Two- and Three-Phase Flow Through a 90 Degree Bend

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Data are presented for two-phase air/water pipeflow and three-phase air/oil/water in a 0.026 m i.d. pipe and elbow bend (R/d = 0.654) for vertical to horizontal flow. The two-phase results were shown to be dependant on the flow regimes present in the system. The elbow bend acted either to smooth the transition from vertical to horizontal flow when the liquid rate was below the bubble rise velocity in the inlet leg (when negative bend pressure losses were achieved), or to generate droplets and increase the bend pressure drop substantially at higher fluid rates.

Three-phase data also showed significant but not such dramatic differences, depending on the combined liquid rate being above or below the bubble rise velocity in the inlet leg. Again the variation of pressure drop for the system could be qualitatively explained by the observed flow regimes.

For both two-phase and three-phase systems, the observed bend pressure drop could be correlated using a Lockhart-Martinelli approach based on the single-phase flow data for the bend.

Introduction

Spedding et al. [1] have detailed the single-phase fluid flow characteristics through 90 degree bends for both laminar and turbulent conditions. For laminar flow the most reliable pressure drop prediction was that due to White [2], while the correlation of Ito [3] sufficed for the turbulent flow when the R/d of the bend was greater than 5. For elbow bends with R/d < 5, turbulent pressure drop can be predicted by the relation of Crawford et al. [4]. These relationships are of importance in any consideration of multiphase flow through bends, not least in the sense that they provide a factual basis on which to test the validity of multiphase-flow experimental apparatus by ensuring that single-phase flow results obtained conform to the above predictions.

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In contrast to the single-phase flow case, the flow of two-phase gas and liquid mixtures around bends has been subjected to very little detailed study although the physical situation is commonly encountered in practice. Most of the work on two-phase flow in curved pipes or elbow bends has been confined to the horizontal plane [5-9] with some work concerned with the vertical orientation of the plane of the bend [10-13]. These studies indicate that two-phase flow through horizontal curved pipes and bends tends to follow the pattern of behaviour found for single-phase flow. There were inconsistencies in the reported effects of orientation of the plane of the bend. Further it was not clear which was the preferred method of data presentation, and the proposed modelling methods did not give consistent results [14, 15]. Very little work has been reported on three-phase oil/water/gas flow in bends. It is the subject of this study to examine the pressure loss characteristics of two-and three-phase flow through a vertical-orientated pipe elbow bend.

Experimental Details

Figure 1 shows a schematic diagram of the apparatus, and the 90 degree elbow bend is detailed in Figure 2. The 0.026 m i.d. pipe and the R/d = 0.654 elbow bend were fed with fluids of rates up to $Q_G = 0.02$ m^3 s^{-1}, $Q_W = 0.00015$ m^3 s^{-1} and $Q_O = 0.0001$ m^3 s^{-1} into the vertical inlet leg X. The flow rates were measured by calibrated rotameters and controlled by valve manipulation. A cyclone separator was used to detach the liquid for recirculation without back pressure effects. Tapping points, with separation cups attached, were used to measure the pressure loss over three sections of the apparatus; the inlet vertical tangent leg X, the elbow bend region Y, and the outlet horizontal tangent leg Z. Liquid holdup measurements were made using quick closing valves on the tangent legs. The oil used was Fina Vestan A5OB (density 829 kg m^3; viscosity 0.0120 kg m^{-1} s^{-1}; 20°C)

Preliminary experiments were conducted in the tangent legs without the elbow bend in place to ensure the effect of the bend was properly quantified, and so that adequate settling down lengths were used. Details of the apparatus and experimental method are given by Woods and Spedding [16].

Results and Discussion

Figure 3 presents the two-phase total elbow-bend pressure drop (ΔP_{BT}) obtained for four liquid rates. At liquid rates below the bubble rise velocity in the inlet vertical tangent leg X, the elbow bend pressure drop was negative. This was in contrast to that obtained at the higher liquid rates where the bend pressure drop was positive and rose steadily in value with the fluid rates. The negative elbow pressure drop region at lower fluid flow rates occurred when the slug flow regime in the inlet vertical tangent leg X was observed to pass smoothly through the elbow bend, and formed the smooth stratified regime in the outlet horizontal tangent leg Z. As the liquid (and gas) rates were increased, the regime in the outlet leg became successively stratified roll wave and then stratified blow through slug with the passing away of the negative pressure loss region, since there was no longer a smooth regime transition within the elbow bend. The pressure drop tended to level off when the flow regime in the vertical inlet

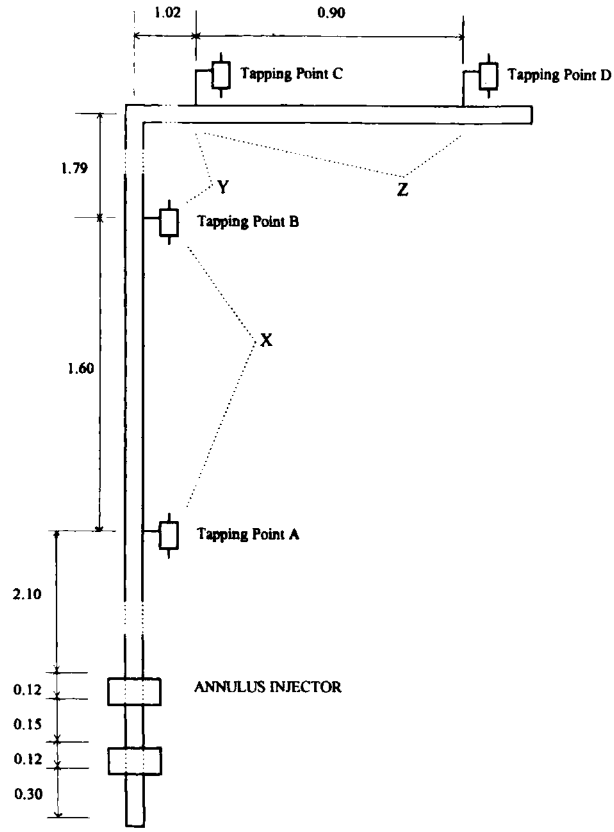

Figure 1. *Schematic diagram of apparatus.*

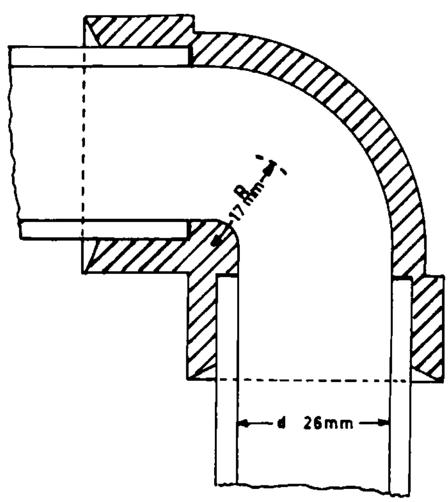

Figure 2. *The elbow bend.*

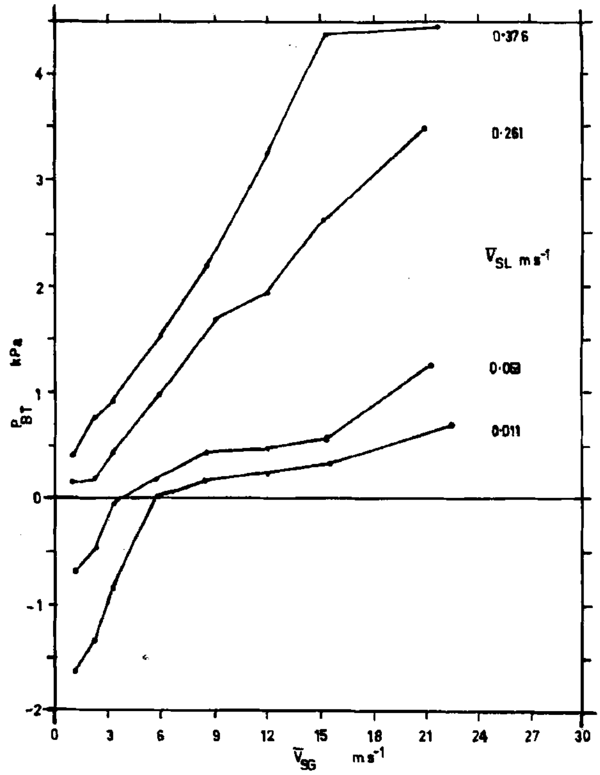

***Figure 3.** Total two-phase elbow pressure drop against $\bar{V}_{SG}$ for various liquid rates.*

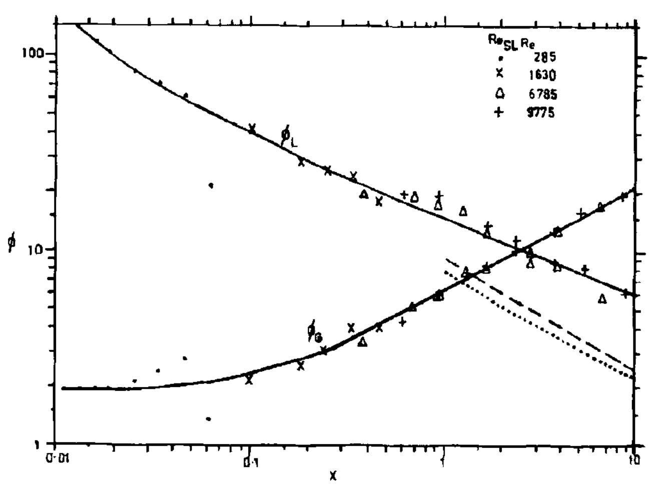

***Figure 4.** Two-phase elbow bend pressure drop according to the Lockhart-Martinelli model (data of Sekoda et al. [6] for d = 0.018 m).*
R/d = 2.36 — — — — — — *R/d = 5.02* ————

tangent passed from churn to semi-annular flow. When the liquid velocity exceeded the Taylor bubble rise velocity, at low gas rates, the slug or blow through slug regimes in the inlet tangent passed through the elbow bend to form the stratified roll wave regime in the outlet tangent, and the elbow bend pressure loss rose rapidly with increased gas rate. In this region the elbow bend acted as a droplet generator causing the pressure loss to rise rapidly.

Detailed study of the bend pressure drop revealed that a consistent correlation of the Lockhart-Martinelli type [14] could be obtained if the single-phase pressure drop employed in the correlation actually referred to that obtained in the bend and not in the straight pipe. Figure 4 shows the data plotted in the following form, and gave a reasonable correlation:

$$\phi_{G,L} = \left[\Delta P_{TPB} / \Delta P_{G,LB}\right]^{0.5} \quad (1)$$

$$X = \left[\Delta P_{LB} / \Delta P_{GB}\right]^{0.5} \quad (2)$$

The data of this work do not agree with the results of Sekoda et al. [6], nor do they give validity to the elementary model of Chisholm [8] or the homogeneous model mentioned by Chenoweth and Martin [5].

For three-phase flow the data are presented in Figure 5 and 6. In each of these figures the pressure loss is presented for straight vertical pipe (SVP), the vertical inlet tangent leg X (VITLX), the outlet horizontal tangent leg Z (OHTLZ) and the elbow bend region Y (EBRY). This latter region was corrected using the method outline previously [1] to give the total bend pressure loss as ΔP_{BP} in Figure 7 and l_e/d in Figure 8 using the VITLX data. It should be noted that a qualitative explanation of the processes taking place in the SVP has previously been presented by Woods et al. [17]. They examined the interplay of phase velocity, thickness and holdup on the flow regimes present in the system, and the effects on the pressure loss. In Figure 5 the VITLX pressure drop passed through a minimum value at $f_o = 0.3$, and then rose to a maximum at $f_o = 0.75$ following inversion from water-dominated (WD) to oil-dominated (OD) flow. There was a slight dip in the relation at $f_o = 0.625$ due to the observed tendency to form the WD water annulus/oil annular plus ripple flow regime just before inversion to OD flow. Other than this, there was no discernable difference between the flow regimes observed for the VITLX and SVP. In general, the pressure drop through the VITLX followed that for SVP with a tendency to be greater at the composition extremities at $f_o = 0$ and 1.0, and to be lower at the inversion region of $f_o = 0.75$. The pressure drop also fluctuated over a wider range in the VITLX when compared to SVP.

The OHTLZ showed a maximum in the pressure drop at $f_o = 0.625$ in the WD region before inversion took place. This was due to the flow pattern passing from WD dispersed stratified plus ripple flow below an f_o of 0.5, to WD dispersed stratified plus roll wave at $f_o = 0.625$. The data of Donnelly [18] for 0.026 m i.d. horizontal pipe, while showing general agreement with the pressure drop of this study, had a maximum point of lower magnitude. Later work by Donnelly [18] for 0.05 m i.d. horizontal pipe possessed a maximum pressure drop at $f_o = 0.65$, and showed better agreement with the results of this present study.

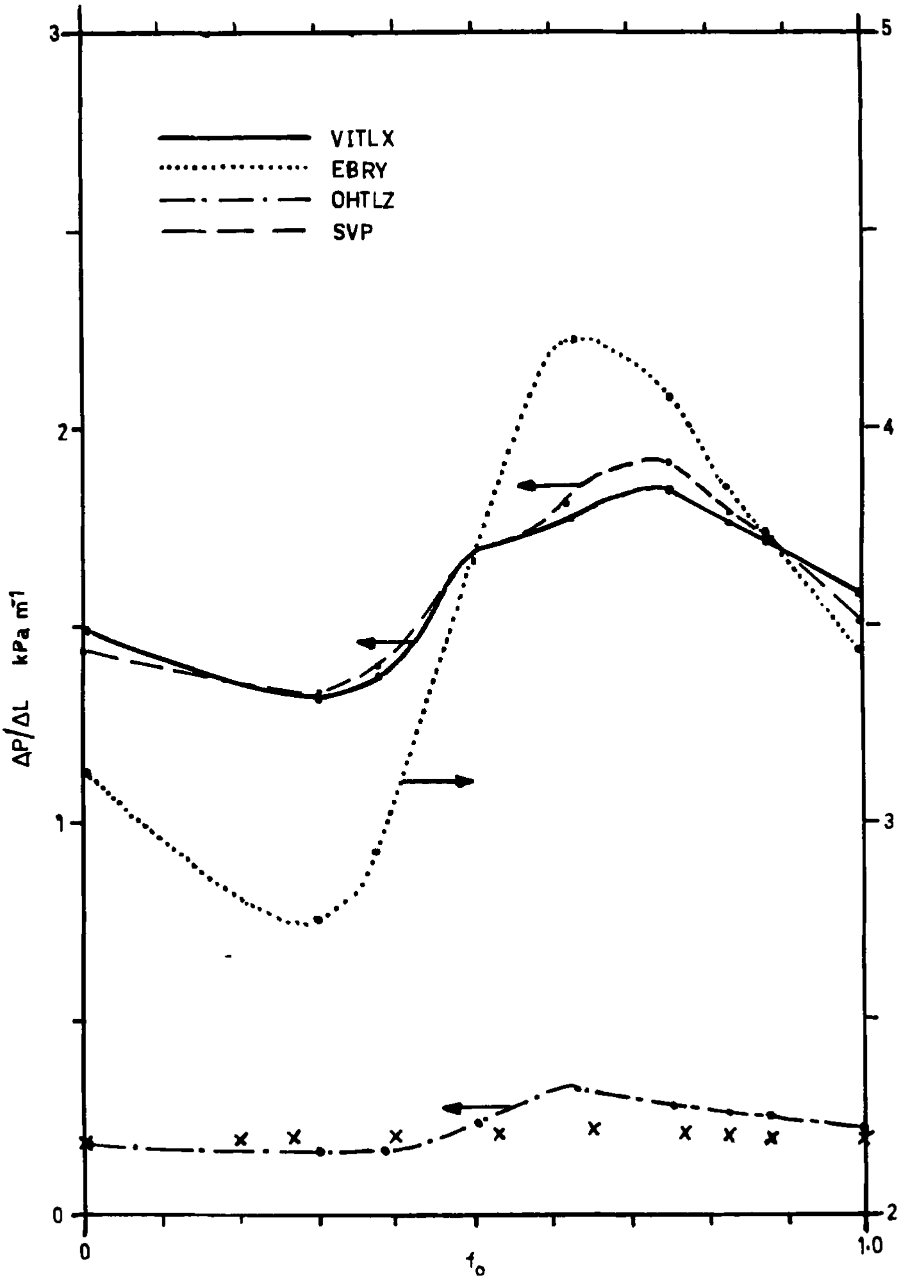

Figure 5. *Three-phase pressure losses through the apparatus over the elements X, Y and Z ($\overline{V}_{SLT} = 0.0628\ ms^{-1}$ $\overline{V}_{SG} = 8.5\ ms^{-1}$ x Donnelly data [18]).*

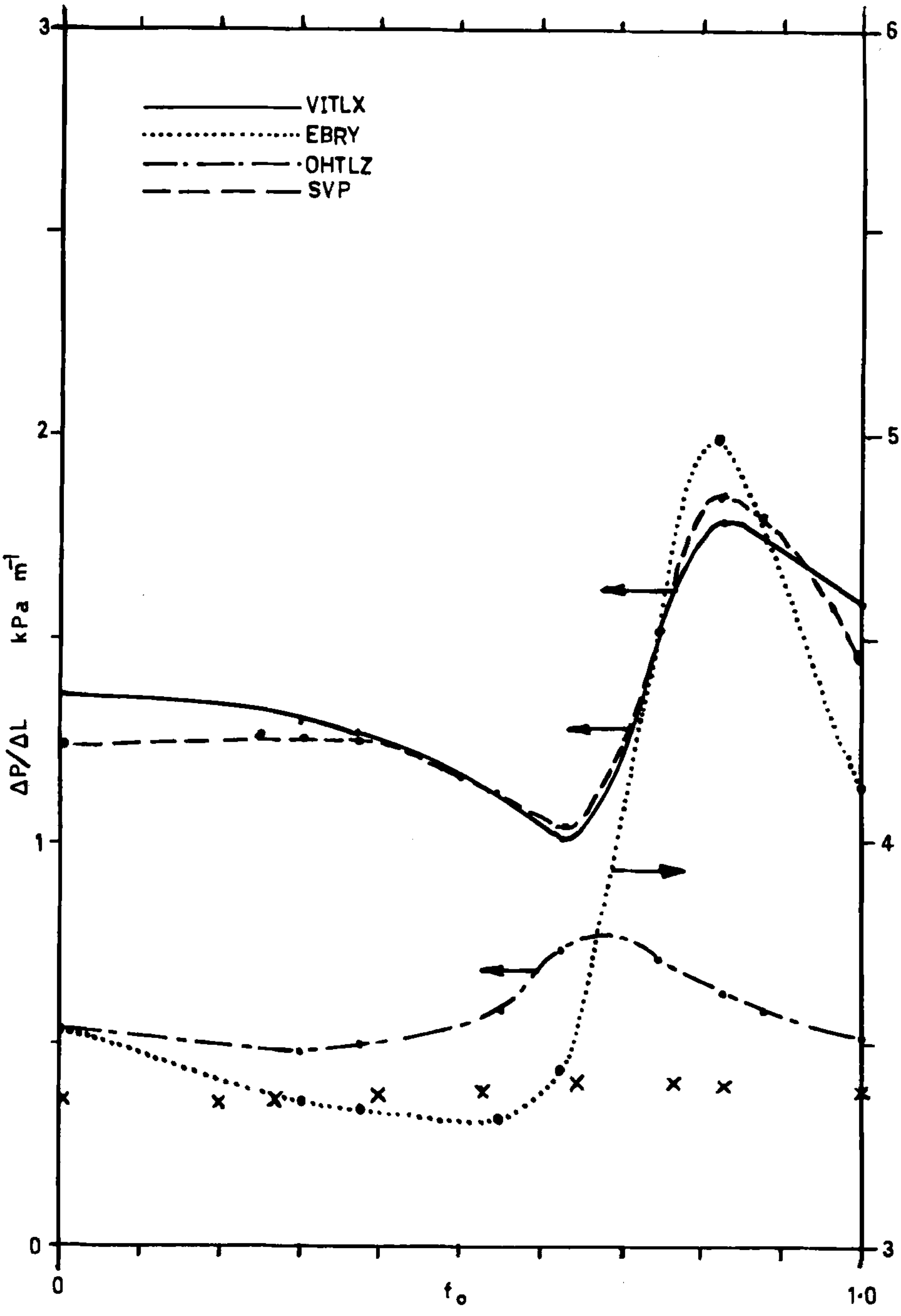

Figure 6. *Three phase pressure losses through the apparatus over the element X, Y and Z ($\overline{V}_{SLT} = 0.0628\ ms^{-1}$ $\overline{V}_{SG} = 14.6\ ms^{-1}$ x Donnelly data [18]).*

The EBRY exhibited a pressure drop variation with f_o that tended to reflect the variation observed in the VITLX. The only exception was that the maximum pressure drop was at $f_o = 0.625$, not $f_o = 0.75$. Figure 6 highlights that there was a difference in this result if the gas rate was below, or above, $\overline{V}_{SG} = 10$ m s^{-1}. The reason being that below $\overline{V}_{SG} = 10$ m s^{-1} the semi-annular (and slug) regime was present in the VITLX where the pressure loss fell with increasing gas rate. Above $\overline{V}_{SG} = 10$ m s^{-1} in Figure 6, the annular regimes were present where the pressure drop rose with gas rate and the general form of the various pressure drop relations altered significantly from that shown in Figure 5, particularly with the VITLX. The minimum deepened and moved to $f_o = 0.625$ while the maximum was increased substantially and moved to $f_o = 0.825$ for all pressure losses except the OHTLZ. In addition, the pressure losses in the OHTLZ were significantly above the data of Donnelly [18] since much more complex stratified flow patterns were involved than observed in straight horizontal pipe without a lead-in bend. The elbow bend pressure drop (ΔP_{BT}) exhibited a very similar variation to that of the EBRY, as shown in Figure 7. However the l_e/d values of Figure 8 were more consistent, having single maxima at $f_o = 0.625$ for all flow rates. The negative values in the elbow bend pressure drop observed in two-phase flow were absent here. The data followed Equation (3) below within a +5% overall average.

$$\ell_e / d = A + K \exp\left[-B(f_o - 0.625)^2\right] \tag{3}$$

where

$$A = -1.465 \times 10^{-7} Re_{SL} Re_{SG} + 0.00179 Re_{SG} + 0.00614 Re_{SL} - 18.0 \tag{4}$$

$$B = 0.0008\, Re_{SG} - 0.0029 Re_{SL} + 20.0 \tag{5}$$

Values of the parameter K in Equation (3) are given in Table 1. Figure 9 presents the data in the form of the Lockhart-Martinelli [14] pressure loss parameters which are defined below in Equations (6) and (7), and using the actual superficial fluid single-phase pressure loss through the bend.

$$\phi_G = [\Delta P_{BT} / \Delta P_{BSG}]^{0.5} \tag{6}$$

$$X = [\Delta P_{BSL} / \Delta P_{BSG}]^{0.5} \tag{7}$$

Using other correlating parameters such as the actual single superficial phase pressure losses in the tangent legs proved not to be useful. These results emphasise the need to quantify the single-phase data of the bend before proceeding to any multiphase study.

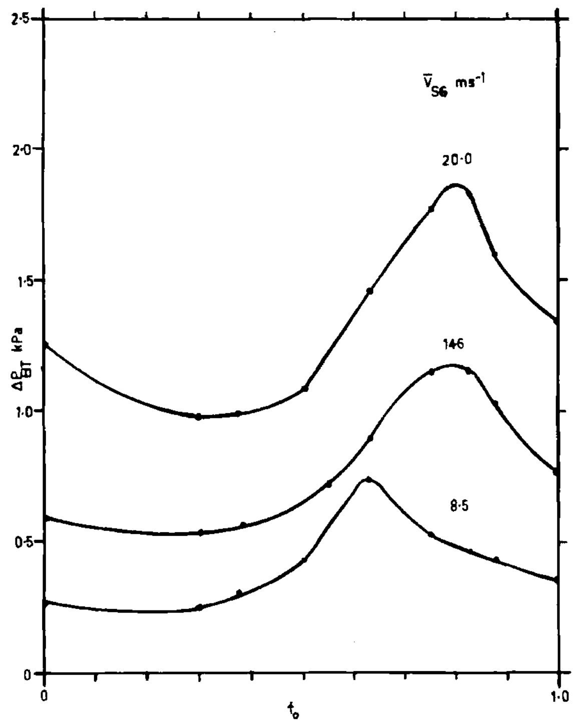

Figure 7. *Three-phase elbow bend pressure loss for $\overline{V}_{SLT} = 0.0628\ ms^{-1}$.*

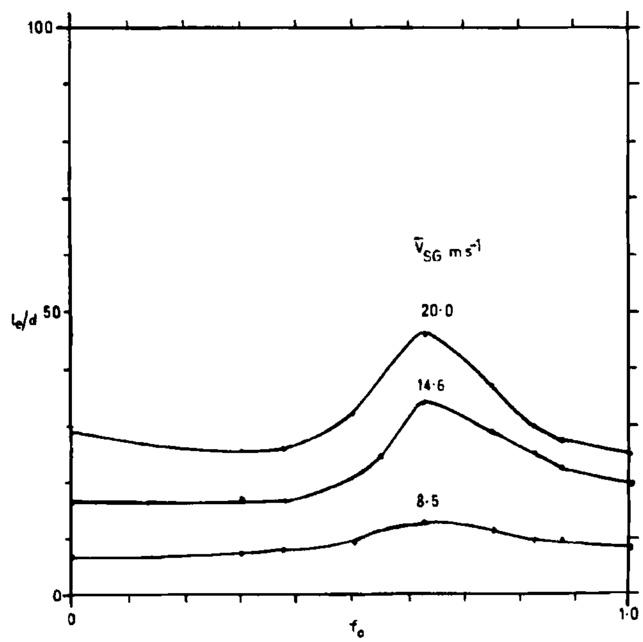

Figure 8. *Three-phase elbow bend pressure loss for $\overline{V}_{SLT} = 0.0628\ ms^{-1}$.*

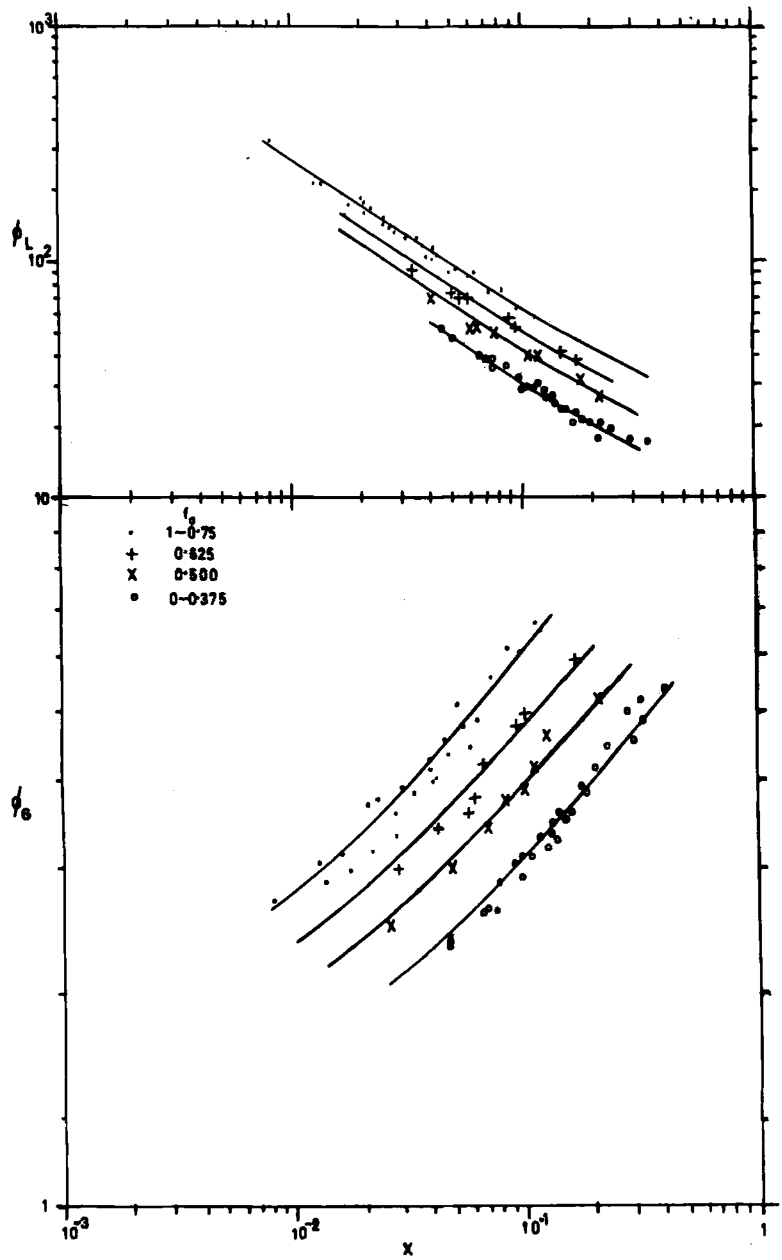

Figure 9. The three-phase elbow pressure drop in the form of the Lockhart-Martinelli parameters.

Table 1. *Values of the parameter K in Equation (3).*

Re_{SL} / Re_{SG}	**1622**	**3260**	**4395**
15,762	6.3	6.8	7.6
27,762	15.6	16.5	18.5
35,822	21.5	22.8	25.8

Conclusions

For two-phase flow, the pressure loss data gave significantly different results when the liquid rate was either above or below the bubble rise velocity on the vertical inlet tangent leg. For the case of low liquid (and gas) flow, then the elbow bend pressure drop possessed a negative value, which was caused by the slug flow regime in the inlet leg passing smoothly through the elbow bend to the smooth stratified flow regime. For increased fluid rates, the elbow bend pressure drop rose steadily with increasing flow rates. At higher liquid flows, the elbow bend acted as a droplet generator causing a rapid rise in the pressure drop. Thus the elbow bend pressure drop depended significantly on the flow regimes present in the system.

A general correlation was obtained using the Lockhart-Martinelli parameters based on the single-phase flow through the bend. This approach contrasted to the poor performance obtained when using other models.

For the three-phase system, there were again significant differences between the pressure drop elements of the apparatus when the liquid rate was either above or below the bubble rise velocity in the inlet leg. The bend pressure drop was always positive and exhibited minima and maxima values, the latter being associated with the inversion from water-dominated to oil-dominated flow. The resultant pressure drop could be qualitatively linked to the observed regime changes within the fluids.

Correlations were developed for the three-phase bend pressure drop through the bend for calculation of either equivalent length or the Lockhart-Martinelli parameters.

Nomenclature

d	Pipe diameter (m)
f_o	Oil to liquid volume ratio
ℓ_e	Equivalent length (m)
ΔP	Pressure drop (kg $m^{-1}s^{-2}$)
Q	Volumetric flow rate ($m^3 s^{-1}$)
R	Elbow bend centre line radius (m)
$\overline{V}$	Velocity (m s^{-1})
X	Lockhart-Martinelli parameter
ϕ	Lockhart-Martinelli parameter

Subscripts

B	Bend
G	Gas
O	Oil
S	Superficial
T	Two-phase
W	Water

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