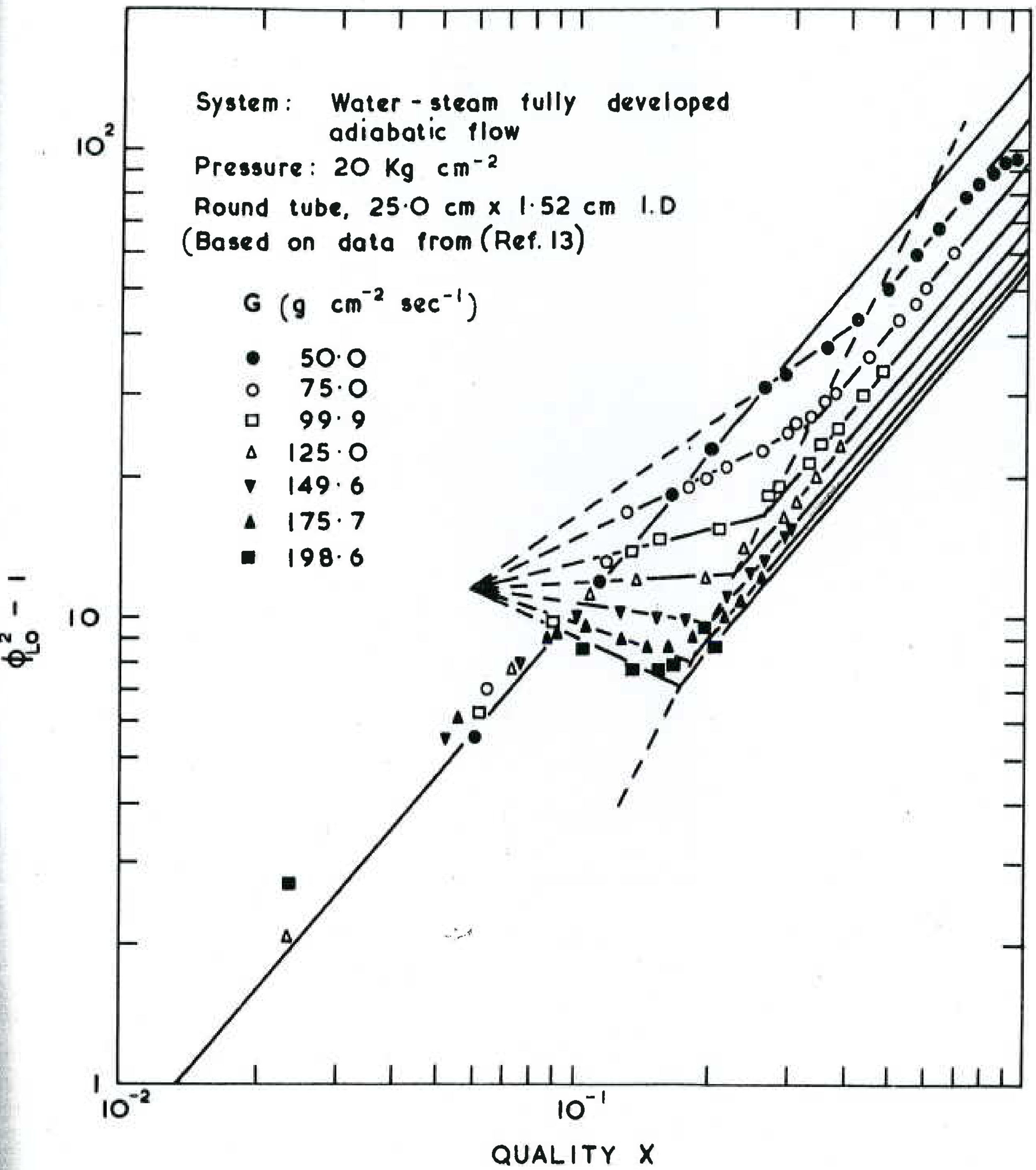


FIGURE 1. REGIME CHANGE EFFECTS IN TWO-PHASE FRICTION

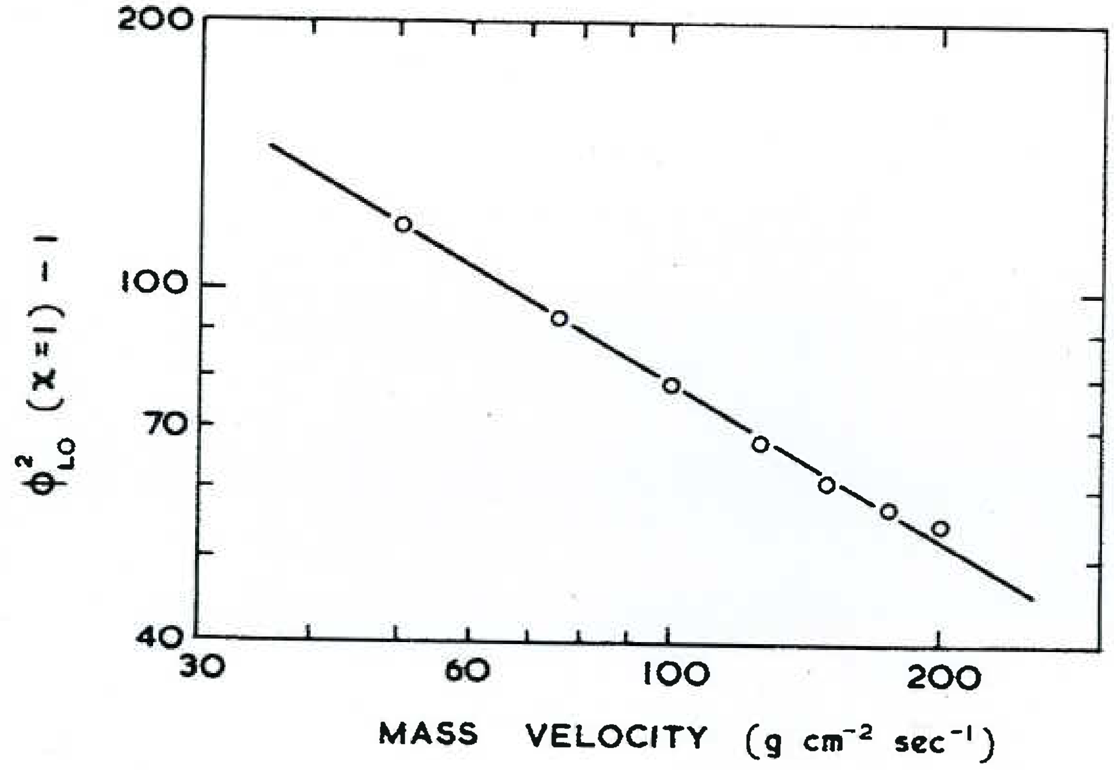


FIGURE 2. DETERMINATION OF MASS VELOCITY DEPENDENCE IN FIGURE 1.

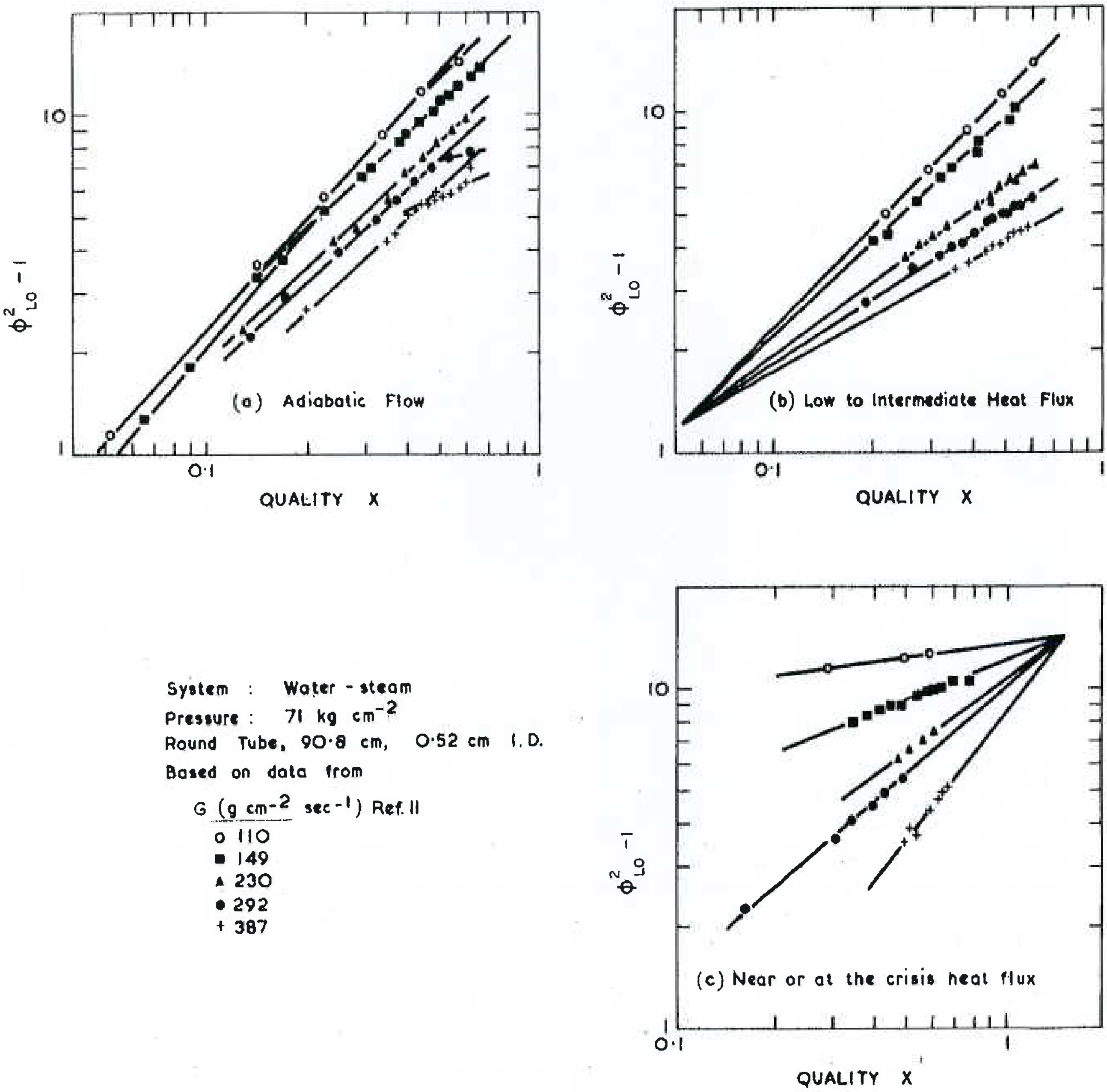


FIGURE 3. EFFECT OF HEAT TRANSFER ON TWO PHASE FRICTION

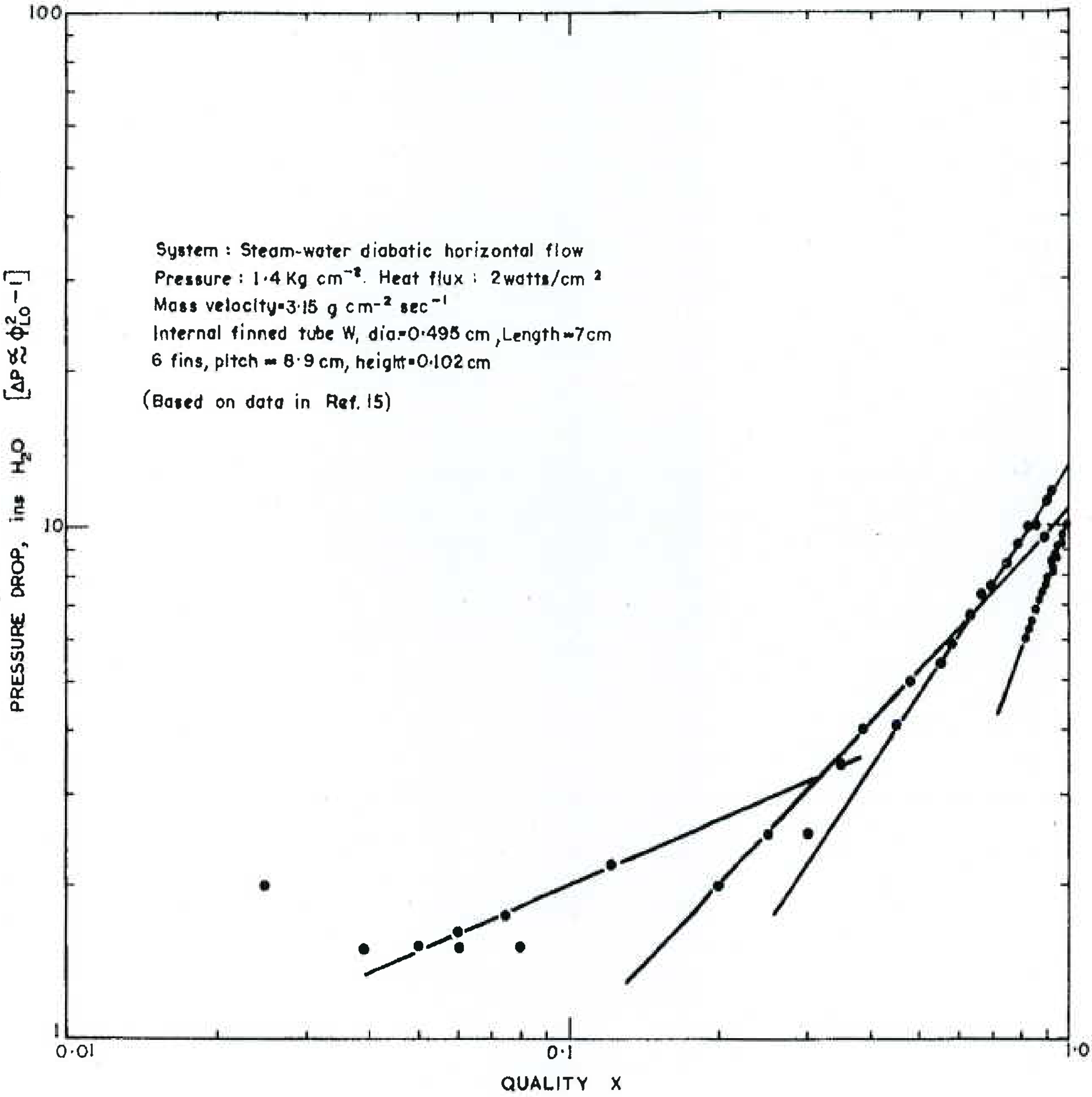


FIGURE 4. DATA SCATTER CAUSED BY FLOW REGIME EFFECTS (HORIZONTAL FLOW)

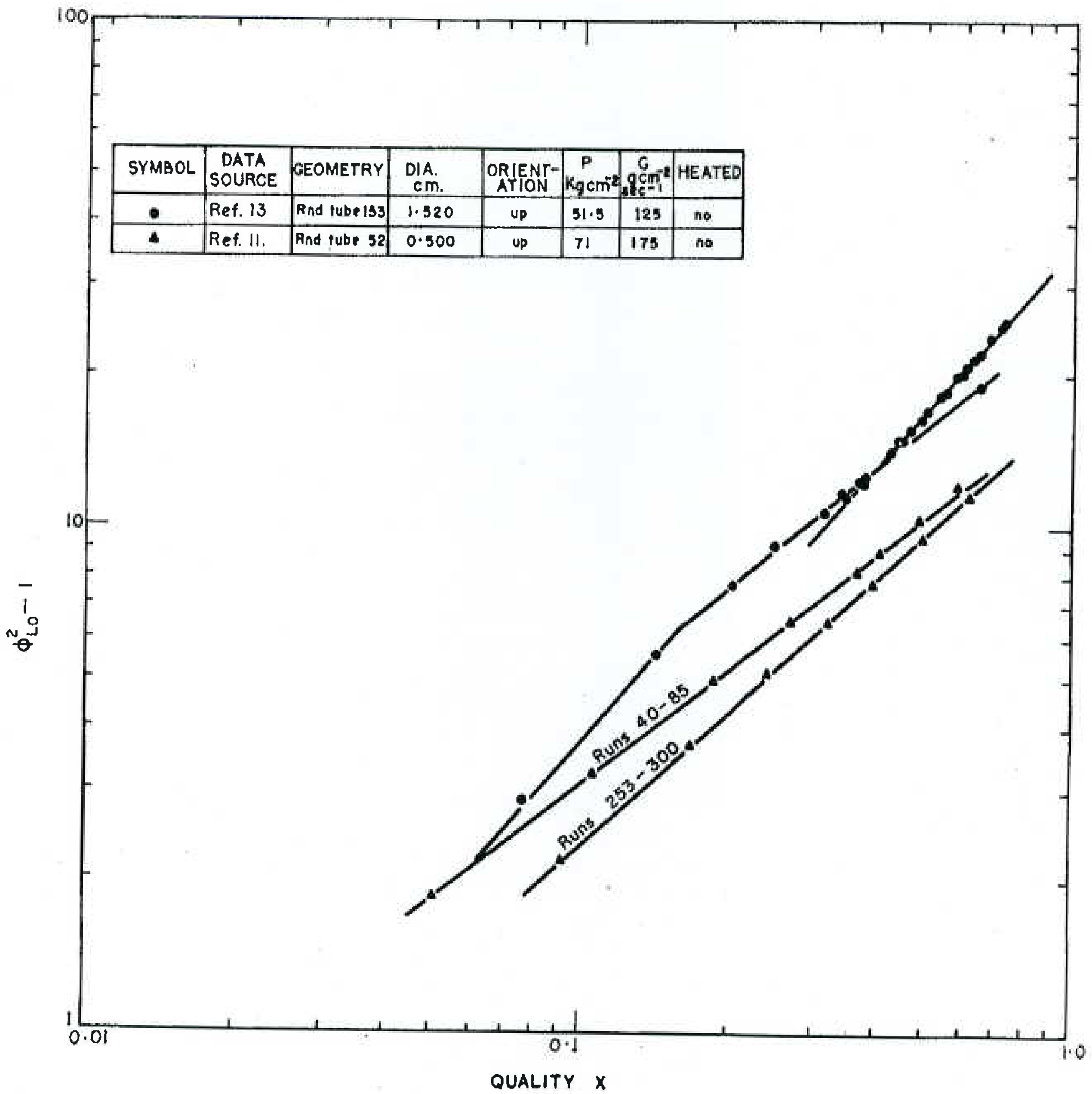


FIGURE 5. DATA SCATTER CAUSED BY FLOW REGIME EFFECTS (VERTICAL UPFLOW)

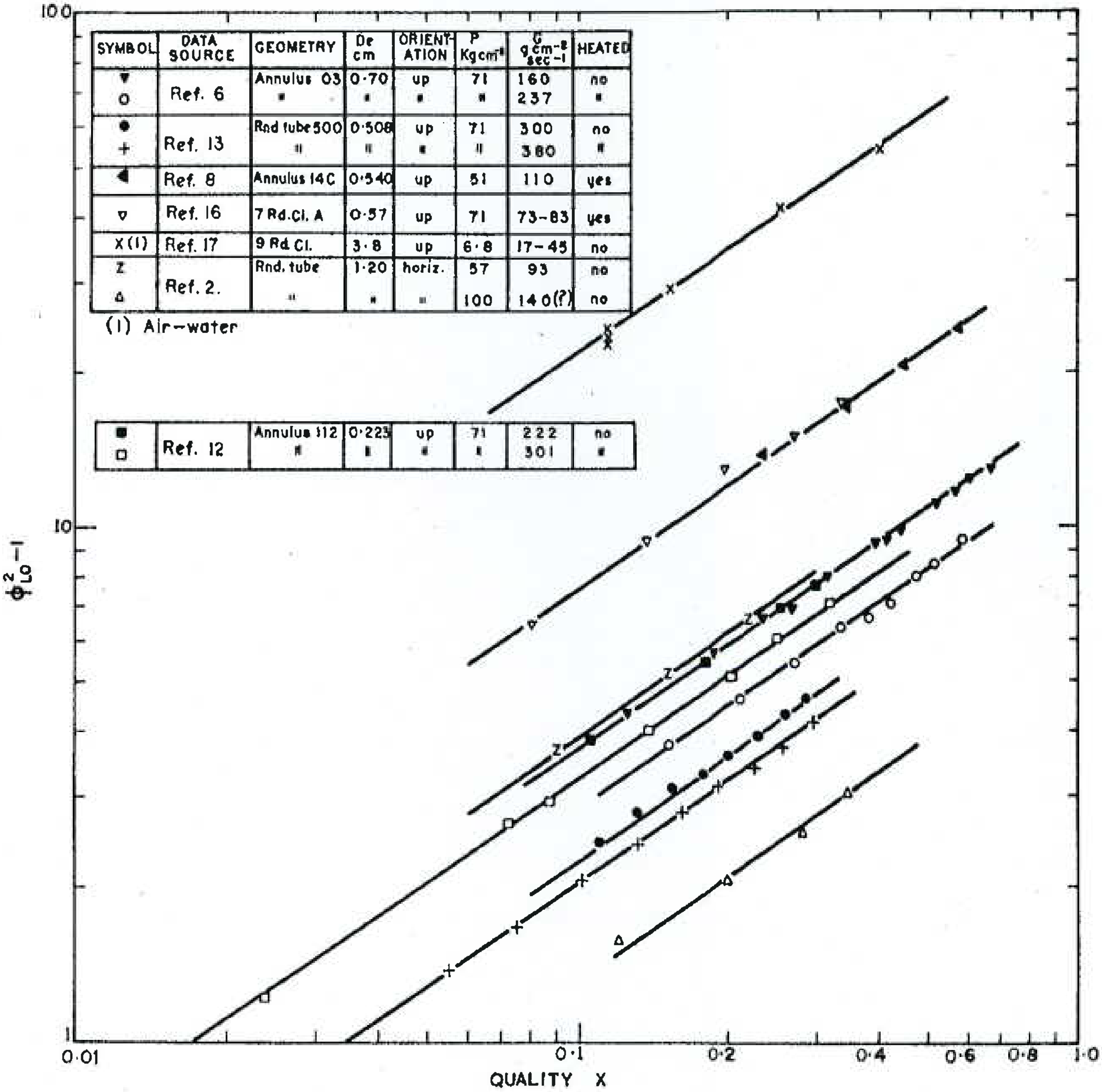


FIGURE 6a. DATA CHARACTERISED BY $\phi^2_{LO}-1+ax^{4/6}$

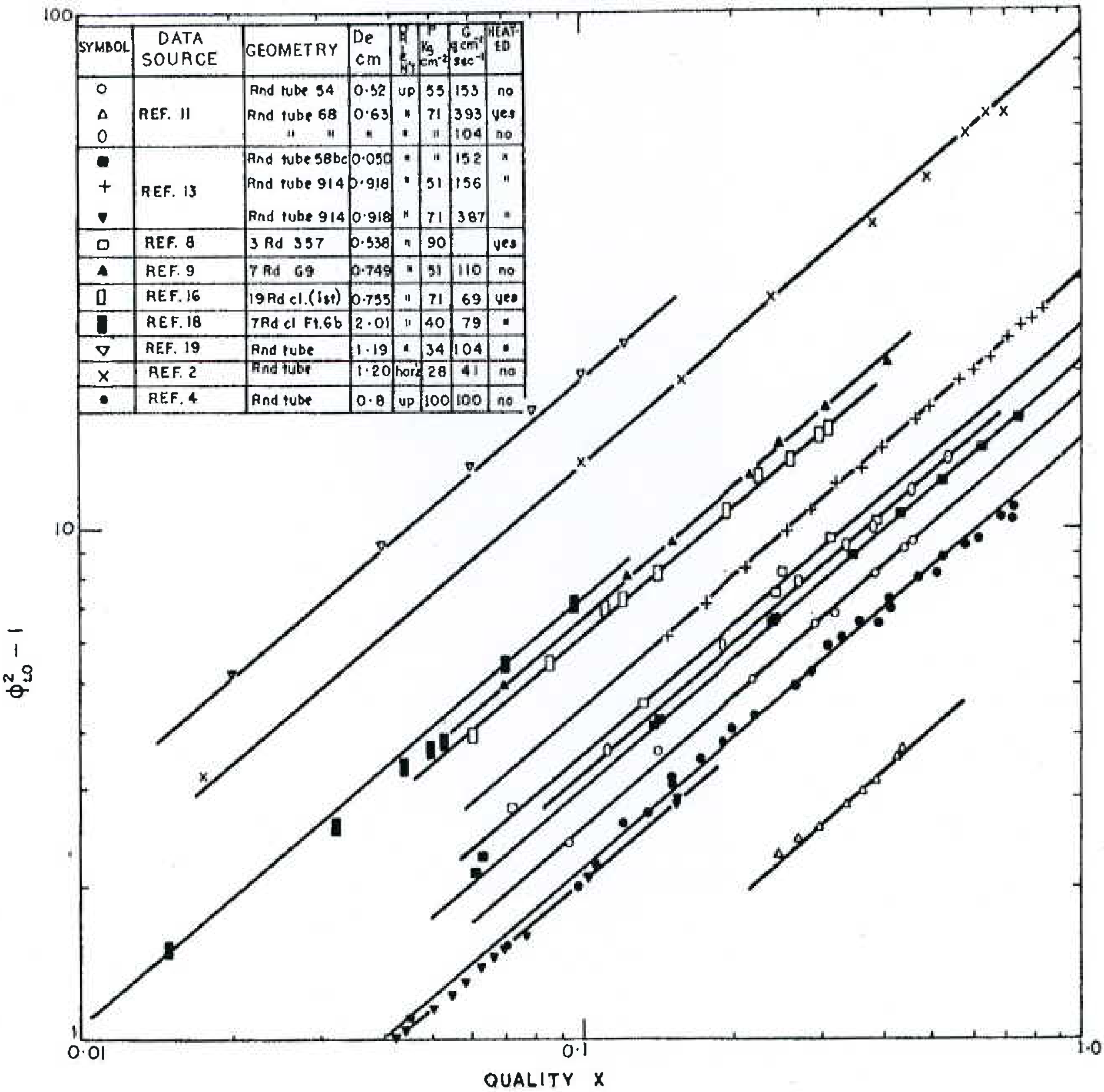


FIGURE 6b. DATA CHARACTERISED BY $\phi^2_{LO} - 1 + a x^{5/6}$

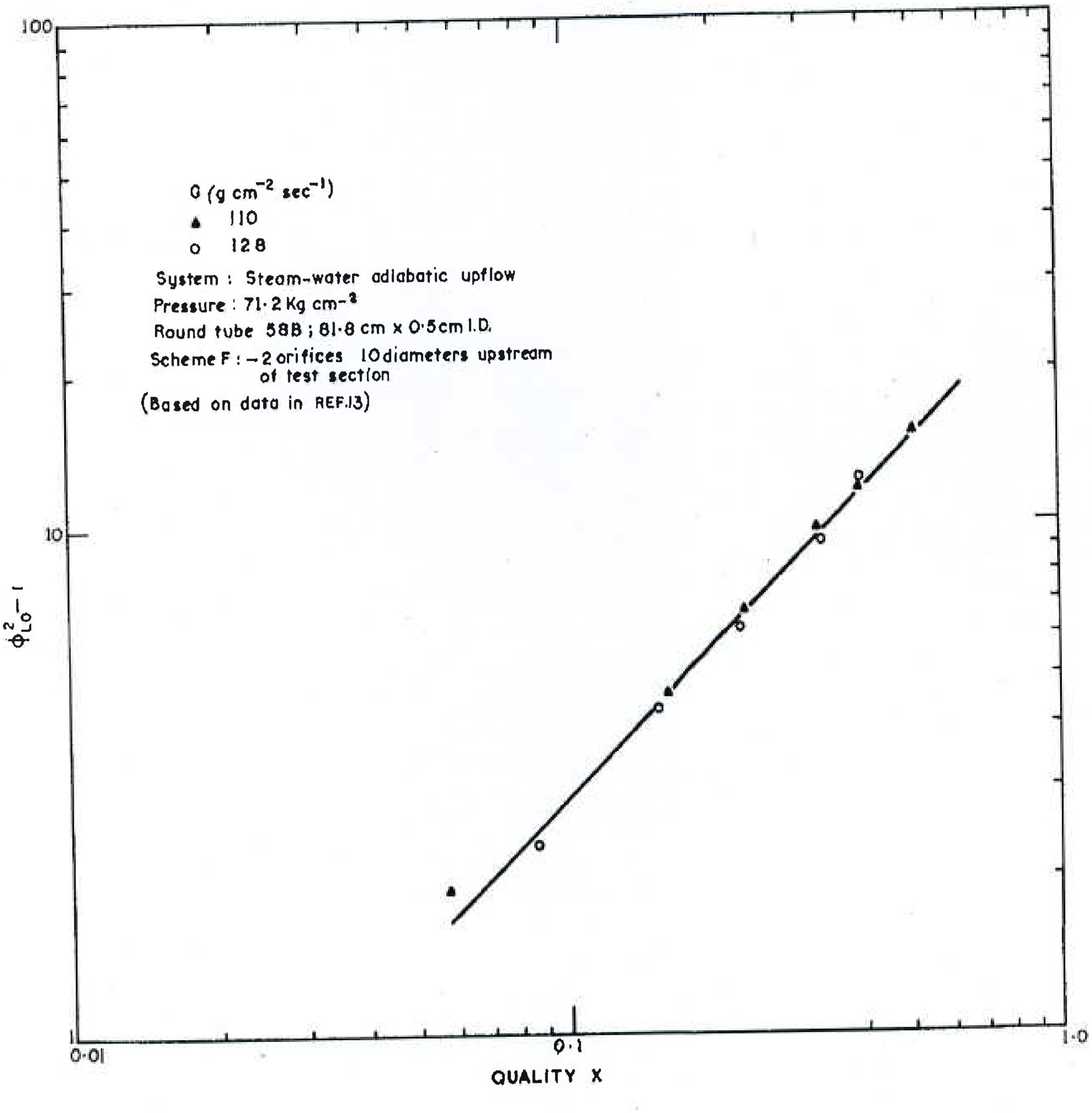


FIGURE 6c. DATA CHARACTERISED BY $\phi^2_{LO} = 1 + ax^{6/6}$

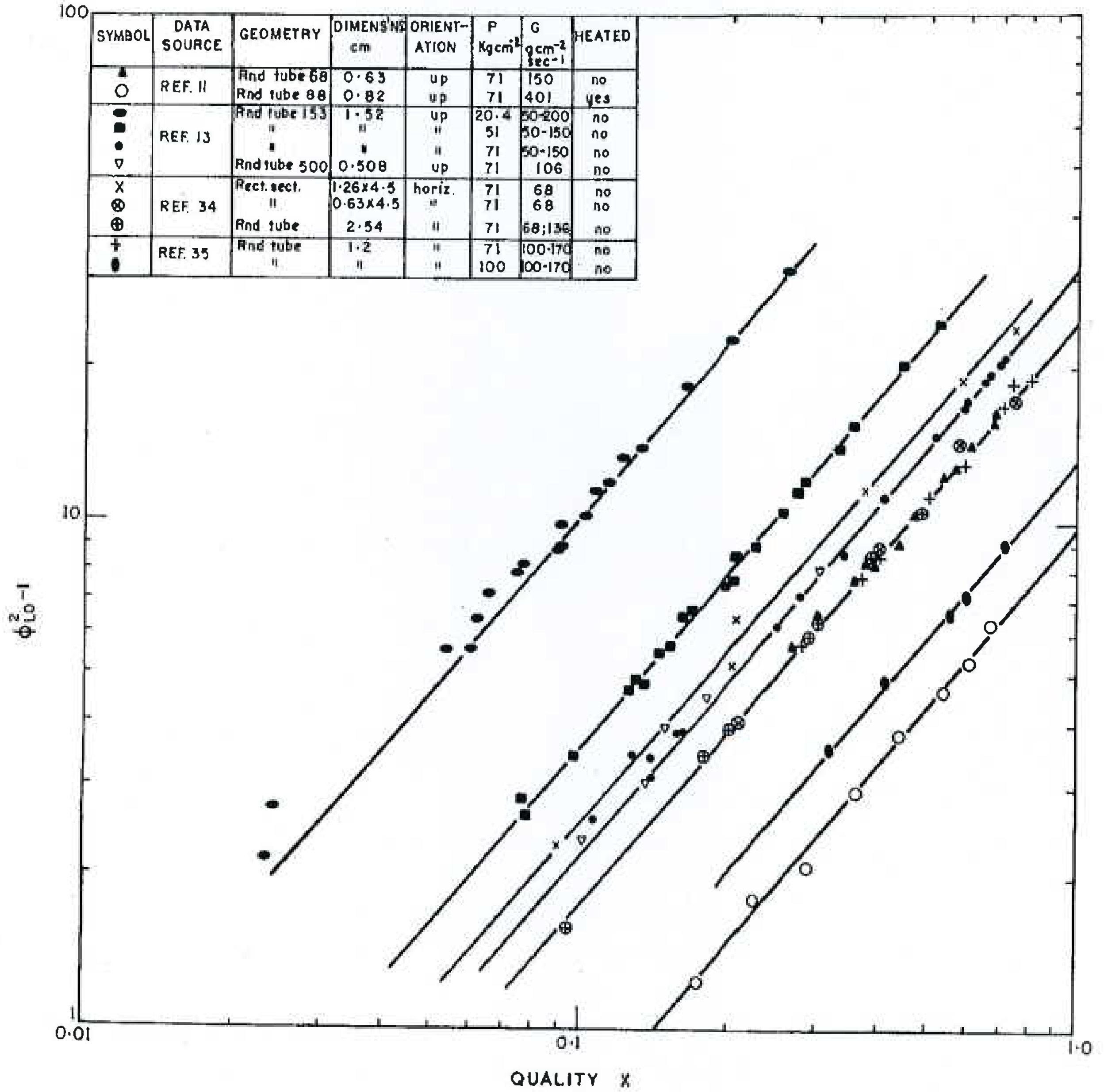
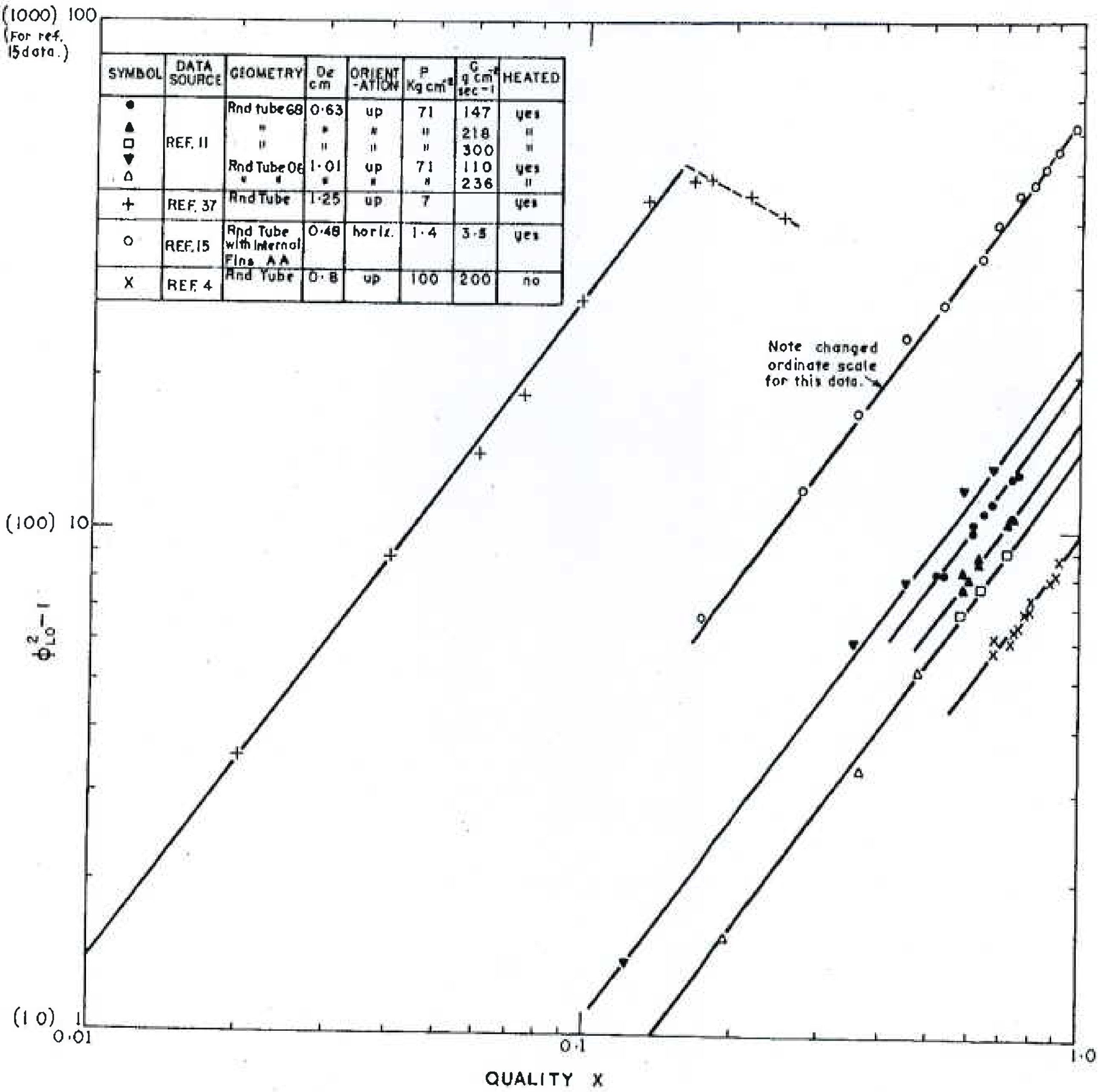
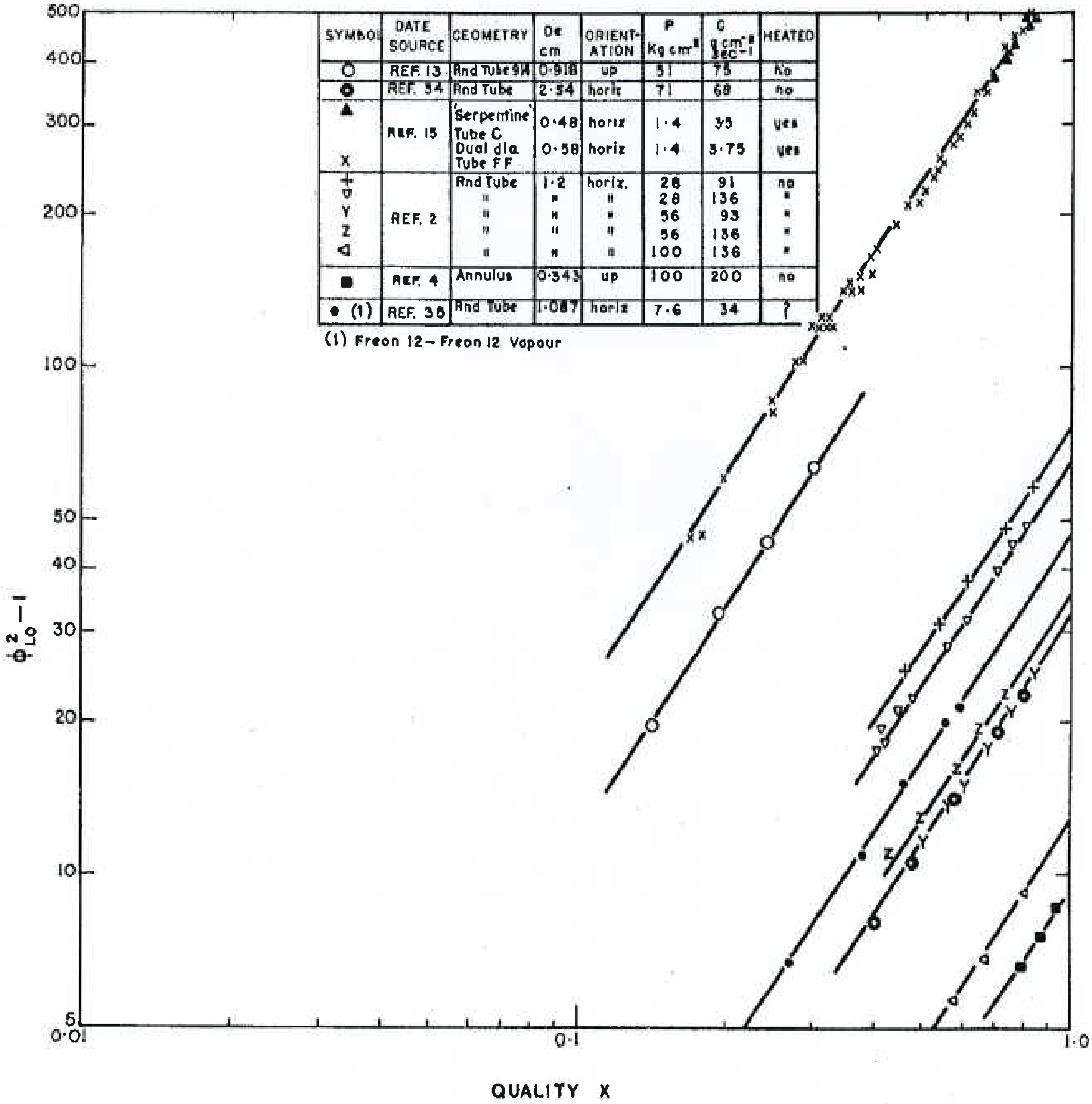


FIGURE 6d. DATA CHARACTERISED BY $\phi^2_{LO} = 1 + ax^{7/6}$



SYMBOL	DATA SOURCE	GEOMETRY	De cm	ORIENT-ATION	P Kg cm⁻²	G g cm⁻² sec⁻¹	HEATED
●	REF. 11	Rnd tube 68	0·63	up	71	147	yes
▲		"	"	"	"	218	"
□		"	"	"	"	300	"
▼		Rnd Tube 06	1·01	up	71	110	yes
△		" "	"	"	"	236	"
+	REF. 37	Rnd Tube	1·25	up	7		yes
○	REF. 15	Rnd Tube with internal Fins AA	0·48	horiz.	1·4	3·5	yes
X	REF. 4	Rnd Tube	0·8	up	100	200	no

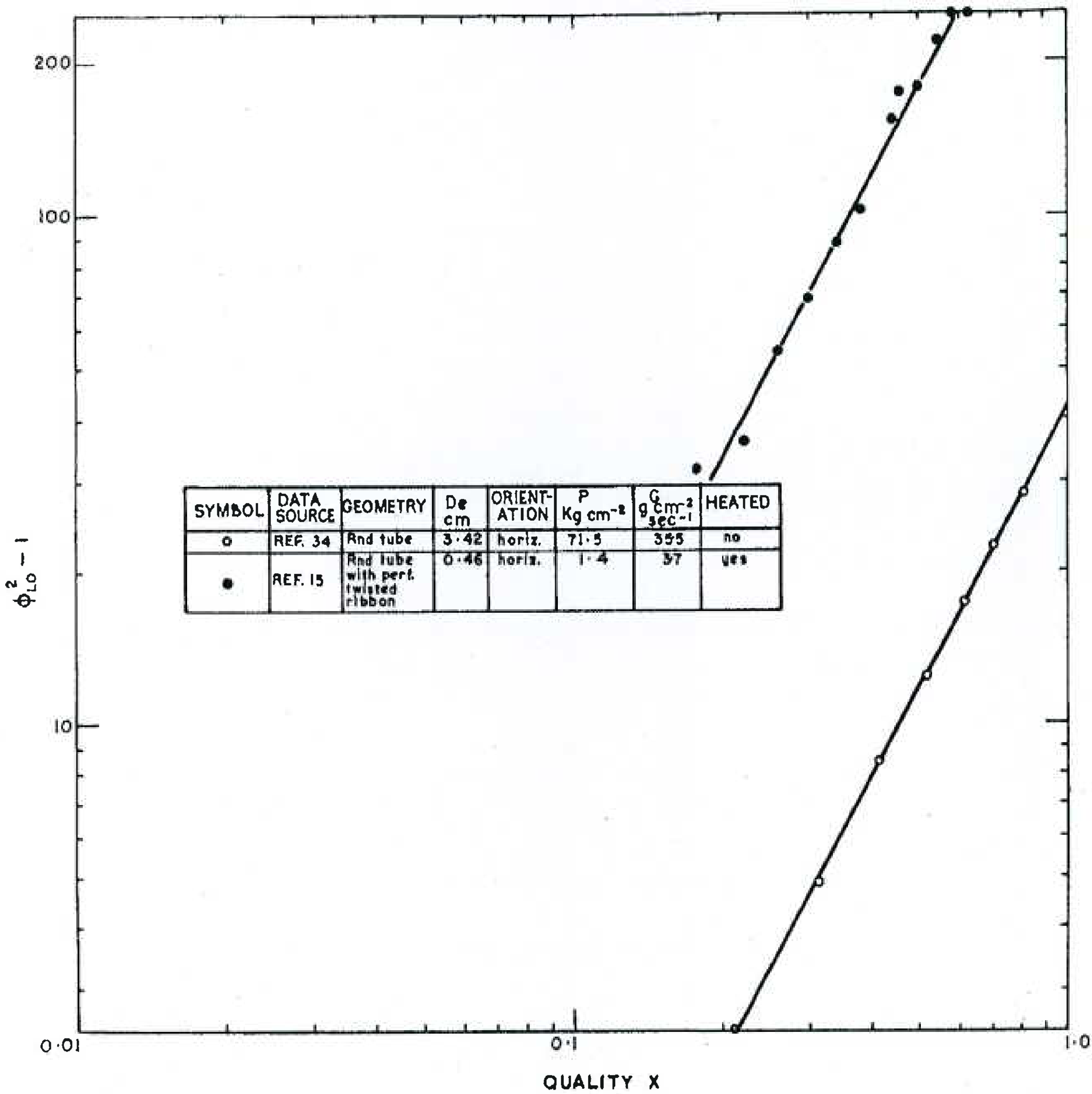
FIGURE 6e. DATA CHARACTERISED BY $\phi_{LO}^2 = 1 + a x^{8/6}$



SYMBOL	DATE SOURCE	GEOMETRY	De cm	ORIENT-ATION	P Kg cm^{-2}	G g cm^{-2} sec^{-1}	HEATED
○	REF. 13	Rnd Tube 9M	0·918	up	51	75	No
⊙	REF. 34	Rnd Tube	2·54	horiz	71	68	no
▲	REF. 15	'Serpentine' Tube C	0·48	horiz	1·4	35	yes
X		Dual dia Tube FF	0·58	horiz	1·4	3·75	yes
+	REF. 2	Rnd Tube	1·2	horiz.	28	91	no
▽		"	"	"	28	136	"
Y		"	"	"	56	93	"
Z		"	"	"	56	136	"
◁		"	"	"	100	136	"
■	REF. 4	Annulus	0·343	up	100	200	no
● (1)	REF. 38	Rnd Tube	1·087	horiz	7·6	34	?

(1) Freon 12 – Freon 12 Vapour

FIGURE 6f. DATA CHARACTERISED BY $\phi_{LO}^2 = 1 + a x^{9/6}$



SYMBOL	DATA SOURCE	GEOMETRY	De cm	ORIENT-ATION	P Kg cm^{-2}	G g cm^{-2} sec^{-1}	HEATED
o	REF. 34	Rnd tube	3·42	horiz.	71·5	355	no
●	REF. 15	Rnd tube with perf. twisted ribbon	0·46	horiz.	1·4	37	yes

FIGURE 6g. DATA CHARACTERISED BY $\phi_{LO}^2 - 1 + ax^{11/6}$

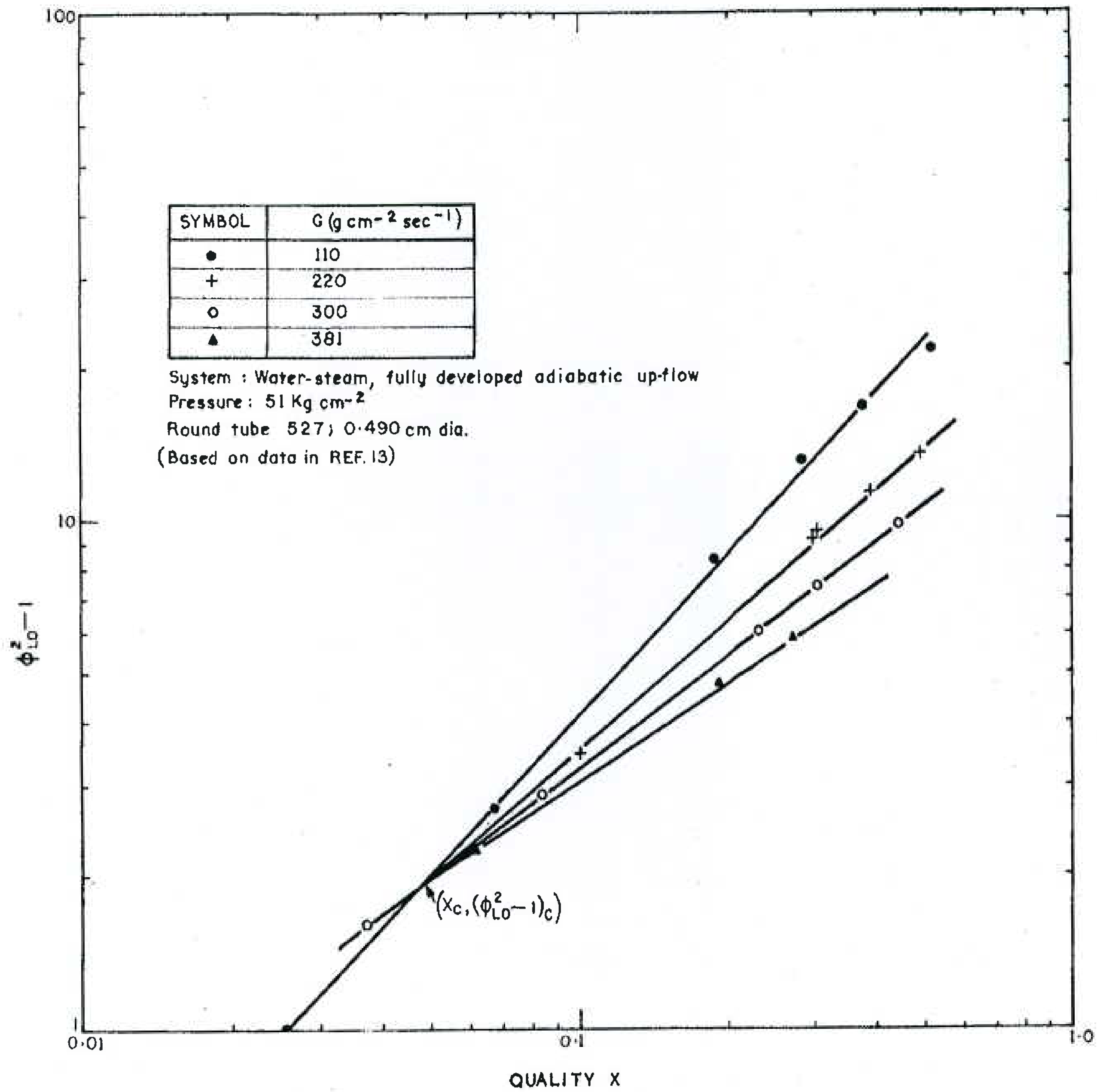


FIGURE 6h. DATA CHARACTERISED BY $\phi^2_{LO} - 1 + (\phi^2_{LO} - 1)_c \left(\frac{x}{x_c}\right)^{b(G)}$

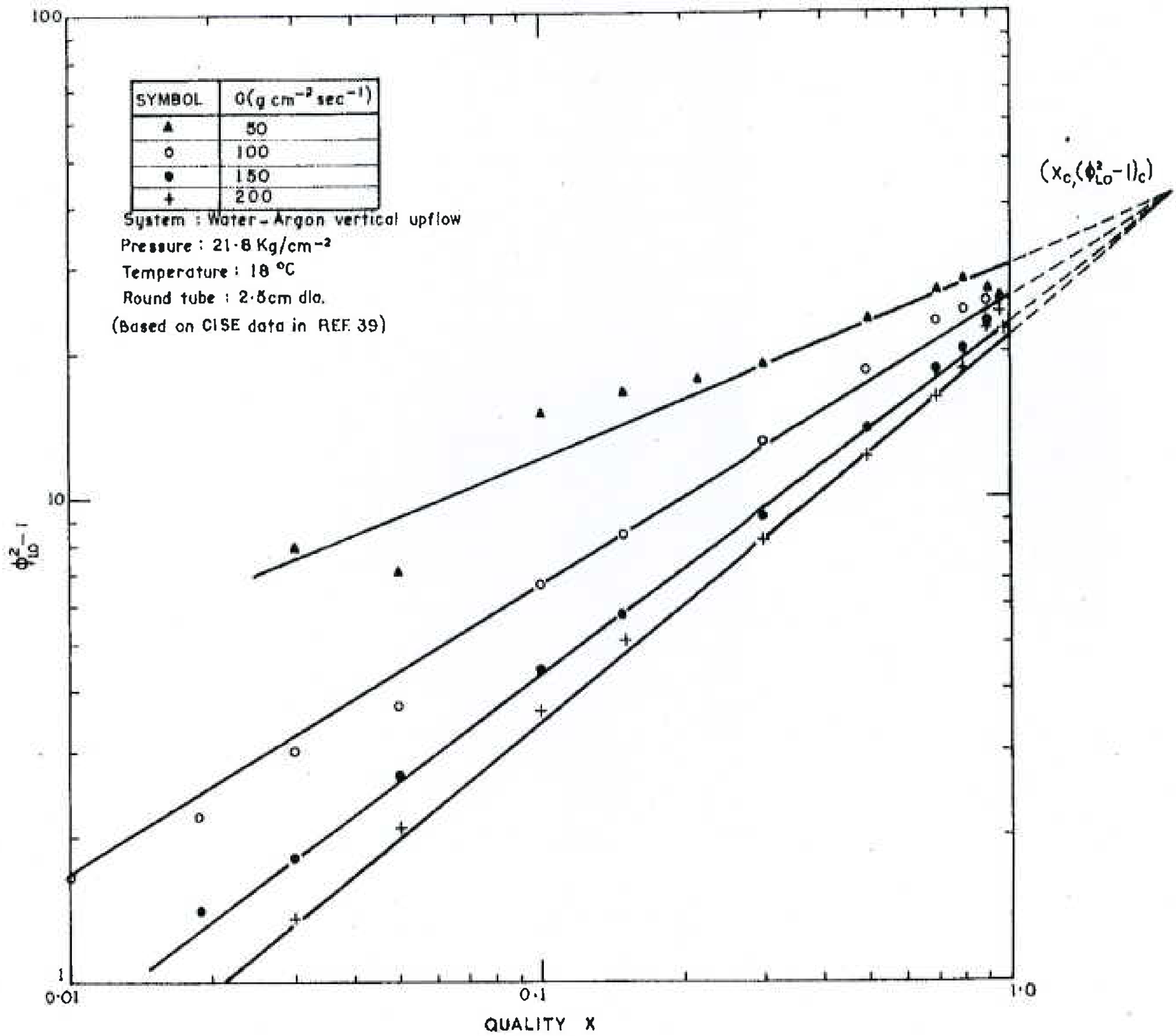
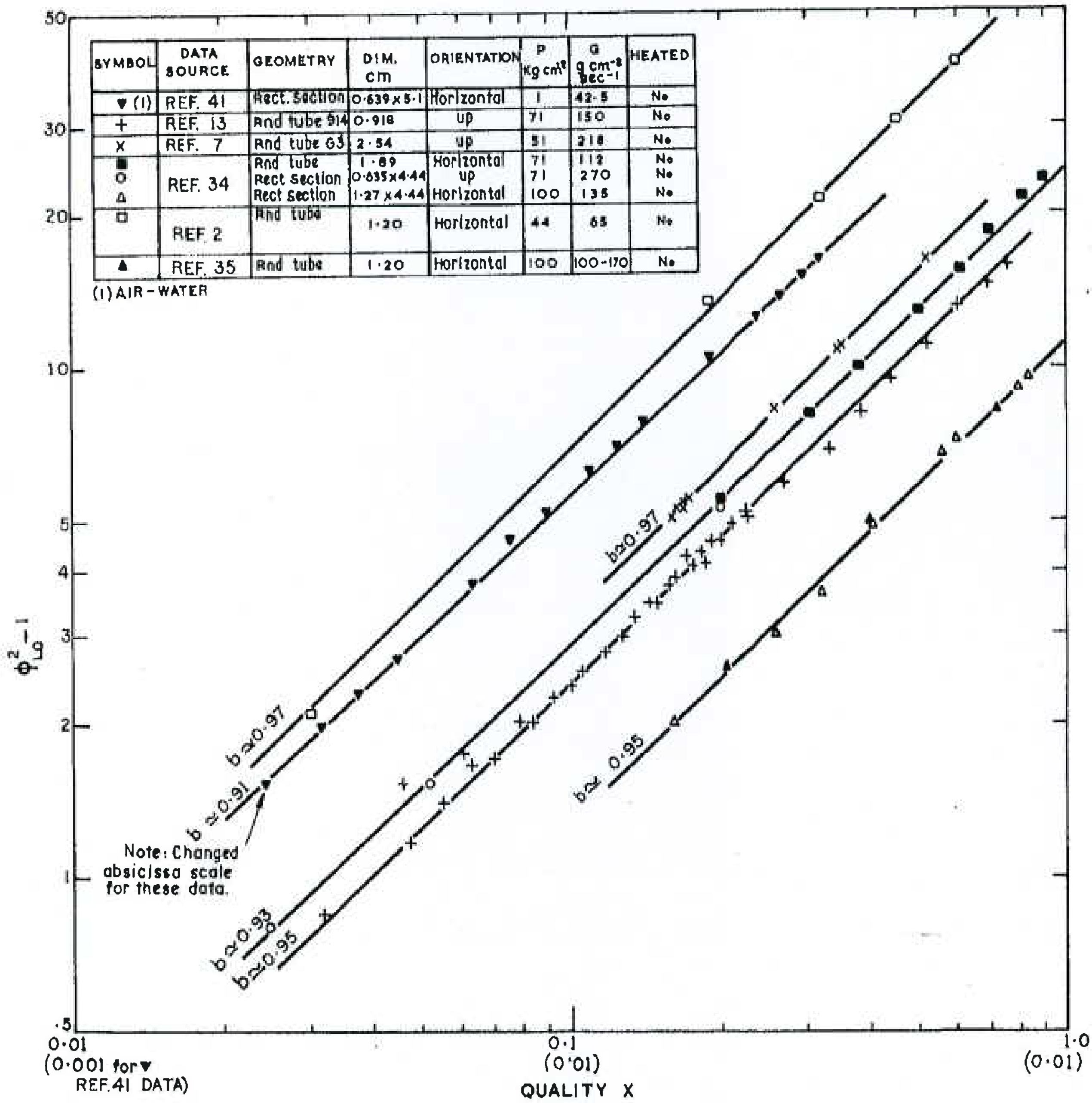


FIGURE 6L DATA CHARACTERISED BY $\phi^2_{LO}-1 + (\phi^2_{LO}-1)_c (\frac{X}{X_c})^{b(G)}$



SYMBOL	DATA SOURCE	GEOMETRY	DIM. cm	ORIENTATION	P Kg cm²	G g cm⁻² sec⁻¹	HEATED
▼ (1)	REF. 41	Rect. Section	0·639 x 5·1	Horizontal	1	42·5	No
+	REF. 13	Rnd tube 914	0·918	up	71	150	No
x	REF. 7	Rnd tube G3	2·54	up	51	218	No
■	REF. 34	Rnd tube	1·89	Horizontal	71	112	No
o		Rect Section	0·635 x 4·44	up	71	270	No
Δ		Rect Section	1·27 x 4·44	Horizontal	100	135	No
□	REF. 2	Rnd tube	1·20	Horizontal	44	65	No
▲	REF. 35	Rnd tube	1·20	Horizontal	100	100-170	No

(1) AIR - WATER

FIGURE 6J. DATA CHARACTERISED BY $\phi^2_{LO} = 1 + ax^b$, $0 \cdot 91 \leq b \leq 0 \cdot 97$