Gas–liquid two phase flow through a vertical 90° elbow bend

P.L. Spedding, E. Benard *

School of Aeronautical Engineering, Queen's University Belfast, BT9 5AH, UK

Abstract

Pressure drop data are reported for two phase air–water flow through a vertical to horizontal 90° elbow bend set in 0.026 m i.d. pipe. The pressure drop in the vertical inlet tangent showed some significant differences to that found for straight vertical pipe. This was caused by the elbow bend partially choking the inflow resulting in a build-up of pressure and liquid in the vertical inlet riser and differences in the structure of the flow regimes when compared to the straight vertical pipe. The horizontal outlet tangent by contrast gave data in general agreement with literature even to exhibiting a drag reduction region at low liquid rates and gas velocities between 1 and 2 m s^{-1}.

The elbow bend pressure drop was best correlated in terms of l_e/d determined using the actual pressure loss in the inlet vertical riser. The data showed a general increase with fluid rates that tapered off at high fluid rates and exhibited a negative pressure region at low rates. The latter was attributed to the flow being smoothly accommodated by the bend when it passed from slug flow in the riser to smooth stratified flow in the outlet tangent.

A general correlation was presented for the elbow bend pressure drop in terms of total Reynolds numbers. A modified Lockhart–Martinelli model gave prediction of the data.

Keywords: Air–water flow; Two phase flow in bend; Bend pressure loss; Prediction of pressure loss

1. Introduction

Single phase pressure drop can be predicted for curved pipes [1]. Recently Crawford et al. [2] extended the prediction ability to tight bends. Early work on two phase flow in curved pipes and bends highlighted difficulties in understanding the pressure drop characteristics [3–6]. Detailed studies of two phase pressure loss have largely been confined to the horizontal plane. Chenoweth and Martin [7] showed that while two phase pressure drop around bends was higher than for single phase flow it could be correlated by an adoption of the Lockhart–Martinelli [8] model developed originally for straight pipe. The correlation was claimed to predict loss in bends and other pipe fittings. Also at high mass velocities agreement was achieved with the homogeneous model. Fitzsimmons [9] presented two phase bend pressure loss data in terms of the equivalent length, l_e/d (i.e. the bend pressure loss over straight pipe frictional pressure gradient) and the Lockhart–Martinelli multiplier ϕ^2_{GB} referred to the single phase gas pressure loss in the bend. Comparison against pressure drop in straight pipe gave a poor correlation. Sekoda et al. [10] also used ϕ^2_{LB} referred to single phase liquid pressure loss in the bend. The two phase bend pressure drop was found to be independent of pipe diameter and depended on R/d in a manner similar to that found for single phase flow. Bruce [11] confirmed that the standard Lockhart–Martinelli parameter over-predicted bend pressure loss. Also the homogeneous model gave acceptable prediction of R_{12} refrigerant for bends presumably at high mass flows. Freeston and Dole [12,13] presented widely scattered geothermal data. For long and short radius bends results were

* Corresponding author. Tel.: +44 28 9097 4180; fax: +44 28 9097 5576.
E-mail address: e.benard@qub.ac.uk (E. Benard).

Nomenclature

d	pipe internal diameter, m	μ	viscosity, kg m^{-1} s^{-1}
G	mass flow rate, kg m^{-2} s^{-1}	ϕ	Lockhart–Martinelli pressure parameter
L	pipe length, m		
ℓ_e	equivalent length, m	*Subscripts*	
P	pressure, kg m^{-1} s^{-2}	A	total mass as liquid
Q	volume flow rate, m^3 s^{-1}	B	bend
R	centre line radius of bend, m	E	equivalent
Re	Reynolds number, $d\overline{V}\rho/\mu$	f	friction
U^*	shear velocity, m s^{-1}	G	gas
$\overline{V}$	velocity, m s^{-1}	L	liquid
W	mass flow rate, kg s^{-1}	P	phase
X	Lockhart–Martinelli parameter, Eq. (4)	S	superficial
X,Y,Z	inlet pipe, bend, outlet pipe, length, m.	T	total
ρ	density, kg m^{-3}	X	fluid

$R/d = 90$, $l_e/d = 225$ [±20%]; $R/d = 1.5$, $l_e/d = 58$ [+30% to −40%]; Tee, $l_e/d = 115$ [+50% to −75%]. Despite wide variation of the data it was used by the Engineering Science Data Unit [14] to develop a model for two phase flow through pipe components. Chisholm [15] presented an elementary model for prediction of two phase flow in bends, based on ϕ^2_{LA}, which was claimed to give prediction for all pipe diameters, R/d values and flow rates. Noersteboe [16] showed the model gave high values of bend pressure loss when checked against refrigerant data. Most studies have taken little interest in the actual flow regimes present. In some cases they are mentioned only in passing. However, Hoang and Davies [17] have realised the significance of flow regimes and have reported data on bubbly flow in vertical return bends. Graf and Neti [18] studied two phase pressure drop in square bends. Reported work on the orientation of the plane of the bend has often given contrary results. Deobold [19] claimed that the horizontal bend, the horizontal to vertical up bend and the vertical down to horizontal bend all gave the same bend pressure loss. However a horizontal to vertical down bend had a pressure drop that was 35% less. The correlation for elevation was assumed to follow the homogeneous model by Deobold [19] but others such as Alves [20] ignored head pressure differences entirely. Peshkin [21] reported that horizontal to vertical down flow had about 10% more bend pressure drop than the corresponding horizontal to vertical up flow case. Kutateladze [22] by contrast concluded the direct opposite that the horizontal to vertical up flow bend created the greater pressure drop. Pressure drop in geothermal expansion loops also reported some contrary results [23–25]. Studies in helical coils and boilers have been conducted [26–33]. Modelling of the pressure drop data have been attempted with the Lockhart–Martinelli parameter [8] or the Baroczy [34] model [32,33]. Hart et al. [30] also developed models for low liquid flows. Rippel et al. [31] showed that the bend pressure loss varied significantly with the flow regime present. Work has recently been presented on water hammer in bends [35] (see Table 1).

It can be concluded that a two phase flow through a curved pipe and elbow bends possesses similar features to those for a single phase flow. It is not clear as to the best method of data presentation and modelling, while the effects of flow regimes on the pressure drop which must be of significance requires elucidation. Currently uncertainties have been handled by over design. Such an approach is suspect particularly where safety issues are involved. For example, conveying to a destructor unit of the sudden release from safety valves where unexpected back pressure could be a real hazard.

In this work two phase air water flow through a vertical 90° to horizontal elbow bend is investigated.

2. Experimental

The apparatus of diameter = 0.026 m pipe is shown schematically in Fig. 1 together with details of the elbow bend. Air and water were fed into the base of the vertical riser and the upper annular injector at rates up to 0.02 m s^{-1} and 0.00015 m^3 s^{-1} respectively. The lower annular injector was blocked out in this work. The actual flow rates were measured by calibrated rotameters and controlled by valve manipulation. A cyclone separator detached the outgoing liquid for recirculation without back pressure effects. Tapping points, with separation cups attached, were used to measure the pressure loss (using a Solomat Zephyr manometer with ±1% accuracy) over three sections of the apparatus; the inlet vertical tangent leg X, the elbow bend region Y and the outlet horizontal tangent leg Z. Additional tapping points set at 0.1 m intervals were also placed at points along the inlet and outlet legs. These were used to determine the bounds of the regions, X, Y and Z and were blocked during data collection. Holdup valves were located in sections X and Z. Preliminary experiments were con-

Table 1
Two phase flow in curved pipe and bends

Fluids	Diameter (m)	$\frac{R}{d}$	Geometry	Flow	Correlation	Ref.
Air–water	0.0780	7.5	180° bend	Horizontal	ϕ^2_{LA} against Q_L/Q_T	[7]
Steam–water	0.0488	1, 1.5, 5.2	90° bend	Horizontal	ϕ^2_{GB} against l_e/d	[9]
Air–water	0.018, 0.0257	2.36, 5.02	90° bend	Horizontal	ϕ^2_{LB}	[10]
Air–water R_{12}	0.019	4.6, 10.5, 14.5, 22.6	90° bend	Horizontal	ϕ^2_{LB}	[11]
Air–water	0.019	1, 2, 3, 4, 5, 6	90° bend	Horizontal	ϕ^2_{LB}	[11]
Steam–water	0.01	0.75, 4.5	90°, 45°, 180° bends	Horizontal	l_e/d against $\overline{V}_L$	[12]
R_{12}, R_{717}	0.0223, 0.0825, 0.120	1.3, 1.4	90°, 180° bends	Horizontal	$\Delta P_{TP} - \Delta P_{LA}/\Delta P_{GA} - \Delta P_{LA}$	[16]
Air–water Air–oil	0.0266	7	180° bend	Horizontal to vertical	l_e/d against Re_{SG}	[20]
Steam–water	0.0266	1.5	90° bends in vertical square coil	Horizontal, up and down vertical	ϕ^2_L	[19]
Steam–water	0.307	1.5	90° bends in expansion loop	Horizontal to up down vertical	ϕ^2_L	[23]
Steam–water	0.201	1.5	90° bends	Up, down vertical to horizontal	ϕ^2_L against W_G/W_L	[24]
Air–water He–water Freon 12–water Air–2/propanol	0.0102	9.95	Up right helical	Down	ϕ^2_G	[31]
Air–water	0.0159	4.8, 7.2, 9.6	Up right helical	Up	Film inversion	[27]
Steam–water	0.0127	22.8, 52.0, 92.9, 101.6	Up right helical	Up	ϕ^2_{LA}	[32]
Air–water Air–aq glycerol	0.0147	14.4	Up right helical	Up	$\overline{R}_L$	[33]
Air–water	0.0254	1, 5, 10	30°, 45°, 60°, 90° vertical to horizontal	Up	Data	[28]
Air–water	0.0254	12	180° vertical	Up/down	Data	[29]

ducted using the full range of flow rates with and without the elbow bend in place to determine pressure gradients etc so as to ensure the settling down lengths used were adequate. With the elbow bend in place preliminary experiments were conducted to determine the pressure profiles across the apparatus (Fig. 2 is an example) and to ensure a linear pressure gradient in regions X and Z so as to allow accurate extrapolation into region Y. The pressure at the base of the inlet leg varied up to 1.35×10^5 kg m^{-1} s^{-2} (a). Single phase experiments were also performed. Further details of the apparatus and method used are given by Woods and Spedding [36].

3. Results

In two phase vertical to horizontal flow the conditions in the tangent legs either side of the elbow bend (in the regions X and Z of Fig. 1) will be dramatically different since the effects of gravity and uplift forces in the inlet vertical tangent leg X will be absent in the outlet horizontal tangent leg Z. Secondly, often the flow regimes and other flow phenomena will be different in the two tangents. Therefore, the calculation of the pressure drop over the elbow bend will be more complex than that for single phase flow where the phase density is essentially constant and the straight pipes frictional pressure loss can be used to calculate elbow bend pressure loss regardless of the orientation of the plane of the bend. This was not the case for two phase flow where the total pressure drop in each tangent must be used in the calculation as detailed in Fig. 2. In the figure A–C and D–F are the actual up and downstream pipe tangent lengths, C–D is the elbow bend total centre line length, B–C and D–E are the up and downstream transitional regions. The point G is the demarcation between the straight pipe pressure drop of the two tangents which was chosen, not half way at the 45° line but at the 90° intersection where gravity effects in the vertical tangent cease. This was done because, in general the pressure loss in the vertical tangent X was orders of magnitude greater than the corresponding horizontal tangent Z pressure drop. The actual pressure distribution in Fig. 2 is abcgdef, while the straight pipe distribution in the two tangent legs are abc′g′ and g′d′e′f′. The corrected pressure distribution abc′g″d‴e‴f‴ includes a straight pipe loss equal to the actual length C–D of the elbow bend centre line, ΔP_{BE}, that is composed of C–G and G–D the two elements from each tangent leg. Thus the total bend pressure drop ΔP_{BT} is composed of the bend pressure loss from the inlet and outlet tangent legs pressure gradients ΔP_B and the equivalent centre line bend length ΔP_{BE}.

In the calculation of ΔP_{BT} it was assumed that the actual pressure drops in the vertical X and horizontal Z

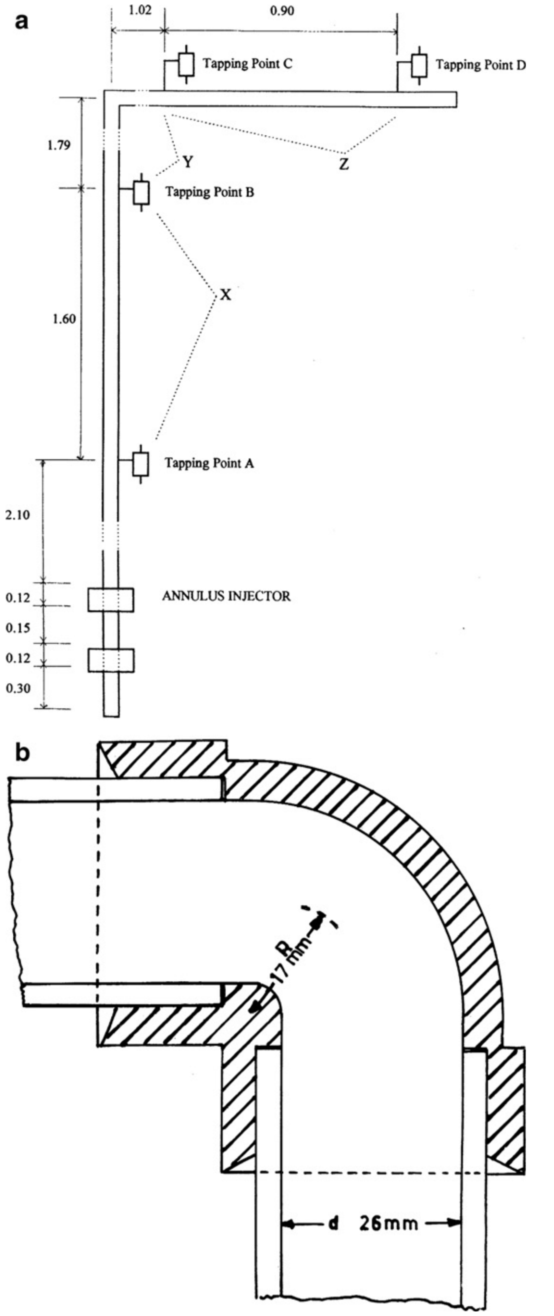

Fig. 1. Schematic diagram of the test section and elbow bend.

tangents should be used to determine ΔP_{BE}. While the latter should not cause any problems the former pressure drop may be different to that in a straight vertical pipe without the following elbow. Spedding et al. [37] showed that for near vertical two phase flow slight disturbances in the distribution of the fluids across the pipe generally led to a rise in pressure drop over that observed for the corresponding straight vertical pipe [38] due, in the main, to increased liquid holdup. Therefore, possible disturbances due to the elbow bend could affect the flow in the vertical tangent X by instituting some measure of choking and increased pressure loss.

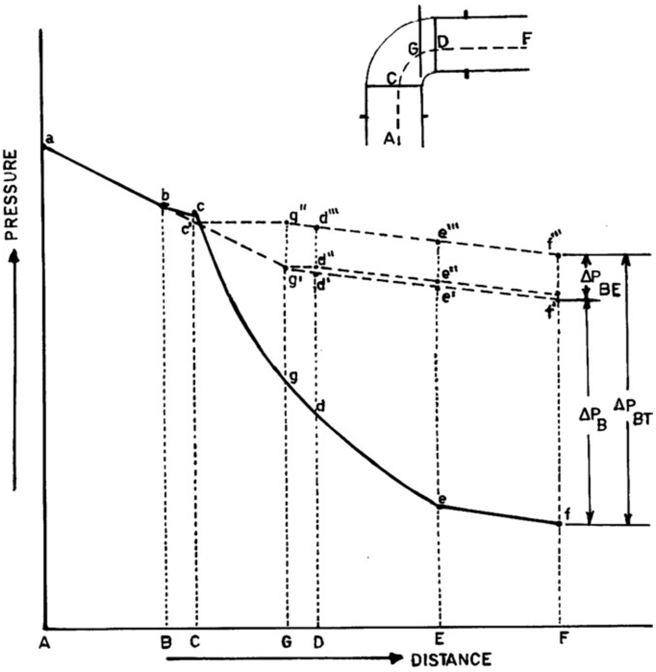

Fig. 2. Schematic diagram of the two phase pressure loss in a horizontal to vertical 90° elbow bend.

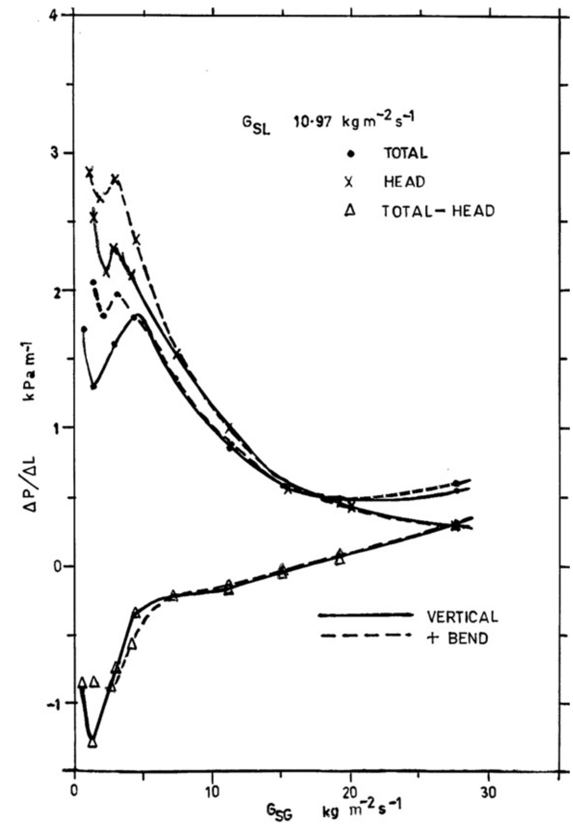

Fig. 3. Pressure drop in the vertical riser leading to the elbow bend compared to straight vertical pipe flow. $G_{SL} = 10.97\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $d = 0.026$ m i.d. Frictional pressure drop, total pressure loss minus head pressure drop calculated from holdup.

Firstly, the actual straight pipe tangent pressure loss in sections X and Z of Fig. 1 were compared with reported two phase data for vertical and horizontal flow respectively. This was done to determine if the elbow bend did indeed have any effect on the flow in the tangent legs. Figs. 3–6 detail the results for four different liquid rates. As the gas rate was increased for a set liquid rate the flow patterns passed successively from slug to churn to semi-annular and then annular flow. At the lowest liquid rate in Fig. 3 the total pressure drop with the elbow bend was above that for undisturbed straight vertical pipe flow in the slug and some churn flows at low gas rates $G_{SG} < 4.2\ \mathrm{kg\,m^{-2}\,s^{-1}}$. Thereafter, at higher gas rates the total pressure drops were the same for both systems. At low gas rates about $G_{SG} = 0.8$–$1.5\ \mathrm{kg\,m^{-2}\,s^{-1}}$ the frictional pressure drop (being the total minus the head) gave a negative value. As the liquid rate was increased from Figs. 3–6 a difference between the total pressure loss between the two systems began to appear which eventually extended progressively across the entire gas range. In the regions where the pressure loss was larger with the inclusion of the elbow bend, the flow regimes between the two systems exhibited subtle differences, e.g. the slugs tended to be of shorter length with the elbow bend resulting in a narrower but

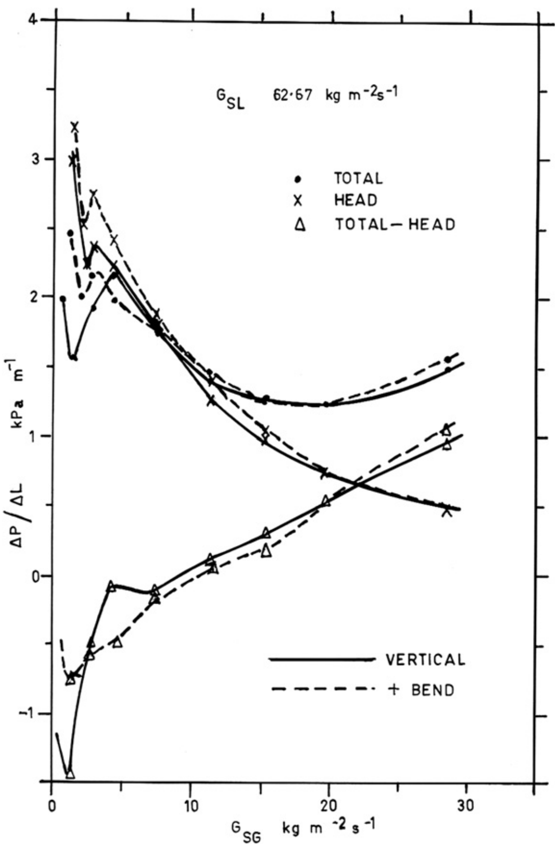

Fig. 4. Pressure drop in the vertical riser leading to the elbow bend compared to straight vertical pipe flow. $G_{SL} = 62.67\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $d = 0.026$ m i.d. Frictional pressure drop, total pressure loss minus head pressure drop calculated from holdup.

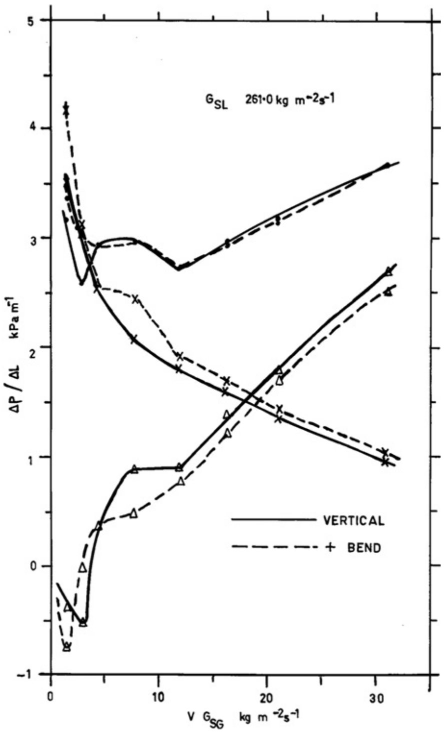

Fig. 5. Pressure drop in the vertical riser leading to the elbow bend compared to straight vertical pipe flow. $G_{SL} = 261.0\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $d = 0.026$ m i.d. ● = total, × = head, △ = frictional, i.e. total-head.

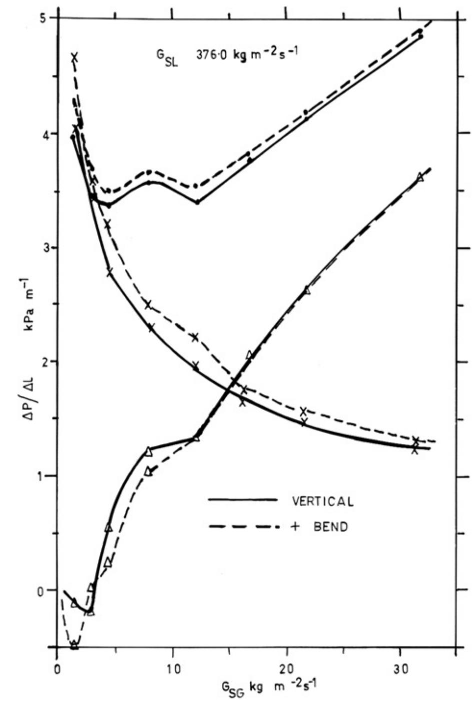

Fig. 6. Pressure drop in the vertical riser leading to the elbow bend compared to straight vertical pipe flow. $G_{SL} = 376.0\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $d = 0.026$ m i.d. ● = total, × = head, △ = frictional, i.e. total-head.

increased frequency of pressure fluctuations. In addition, the liquid holdup tended to be higher with the elbow bend

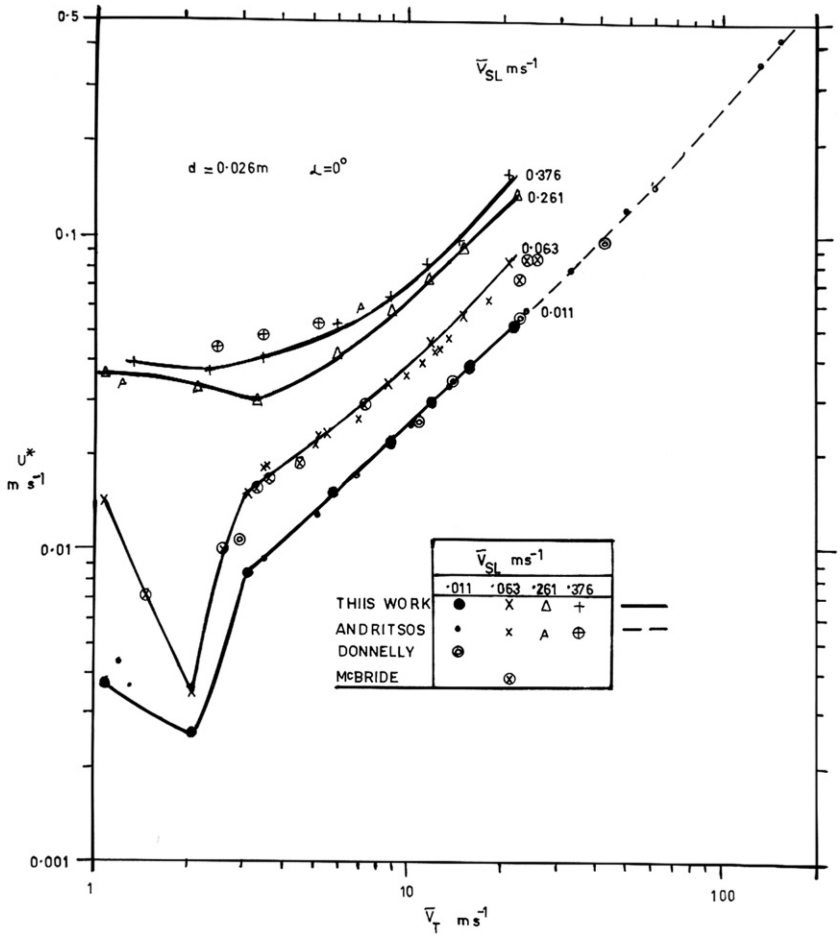

Fig. 7. Pressure drop in the horizontal outlet tangent leg.

which, particularly at the higher liquid rates, led to the head pressure loss with the elbow bend being above that of the straight vertical pipe. Indeed the head pressure loss exhibited a more marked effect with increasing gas rate than the total head loss. The effect of uplift was less noticeable with the elbow bend in place and the frictional loss was virtually unaltered from that of the straight vertical pipe. Thus the inclusion of the elbow bend gave a similar effect to that noted by Spedding et al. [37], for the case when the pipe was slightly off the vertical where the anisotropy of the liquid flow caused an increase in both liquid holdup and pressure drop over vertical pipe under similar conditions. In addition the elbow bend caused an increase in the absolute pressure within the inlet vertical tangent leg X due to a measure of throttling of the flow by the elbow bend. Thus the presence of the elbow bend often led to an increase in pressure drop in the inlet vertical tangent leg X that resulted in an increase in ΔP_{BE}. Figs. 3–6 therefore are of value as they provide some estimate of the excess pressure expected in the inlet vertical tangent leading to an elbow bend.

The outlet horizontal tangent leg Z exhibited a pressure drop that showed agreement with other reported horizontal data [39–41] as shown in Fig. 7. The data were presented in terms of shear velocity

$$U^* = \sqrt{\left(\frac{\Delta P}{\Delta L}\right)_f \frac{d}{4\rho_L}} \tag{1}$$

following the method of Spedding et al. [42]. One interesting feature in Fig. 7 was that at low liquid velocities and gas rates $\overline{V}_{SG} = 1.5$–$2.5\ \mathrm{m\,s^{-1}}$ there was a region of drag reduction where $\left[\frac{\Delta P_{TP}}{\Delta P_{SG}}\right]^{0.5} = \phi_G < 1.0$. This was in agreement with the findings of Ferguson and Spedding [43] who reported on this phenomenon in two phase horizontal flow in pipes with a size range of 0.045–0.051 m i.d. This work shows that the effect appeared at the lower diameter of 0.026 m as well. Fig. 8 gives the total elbow bend pressure drop ΔP_{BT} for four liquid rates. At the lower liquid rates, the elbow bend positive pressure drop passed through a slight minimum value as $\overline{V}_{SG}$ was increased. As the liquid rate increased the pressure drop rose steadily with $\overline{V}_{SG}$ and possessed very few other features. There was an observable difference between the pressure drop relation that depended on whether $\overline{V}_{SL}$ was below or above the free bubble rise velocity in the inlet vertical tangent leg X. At the lower liquid (and gas rates) the elbow bend pressure drop was negative while at the highest liquid (and gas rate) the pressure drop commenced to level off.

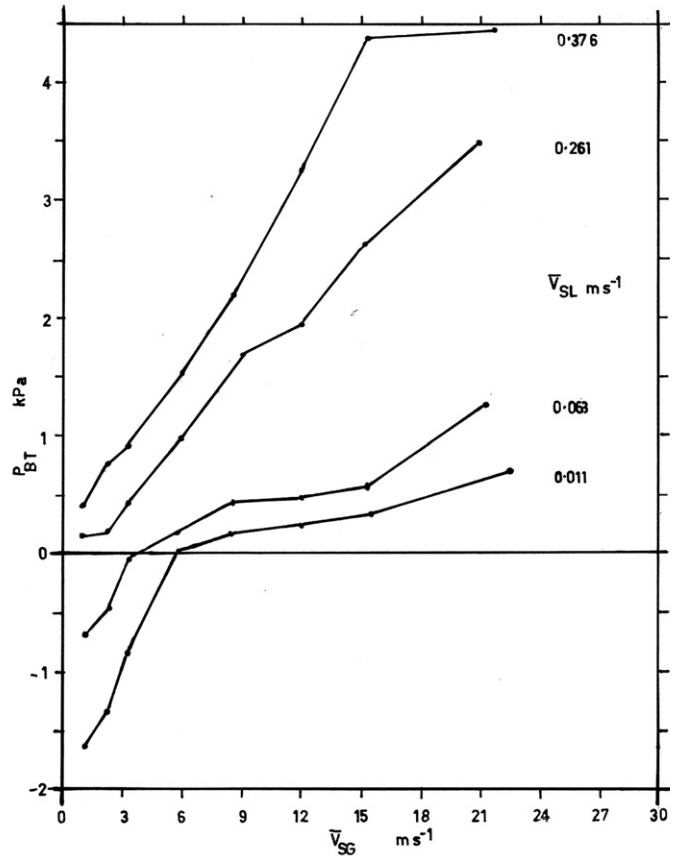

Fig. 8. Total elbow bend pressure drop against $\overline{V}_{SG}$ for various liquid rates.

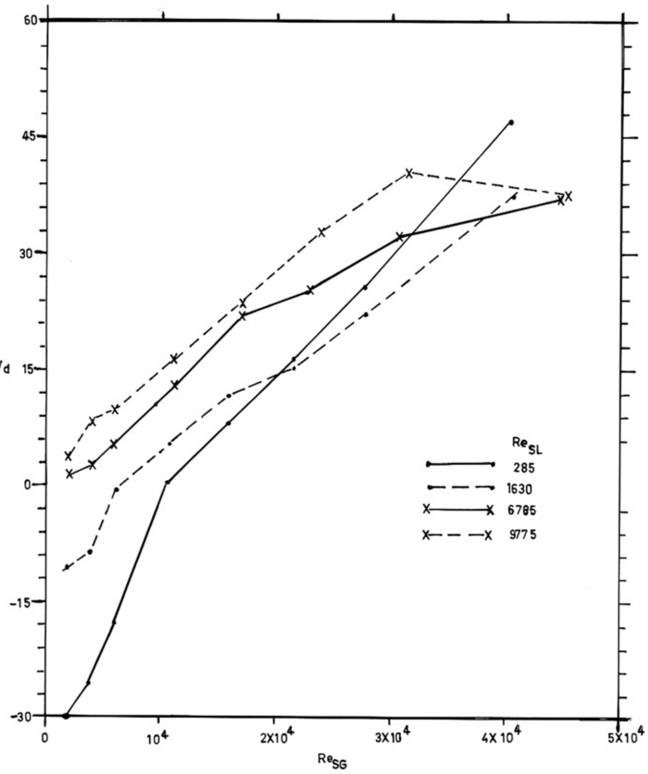

Fig. 9. Elbow bend pressure drop as l_e/d against Re_{SG}.

These observed effects can be attributed to the flow regimes present in the two tangent legs of the elbow bend. The negative elbow bend pressure drop region at the lower phase flow rates occurred when the slug regime in the inlet vertical tangent leg X passed smoothly through the elbow bend and formed the smooth stratified regime in the outlet horizontal tangent leg Z. As the liquid (and gas) rate was increased the regime in the outlet horizontal tangent leg Z became successively stratified plus roll wave flow and stratified blow through slug and the negative pressure loss region passed 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 inlet vertical tangent leg X passed from churn to semi-annular flow. A slight minimum in the pressure drop relation occurred when the flow regime in the outlet Z passed from stratified roll wave to either annular roll wave or film plus droplet flow. When the liquid velocity in the inlet vertical tangent leg X exceeded the Taylor bubble rise velocity at low gas rates the slug or blow through slug regimes initially occurred in the outlet Z and the elbow bend pressure drop relation against $\overline{V}_{SG}$ tended to be rather flat. When the regimes changed to stratified roll wave as the gas rate was increased, the elbow bend pressure loss started to rise. In this region the elbow bend commenced to act as a droplet generator causing the pressure loss to rise rapidly.

Because of the low R/d value of the elbow bend used in this work, the contribution of ΔP_{BE} to the total elbow bend pressure drop ΔP_{BT} was only a few percent, but flow regimes present in the tangent leg had a considerable effect on ΔP_B. When the elbow bend pressure loss ΔP_{BT} was expressed as l_e/d, using the actual pressure drop in the inlet vertical tangent leg X for the calculation of the equivalent pipe length l_e, the data drew closer together and exhibited a general upward rising trend as shown in Fig. 9. The only regions not following the general trend were at the low phase flow conditions where negative pressure drops were in evidence and the highest phase flow conditions where the pressure drop tended towards a l_e/d value of about 37.

The data did not exhibit a regular relationship if other pipe friction values were used such as the straight vertical pipe or outlet pressure drops. The same was true when other correlating parameters such as W_G/W_L or $\overline{V}_L$ were employed. This observation adds weight to those made by a number of workers and mentioned earlier that a better correlation of the Lockhart–Martinelli type was obtained if the single phase pressure loss used in the correlation referred to that actually obtained through the bend and not in straight pipe.

The data in Fig. 9 was correlated by

$$l_e/d = 0.001384Re_T - 13.53 \quad (2)$$

for the elbow bend pressure drop for two phase gas–liquid flow through a vertical upwards to horizontal $R/d = 0.6539$

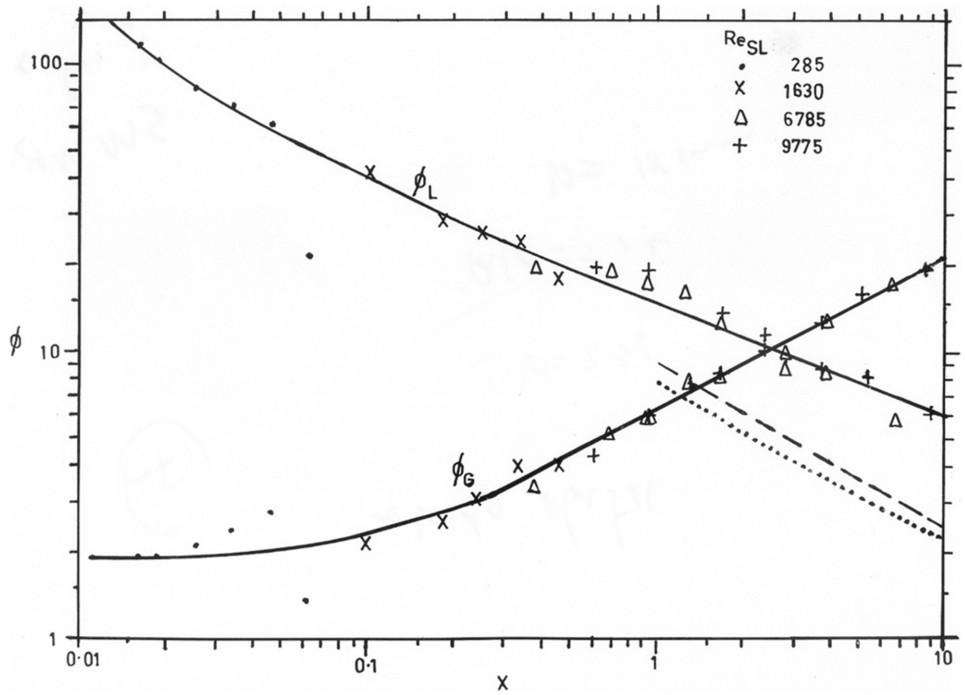

Fig. 10. Elbow bend pressure drop according to the Lockhart–Martinelli model. Data: Sekoda et al. [10]; $d = 0.018$; ... $R/d = 2.36$; - - - $R/d = 5.02$.

bend over the ranges of positive l_e/d values from $Re_{SG} =$ 2000–30,000 and $Re_{SL} = 280$–9800. Over these ranges of Reynolds numbers the accuracy of prediction was with 1% average (range +56% to −38%).

Fig. 10 shows the data of this work plotted after the Lockhart–Martinelli [8] model as suggested by Fitzsimmons [9] and Sekoda et al. [10].

$$\phi_x = \left[\frac{\Delta P_{TP}}{\Delta P_{SX}}\right]_B^{\frac{1}{2}} \tag{3}$$

$$X = \left[\frac{\Delta P_{SL}}{\Delta P_{SG}}\right]_B^{\frac{1}{2}} \tag{4}$$

These data follow a consistent pattern only when expressed in terms of the single phase pressure loss in the bend. The use of other pressure drops such as that in the riser tangent or outlet horizontal tangent did not present a logical picture. The data obtained here do not follow the results of either Fitzsimmons [9] or Sekoda et al. [10], neither do they show agreement with the ESD [14] model, the elementary model of Chisholm [15] or the homogeneous model mentioned by Chenoweth and Martin [7], but suggest that the plane of the bend had an important influence on the elbow bend pressure loss. Data from Sekoda et al. [10] are given to illustrate the difference between this work.

4. Conclusions

The pressure loss in the inlet vertical tangent leg X showed significant differences to that for the straight vertical pipe, particularly at the higher fluid flow rates. This was caused by the following elbow bend providing some measure of choking of the flow that resulted in a build-up of pressure and liquid in the inlet vertical tangent leg X when compared to the straight vertical pipe.

The outlet horizontal tangent leg Z gave pressure loss results that were in agreement with reported data. A drag reduction region was shown to exist for the lower liquid flow rates under $0.07\ \mathrm{m\,s^{-1}}$ and gas flows of 1–$2\ \mathrm{m\,s^{-1}}$. The elbow bend pressure loss also exhibited a negative pressure loss regime at low fluid flow rates. The effect was attributed to the smooth conversion by the elbow bend of the slug flow in the inlet vertical tangent leg X to smooth stratified flow in the outlet horizontal tangent leg Z.

A general correlation was presented for the elbow bend pressure drop in terms of the total Reynolds numbers. It was shown that the elbow bend pressure loss was best handled in terms of l_e/d calculated using the actual pressure loss in the inlet vertical tangent leg X. Further the Lockhart–Martinelli bend parameters gave a useful method of presenting the data.

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