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TWO-PHASE STRATIFIED FLOW SPLITTING AT A T-JUNCTION WITH AN INCLINED BRANCH ARM

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Abstract—The objective of this study is to investigate, experimentally and theoretically, two-phase splitting under stratified wavy flow conditions at a regular horizontal T-junction with an inclined branch arm.

Experimental data have been acquired with the side arm at horizontal conditions, downward inclination angles of −5, −10, −25, −40 and −60°, and upward inclinations of 1, 5, 10, 20, and 35° from the horizontal. The data reveal that gravity forces have a significant effect on the flow splitting. For downward inclination of the side arm more liquid is diverted into the branch arm, as compared to the case in which the side arm was horizontal. All the liquid was found to be diverted into the branch arm when the branch arm inclination was increased to −60°. For upward inclination angles a significant amount of the inlet gas has to be diverted into the side arm in order to get any liquid to flow into that arm. However, once liquid has started flowing, not much more additional gas has to be diverted into the side arm to get all of the liquid to flow into the branch. At 35° almost all the gas has to be diverted for any liquid flow into the branch.

A mechanistic model has been developed for the prediction of the splitting phenomenon for both the horizontal and the downward orientations of the side arm. The model is based on the momentum equations applied for the separation streamlines of the gas phase and the liquid phase. Very good agreement is observed between the prediction of the model and the data acquired for all the cases. Copyright © 1996 Elsevier Science Ltd.

Key Words: splitting, stratified-flow, T-junction, inclined-arm

1. INTRODUCTION

When liquid and gas flowing in a pipe encounter a T-junction, the two phases very rarely split in the same ratio. Sometimes all the liquid may be diverted into the branch arm and at other times all the liquid may go straight into the run arm. The fraction of liquid diverted into the branch can be very different from that of the gas. This unpredictable splitting of the liquid phase between the branch and the run arms is complicated due to the large number of variables that influence it. Geometry of the tee arms, flow pattern upstream of the T-junction, the inclination of the branch arm, the gas and the liquid flow rates, and the gas fraction diverted into the branch are the important variables that determine the liquid phase splitting between the two arms of the tee.

Two-phase flow splitting at a T-junction has gained increasing interest due to its common application in oil and gas transportation pipeline networks, and in the chemical process and nuclear industries. The unequal splitting of gas and liquid at T-junctions was observed to create problems in these industries. In gas distribution networks, condensate can be formed in pipelines in winter due to low temperatures. It was found that the condensate appears at some delivery stations while the other stations receive only dry gas. This kind of uneven splitting may result in creating operational and separation problems. In enhanced oil recovery, steam generated at a central boiler is transported to various wells through a pipeline network, which inherently possess many T or Y junctions. The hot water condensed from the steam takes a preferential route at these junctions, resulting in a non homogeneous injection of steam and water between different wells. The analysis of loss of coolant accident (LOCA) problems in pressurized water nuclear reactors is required for planning safety procedures. This analysis should include splitting flow determination, in order to predict the liquid phase flow behavior.

Large amounts of data have been acquired and a number of models have been developed so far, on two-phase flow splitting at T-junctions. Unfortunately, none of these works give a complete understanding of the splitting phenomenon, nor are they able to predict the liquid split very accurately. Initially, various investigators tried to resolve the problem with empirical correlations developed from data they collected in the laboratory. Later, physically based mechanistic models replaced these correlations and improved the prediction capabilities to a better extent. Most of the work done in earlier times was on T-junctions with a horizontal branch arm. A summary of the available literature for horizontal flow splitting is given by Ashton (1993) and Penmatcha (1993).

Tees encountered in the field are seldom horizontal, and very often have an inclined branch arm. However, very limited work has been done in this area. The pioneering study for inclined tees was conducted by Seeger *et al.* (1985). They performed phase separation experiments for a horizontal inlet tee and three side-arm orientations: horizontal, upward vertical and downward vertical. In a subsequent paper, Seeger *et al.* (1986) presented empirical correlations for flow splitting of liquid under the above three orientations of the branch arm.

The pressure drops in the run arm and the branch arm were reported by Reimann & Seeger (1986). Data were collected with air–water and steam–water flow in a T-junction with equal diameters for horizontal, upward vertical and downward vertical branch arms. A correlation was developed to predict the pressure drop. The authors concluded that the results of the model were unsatisfactory for vertical upward orientation of the branch arm.

Ballyk *et al.* (1991) conducted an experimental investigation to study the effect of branch arm size and its orientation on annular steam–water split at T-junctions with a horizontal inlet. Three orientations and three different sizes of the branch arm were studied. The three orientations of the branch arm included horizontal, 45° downward and 90° downward. Reported phase separation was severe when the branch arm diameter was decreased. The liquid taken into the branch arm increased as the side arm was inclined further downward.

The effect of side arm orientation and downstream geometry on stratified wavy and annular flow has been studied recently by Azzopardi & Smith (1992). A horizontal main pipe with horizontal and vertically upward oriented side arms was studied. The geometry downstream of the main pipe was found to affect the amount of liquid taken off in stratified wavy flow, while it had no effect in annular flow.

The literature review reveals that there is a lack of both systematic experimental data for the entire range of side arm inclinations and pertinent theory for two-phase splitting in non-horizontal tees. It is the intention of this paper to extend the study to tees with a horizontal inlet but an inclined side arm. The entire range of side arm inclination angles are considered and a mechanistic model is developed to predict the liquid splitting for downward orientations of the side arm.

2. EXPERIMENTAL PROGRAM

A schematic diagram of the two-phase flow splitting loop is shown in figure 1. Air and water are metered and combined at a standard mixing tee. The air–water mixture flows through a 19.8 m long, straight, 50.8 mm pipe and then encounters a 180° bend. The flow direction is thus reversed, and the mixture continues to flow through a 13.7 m long section, of 50.8-mm R-4000 transparent PVC pipe. This represents an effective $L/D > 600$, which ensures fully developed flow at the tee-junction.

The splitting tee is a regular 50.8 mm tee constructed of clear PVC R-4000. The lengths of the inlet and run arms are 1.016 m from the end to the center of the tee, and the branch arm length is 0.838 m. Six pressure taps, 3.18 mm in diameter are drilled in each arm. The first three pressure taps from the center of the T-junction in each arm are located 76.2 mm apart, while the remaining three taps are 177.8 mm apart. The pressure profile is determined by connecting one part of a differential pressure transducer to the first pressure tap, and the other part to the remaining pressure taps.

Special flanges are connected to the branch-arm splitting tee to enable rotation of the tee through the entire range of inclination angles from 90° upward to −90° downward. The branch arm is supported by a mechanism consisting of two vertical poles and a cross-beam to which the

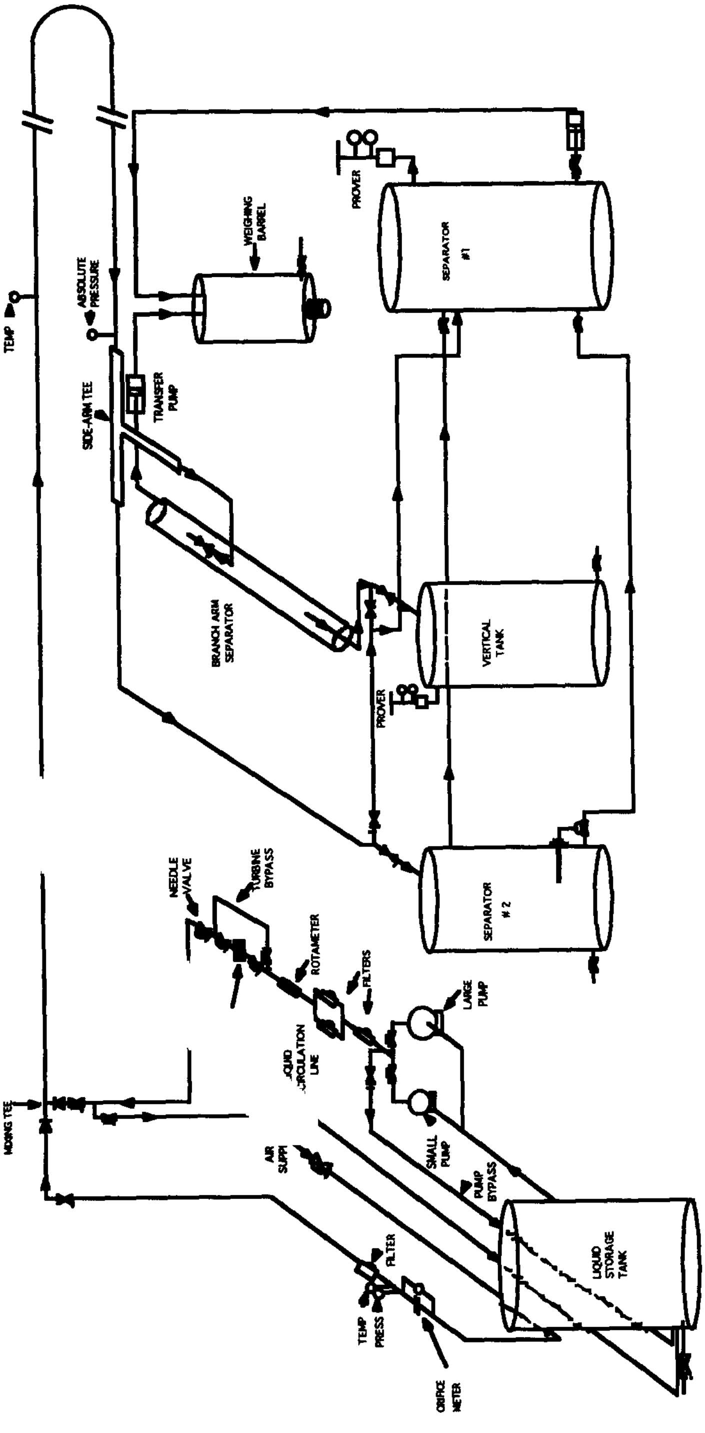

Figure 1. Schematic diagram of the experimental facility.

branch arm is attached. This support is designed to allow measurements to be taken at any inclination angle of the branch arm. A flexible hose is used to connect the branch arm outlet to the horizontal branch arm separator.

The two-phase mixture from the branch arm flows into the branch-arm separator, placed below the T-junction. This separator has dimensions of 0.406 m × 3.353 m and is positioned horizontally, close to the ground. The liquid remains in the separator until the end of the run while the gas exits the separator and flows through a vertical tank. The gas is discharged outside the building through a flow prover (an orifice meter, where the downstream side is open to the atmosphere). The two-phase mixture from the run arm flows into separators #1 and #2. These two separators are connected at the bottom to allow the liquid levels to equalize in each separator. Another connection is made at the top to allow continuous gas flow through both separators to one flow prover. The liquid remains in the separators until the end of the run, while the gas is metered continuously though a flow prover before being discharged outside. At the end of each run, the liquid accumulated in each separator is transferred to the weighing barrel by a small piston pump, where it is measured.

Upstream of the side-arm tee there are an absolute pressure transducer, a trap section, and a double-ring capacitance sensor. Due to the inconsistency of the capacitance sensor performance, the trap section was used for liquid holdup measurements. A data acquisition system, manufactured by National Instruments was installed on a Mac IIci for the data collection. The software Lab VIEW, made by the same company, has a new concept of programming and a new graphical language that is easy to use.

All the experimental flow splitting runs were conducted under stratified wavy flow conditions. The average superficial velocity of the gas phase is fixed at $V_{SG} = 6.1$ m/s. This gas flow rate falls approximately at the center of the stratified wavy region in the flow pattern map for an air–water system at the experimental conditions. The superficial velocity of the liquid phase is varied as follows: $V_{SL} = 0.059$, 0.030, 0.015 and 0.0051 m/s. Various runs were conducted for each pair of V_{SG} and V_{SL}, varying the branch to run gas flow rate ratios, and measuring the resulting splitting ratio of the liquid phase between the branch and the run and the pressure distribution. This procedure was repeated for each inclination angle.

Since the system operates in a "batch" mode, efforts are made to minimize initial unsteady state effects. Initially the system is setup with single phase gas flow. This fixes the desired inlet gas flow rate and the gas splitting ratio between the branch and the run. (The gas splitting flow rates are controlled by two ball valves upstream of the separators.) Once steady state conditions are reached, the liquid phase is introduced into the mixing tee, and two-phase flow occurs. The actual experimental run starts at this time and continues for approximately 1 h.

All the experimental runs were carried out under stratified wavy flow conditions. About 200 experimental runs were conducted. The pressure at the T-junction was maintained at 295 kPa absolute for all these experimental runs. Data were collected for horizontal, downward inclinations and upward inclinations of the side arm. All the liquid was diverted into the branch arm when the branch arm's downward inclination was increased to $-60°$. Also, it was found that a negligible amount of liquid goes into the branch when the branch arm is inclined about 35° upward. As a result, the data were acquired for downward inclination from horizontal to $-60°$ and for upward inclination to 35°. Complete phase separation will take place beyond these inclinations.

Horizontal conditions

Initial experimental data were acquired with the side arm in the horizontal position. The results obtained, given in figure 2, could then be compared to published data of Shoham *et al.* (1987) as shown in figure 3. Comparing the two sets of data, it can be seen that for low fractions of the gas diverted into the side arm (less than 60% diverted into the side arm) (F_{BG}), there was good agreement for the resulting liquid splitting ratios. This was also the case for higher fractions of gas intake (over 60% divert into the side arm) with low liquid superficial velocities. However, with a high gas intake fraction and high liquid superficial velocities, more liquid was observed to flow into the branch in the present study than in the Shoham *et al.* results. It is believed that this difference can be attributed to two factors: the different characteristics of the T-junction, rounded

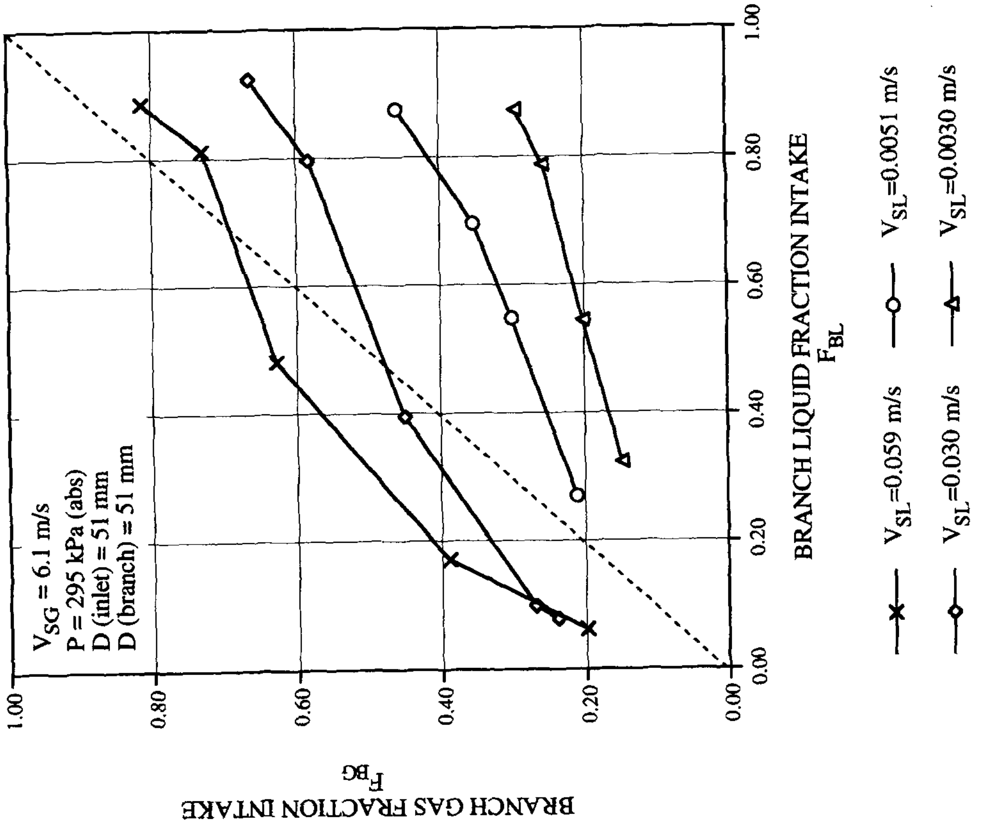

Figure 2. Experimental results for splitting ratios: branch arm horizontal.

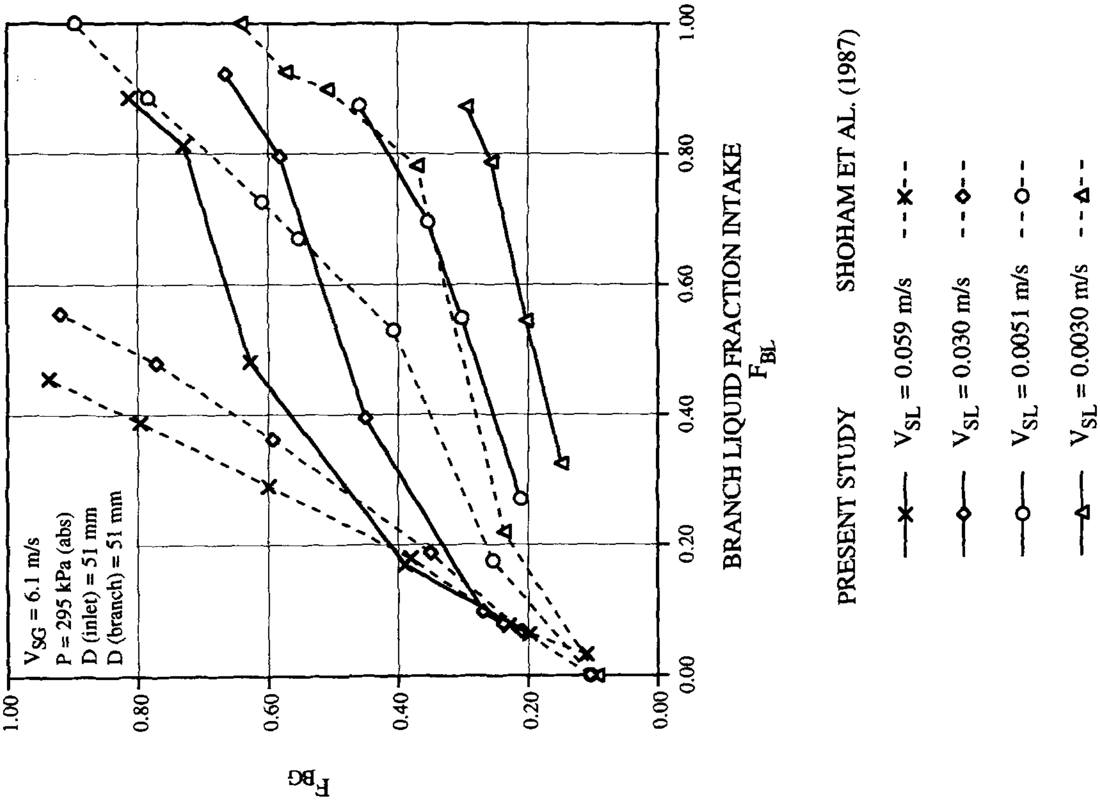

Figure 3. Comparison between present study and Shoham *et al.* (1987) data.

edge in this study vs sharp edge in Shoham *et al.*; or, due to slight deviations of the side arm inclination from the horizontal in one of the studies.

Downward inclination angles

As the branch arm is inclined downward, it was found that liquid easily diverts into the branch arm as compared to the case where the branch arm was horizontal. Data were acquired with the side arm inclined downward at angles from the horizontal of −5, −10, −25, −40 and −60°. The results can be seen in figures 4–7, respectively.

Figure 4 shows the results when the branch is inclined at −5°. For the highest liquid flow rate ($V_{SL} = 0.059$ m/s), the gravity forces acting on the liquid phase are so high that the effect of the pressure drop in the side arm is not felt by the liquid until about 55% of the gas is diverted into the branch. For $F_{BG} > 55\%$ and $V_{SL} = 0.059$ m/s, any slight increase in the gas fraction intake into the branch drives a lot of liquid into the branch, as depicted by the relatively flat curve in that region. As the liquid flow rate is decreased, the lower inertial forces on the liquid phase makes it easier to divert more liquid into the branch. For example, when $F_{BG} = 20\%$, about 20% of the liquid is diverted into the branch for the highest liquid flow rate (i.e. $V_{SL} = 0.059$ m/s), while about 70% of the liquid is diverted into the branch for the lowest liquid flow rate ($V_{SL} = 0.0051$ m/s).

Figure 5 shows the results for −10° inclination angle. While the curves for all liquid flow rates retain the same shape as for the case of −5°, the shift of the curves toward the right side of the plot shows that more liquid is going into the branch for −10° downward than for −5° downward. This is due to the higher gravity forces for the −10° downward case.

Similarly, the plots for −25, −40 and −60° downward inclination show a gradual shift of the curves to the right side of the plot, as the branch arm is inclined more downward, diverting more liquid into the side arm. Figure 7 shows that for −60° downward inclination, almost 100% of the liquid is diverted into the branch, resulting in a complete phase separation. For this system, any further lowering of the branch arm inclination over −60° would not yield any new results, since the T-junction acts as a separator, where all the liquid is diverted into the branch arm.

Upward inclination angles

Data were also acquired with the side arm inclined at 1, 5, 10, 20 and 35° upwards from the horizontal, and the results can be seen in figures 8–12, respectively. There is a significant change in the splitting ratios for upward inclinations of the side arm.

The results for the inclined side arm show similar characteristics throughout the upward angles. A significant amount of the inlet gas has to be diverted into the side arm in order to get any liquid to flow into that arm. However, once liquid has started flowing, not much more additional gas has to be diverted into the side arm to get all of the liquid to flow into the branch. A good example of this phenomenon can be seen in figure 9, showing the results for 5° upwards. For all of the liquid flow rates, a gas splitting ratio of over 50% has to be maintained in order to get any liquid flow into the branch. However, once F_{BG} reaches 70%, then all of the inlet liquid is diverted into the side arm. It is also apparent from the results that for higher side arm inclination angles, more diverted gas is required to start the liquid flowing into the side arm. Once the side arm is inclined at 35° (figure 12), over 80% of the inlet gas has to flow into the side arm for any of the liquid to flow into that arm. At this inclination angle the T-junction can act as a simple separator. For example, in order to prevent any liquid from flowing into the downstream facilities past the side arm, a gas split of 70% could be used. This would allow only gas to flow into the side arm while all of the liquid and the remaining gas would flow into the run arm. As this phenomenon would be repeated for further inclination angles, this was the highest upward inclination angle used in the study.

Another important result that the figures highlight is that the splitting ratios become independent of the inlet liquid velocities. This means that the most important factors in determining the liquid splitting ratios are the gas splitting ratio and the inclination angle of the side arm.

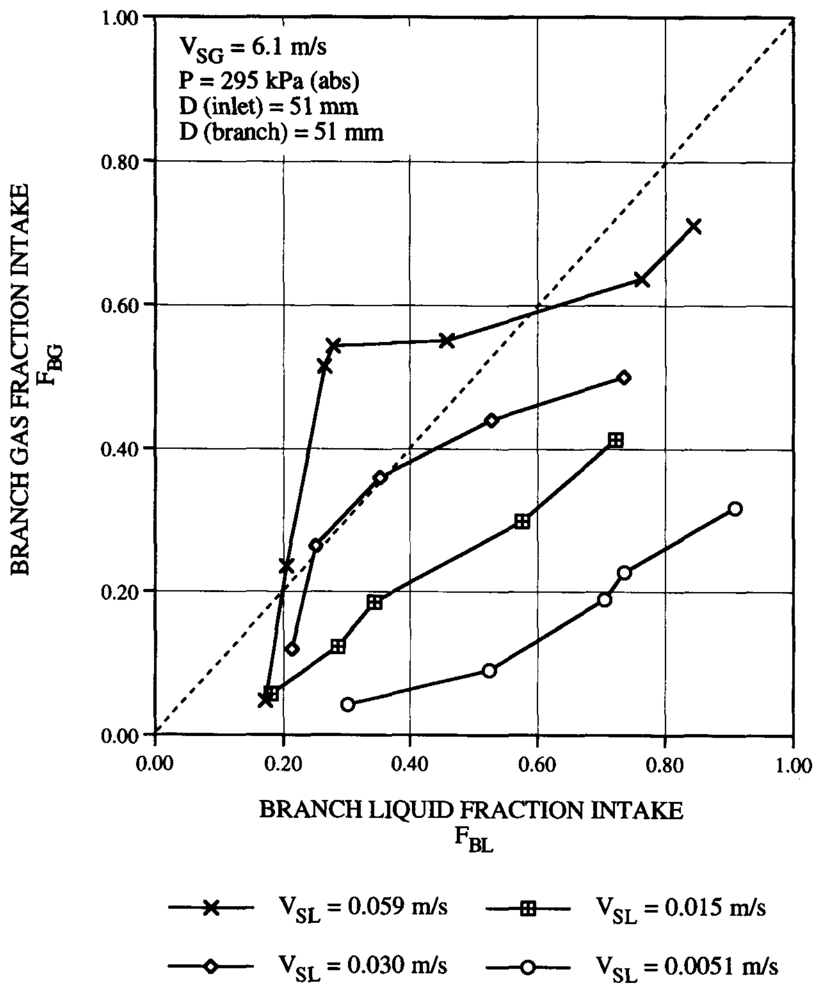

Figure 4. Experimental results for splitting ratios: branch arm 5 degrees downward.

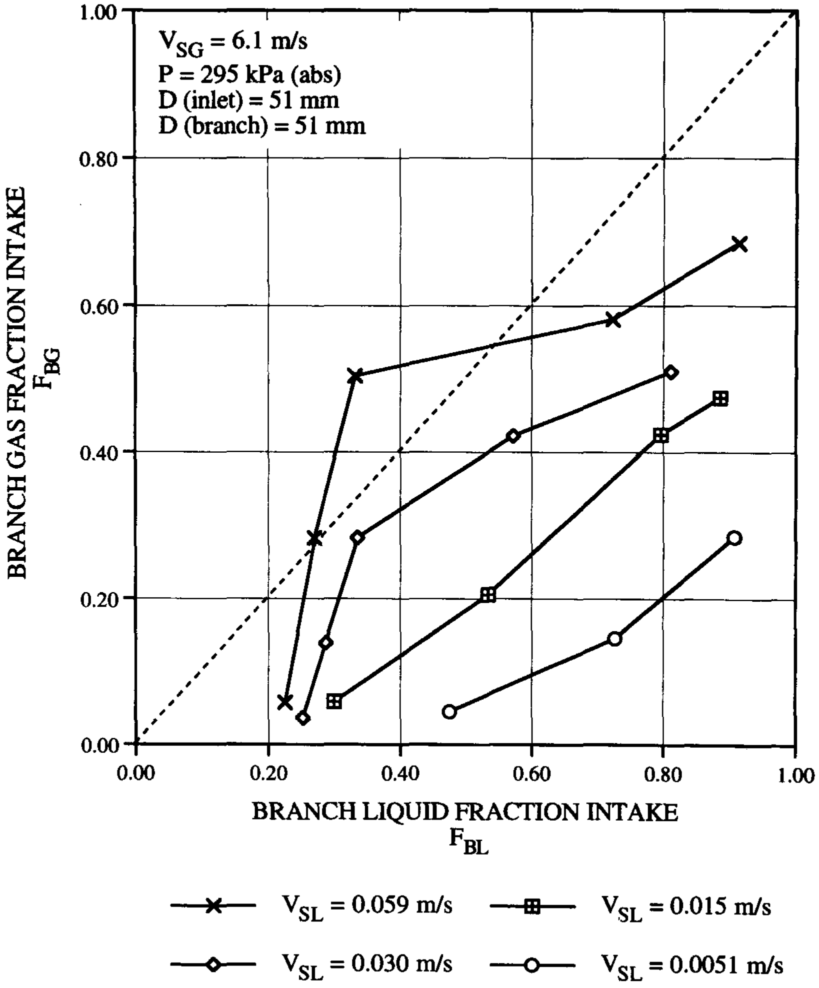

Figure 5. Experimental results for splitting ratios: branch arm 10 degrees downward.

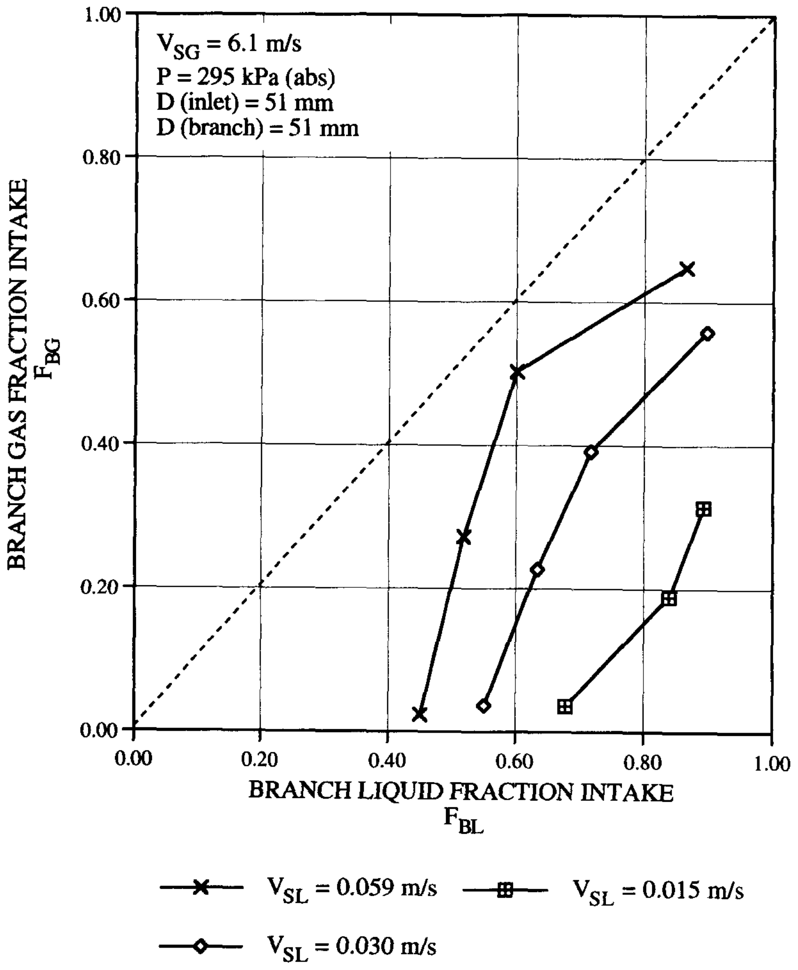

Figure 6. Experimental results for splitting ratios: branch arm 25 degrees downward.

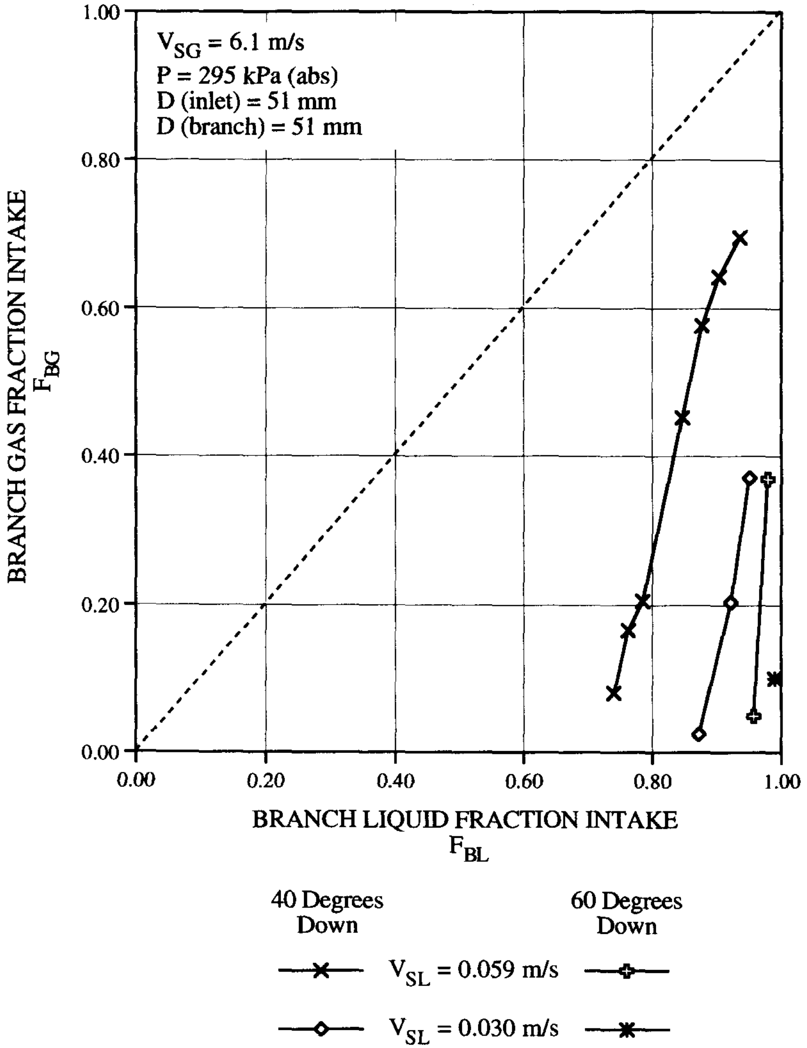

Figure 7. Experimental results for splitting ratios: branch arm 40 and 60 degrees downward.

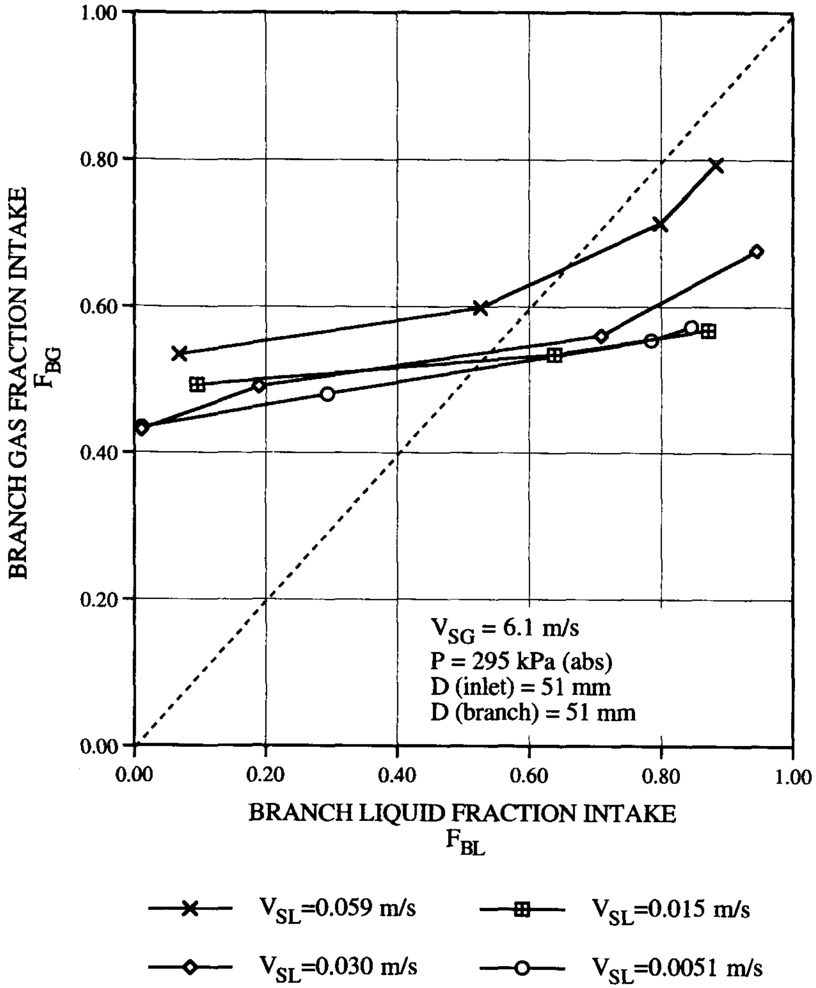

Figure 8. Experimental results for splitting ratios: branch arm 1 degree upward.

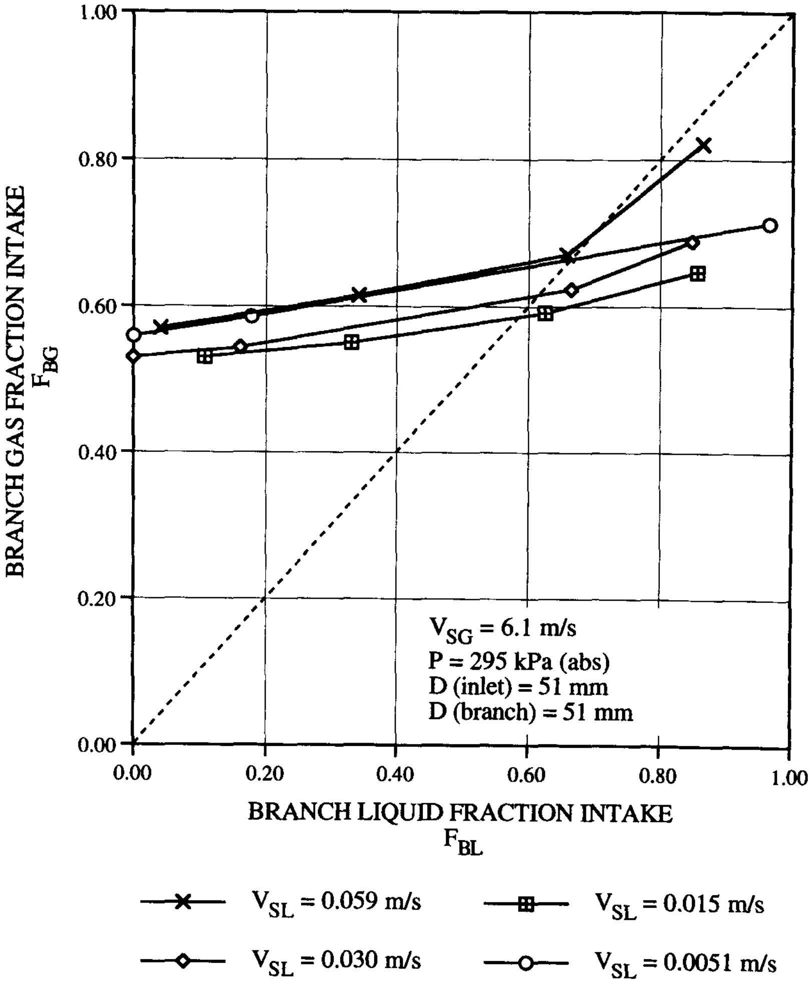

Figure 9. Experimental results for splitting ratios: branch arm 5 degrees upward.

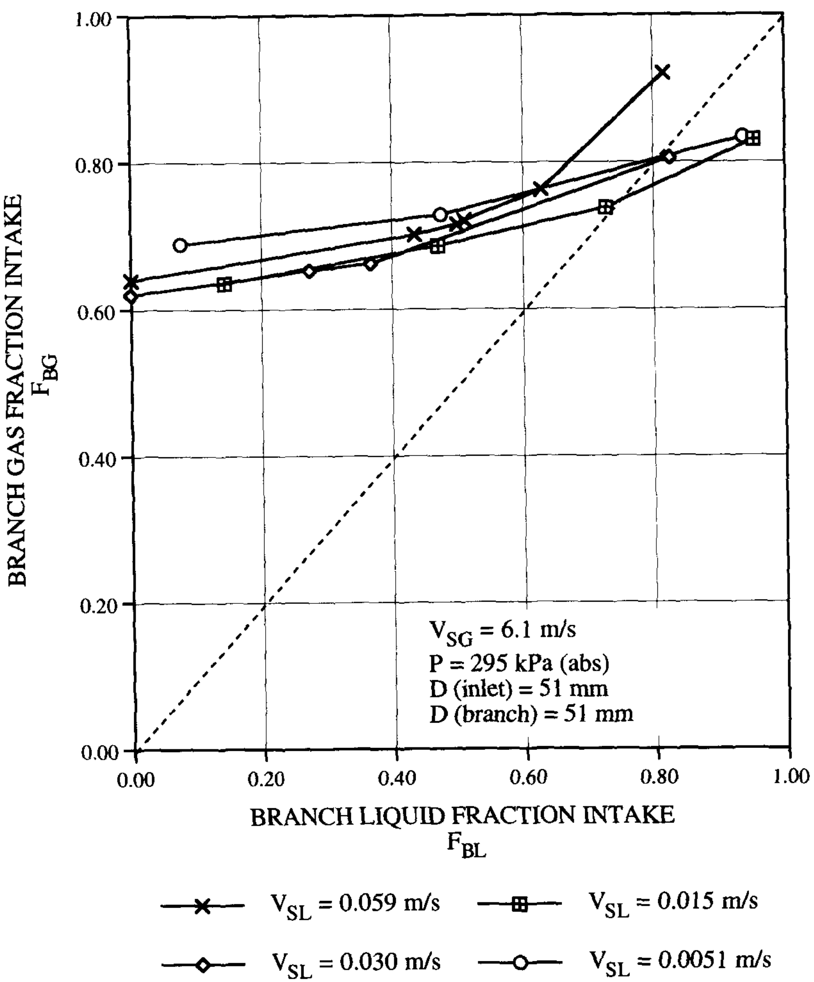

Figure 10. Experimental results for splitting ratios: branch arm 10 degrees upward.

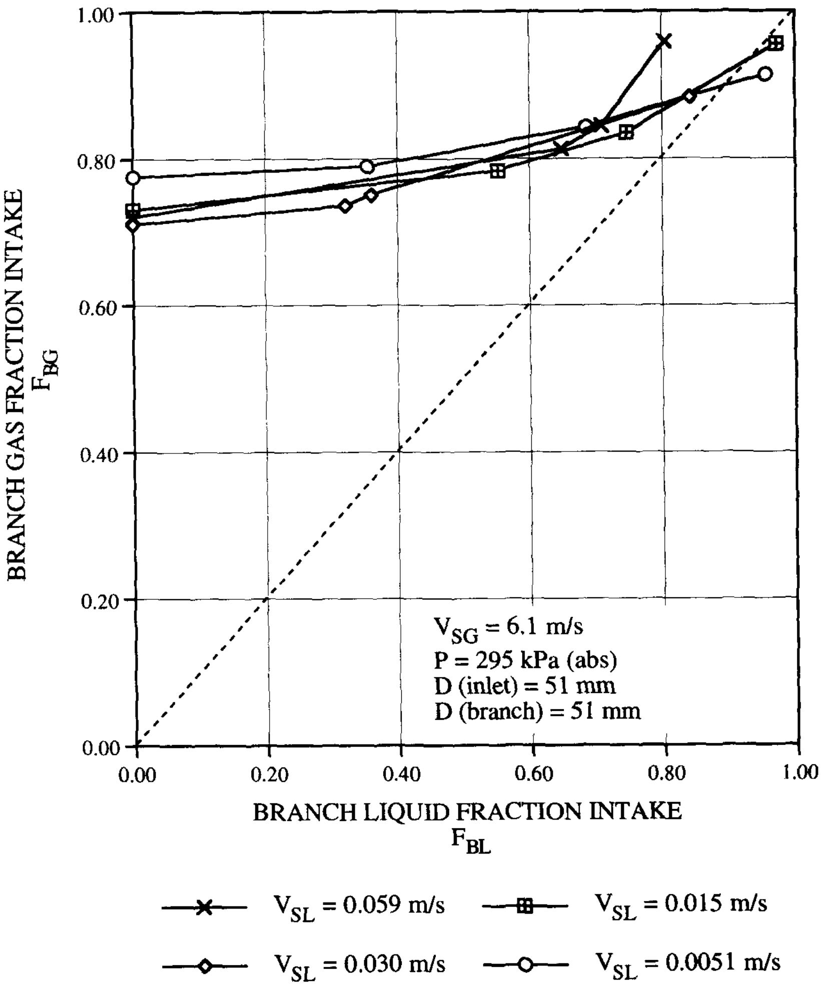

Figure 11. Experimental results for splitting ratios: branch arm 20 degrees upward.

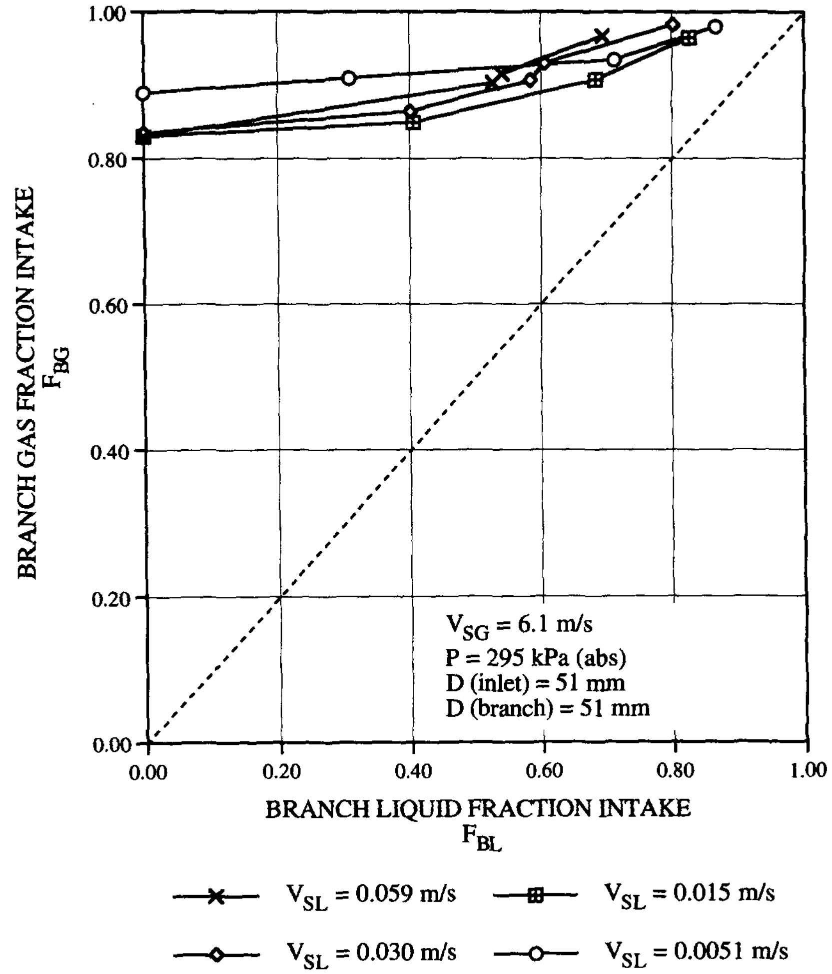

Figure 12. Experimental results for splitting ratios: branch arm 35 degrees upward.

Pressure drop measurements

A typical pressure distribution in the three arms of the T-junction is shown in figure 13. The pressure distribution is similar to that reported in the literature for the horizontal case. The pressure drop across the T-junction was measured using pressure taps drilled in the tee. As can be seen, as a part of the gas is diverted into the branch, due to the Bernoulli effect, there is a pressure rise in the run arm. In the branch arm, there is a pressure drop which provides the momentum change for the fluids moving from the inlet into the branch arm. Details on the experimental facility and the experimental results are given by Penmatcha (1993) and Ashton (1993).

3. MODELING

The model presented in this section pertains only to the downward inclination configuration of the side arm due to its simplicity. The flow splitting mechanisms for upward and downward inclinations of the side arm are quite different. For downward inclinations, the flow pattern in the side arm remains to be stratified flow. As a result, the flow in the side arm has negligible effect on the splitting mechanism at the T-junction. In contrast, for upward inclinations, the flow pattern in the side arm abruptly changes to intermittent flow. For this case, liquid flows up and down the side arm making the splitting mechanism complex.

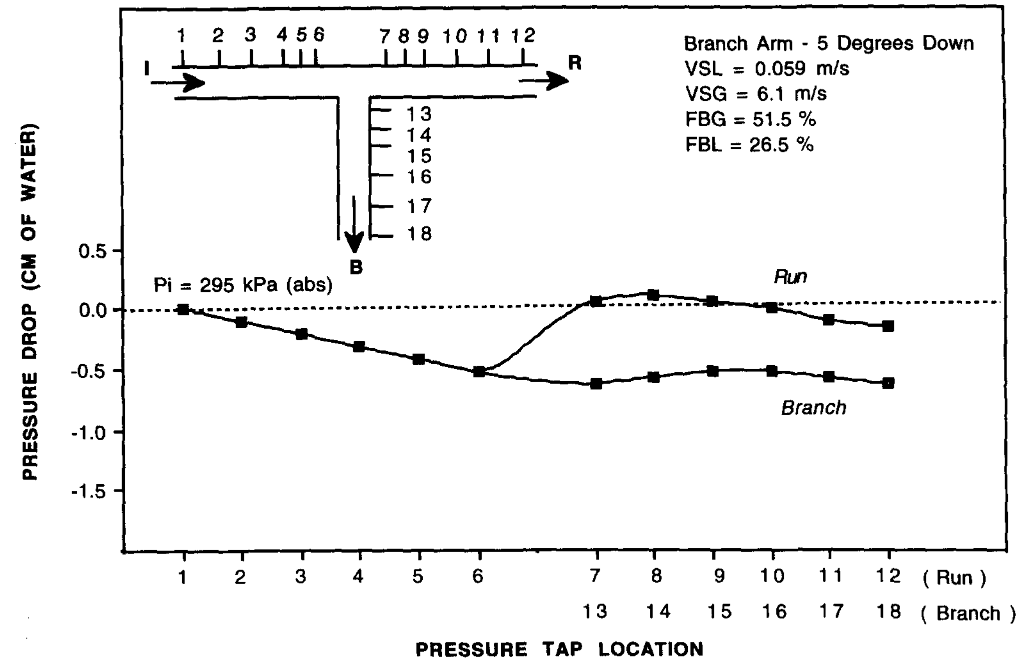

Figure 13. A typical pressure distribution at the tee.

Figure 14 shows the T-junction system at dynamic equilibrium, in which the gas and liquid phases are splitting unevenly at a T-junction. It can be assumed that the fluid particles in both the phases travel along streamlines. As these streamlines are deflected toward the branch arm, some succeed in entering the branch. The other streamlines, being far away from the opening of the branch arm, cannot reach it and hence flow into the run arm.

An imaginary separation streamline is assumed at the interface in each of the two phases. These streamlines divide vertically the fluids that enter the branch arm and the run arm. This kind of streamline approach was used by previous investigators like Shoham *et al.* (1987) and others. As shown in figure 14, AB is the dividing streamline for the liquid phase, while CB is the dividing streamline for the gas phase. The two streamlines considered, meet the wall at the junction point B, which is located at the intersection of the interface and the pipe wall at the inlet of the branch arm. It is assumed that the fluid to the right side of the gas and the liquid separation streamlines will be diverted into the branch, and that on the left side will go straight into the run arm. Note that the imaginary separation streamlines for the gas and the liquid are not the same.

The objective of the proposed model is to develop a method to predict the fraction of liquid going into the branch F_{BL}, when F_{BG} the fraction of gas diverted into the branch, and the downward orientation of the branch arm "θ" are given. As the gas fraction taken into the branch arm is known, the pressure gradient created at the side arm to accomplish this can be calculated. The same pressure gradient acts also on the liquid phase. In addition, a gravity force acts on the liquid which can be calculated from the inclination of the branch arm. The gravity force on the gas phase can be neglected. The horizontal branch arm is a special case in which the gravity force will become zero. Based on the knowledge of these forces, the liquid intake into the branch F_{BL} can be calculated according to the following procedure.

The gas and liquid average velocities approaching the T-junction are V_G and V_L, respectively. The gas streamline CB is analyzed first. Since F_{BG} is given, Y_G, the distance of the gas streamline from the wall on the branch side can be calculated using geometrical relationships. For a fluid element traveling along the streamline CB, the momentum equation in the Y direction for steady state flow with no frictional losses can be written as,

$$\frac{\partial P}{\partial Y} + \rho_G g \sin\theta + \rho_G \frac{dV}{dt} = 0, \qquad [1]$$

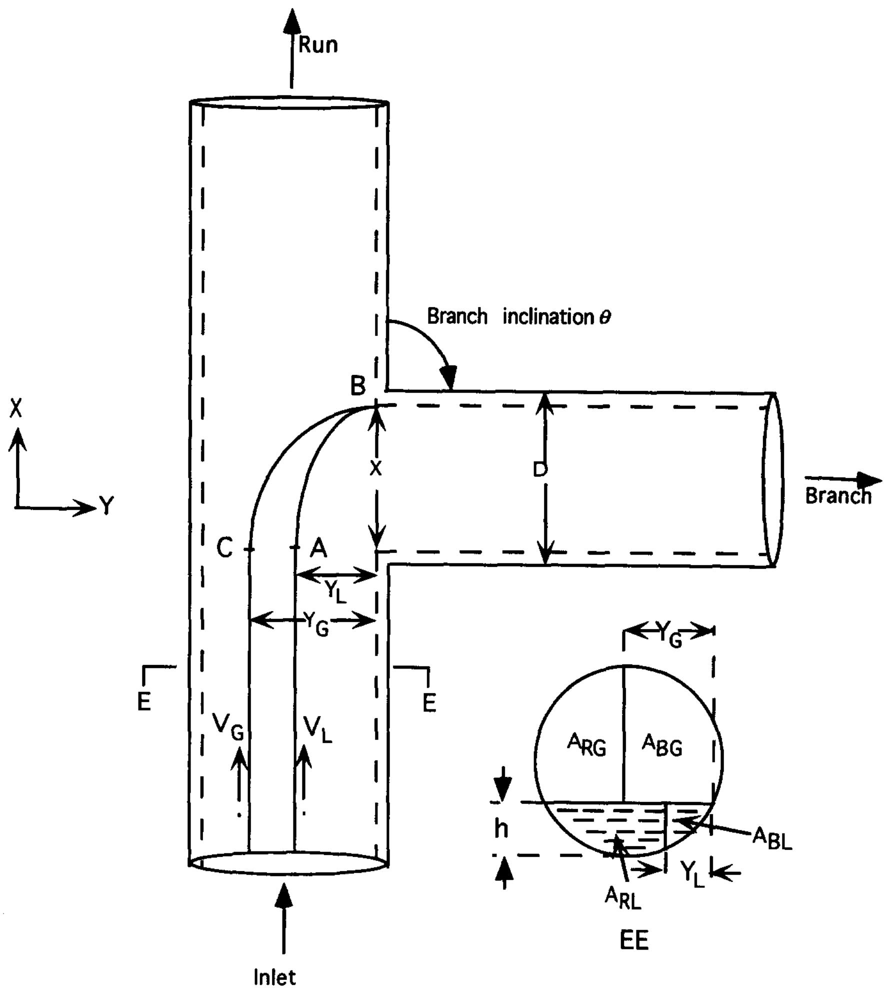

Figure 14. The physical model for gas and liquid splitting at a tee junction.

where P is the pressure and ρ is the density. In the above equation, θ is positive upward and negative downward. Since the gravity term can be neglected for the gas phase, [1] can be rewritten as

$$\frac{\partial P}{\partial Y}+\rho_{\mathrm{G}}\frac{\mathrm{d}V}{\mathrm{d}t}=0. \qquad [2]$$

V_{GC} and V_{GB} are designated as the components of gas velocity in the Y direction for the streamline considered, at points C and B, respectively. The pressure drop between the same points C and B, and in the same direction Y, is ΔP_{G}.

Assuming that $\partial P/\partial Y=$ constant, and since $V_{\mathrm{GC}}=0$, integrating [2] from C to B gives,

$$\frac{\Delta P_{\mathrm{G}}}{Y_{\mathrm{G}}}+\rho_{\mathrm{G}}\frac{V_{\mathrm{GB}}}{t_{\mathrm{G}}}=0. \qquad [3]$$

The axial distance traveled by the gas fluid element from C to B is X_{G} (the interfacial length S_{i}) and t_{G} is the time taken to accomplish this. We can also write,

$$t_{\mathrm{G}}=\frac{X_{\mathrm{G}}}{V_{\mathrm{G}}}. \qquad [4]$$

The radial distance Y_{G} traveled by the fluid element can be determined from the radial acceleration, a_{RG}, as

$$Y_{\mathrm{G}}=\frac{a_{\mathrm{RG}}t_{\mathrm{G}}^{2}}{2}=\frac{V_{\mathrm{GB}}}{2}\frac{X_{\mathrm{G}}}{V_{\mathrm{G}}}. \qquad [5]$$

Rearranging [5], yields

$$V_{GB} = 2V_G \frac{Y_G}{X_G}. \quad [6]$$

Substituting [4] and [6] into [3] gives,

$$\Delta P_G = -2\rho_G V_G^2 \frac{Y_G^2}{X_G^2}. \quad [7]$$

Similarly, for the liquid phase, the momentum balance equation in the Y direction for an element traveling along the streamline AB can be written as,

$$\frac{\partial P}{\partial Y} + \rho_L g \sin\theta + \rho_L \frac{dV}{dt} = 0. \quad [8]$$

For the fluid element considered, V_{LA} and V_{LB} are designated as the components of the liquid velocity in the Y direction at points A and B, respectively.

Assuming that $\partial P/\partial Y = \text{constant}$, and since $V_{LA} = 0$, integrating [8] from A to B gives,

$$\frac{\Delta P_L}{Y_L} + \rho_L g \sin\theta + \rho_L \frac{V_{LB}}{t_L} = 0. \quad [9]$$

where t_L is the time taken by the liquid phase element to travel from A to B. Since the pressure gradient in the liquid and gas phases should be equal,

$$\frac{\Delta P_L}{Y_L} = \frac{\Delta P_G}{Y_G}. \quad [10]$$

Similar to the gas phase case, given in [4] and in [6], for the liquid phase we can write

$$t_L = \frac{X_L}{V_L}. \quad [11]$$

and

$$V_{LB} = 2V_L \frac{Y_L}{X_L}. \quad [12]$$

Equations [10]–[12] can be substituted in to [9] to solve for Y_L as,

$$Y_L = -\left(\frac{\Delta P_G}{Y_G} + \rho_L g \sin\theta\right)\frac{X_L^2}{2\rho_L V_L^2}. \quad [13]$$

Substituting for ΔP_G from [7] and from

$$X_G = X_L = S_i, \quad [14]$$

[13] can be solved for Y_L.

After evaluating Y_L from [13], the fraction of liquid diverted into the branch, F_{BL}, can be calculated using simple geometrical relationships.

4. RESULTS AND DISCUSSION

The results obtained from the proposed model are compared with the experimental data in figures 15–20. The measured values of the liquid holdup were used for the determination of the in situ velocities of the gas and liquid phases. As can be seen, the model predictions are very close to the experimental data, both for the horizontal branch arm and for all the downward inclinations of the branch arm.

When the Taitel & Dukler (1976) model was used to determine the liquid holdup, the predictions of the model were less accurate. The reason for this discrepancy is due to the under predictions of liquid holdups by the Taitel & Dukler model. The predicted liquid holdups for the

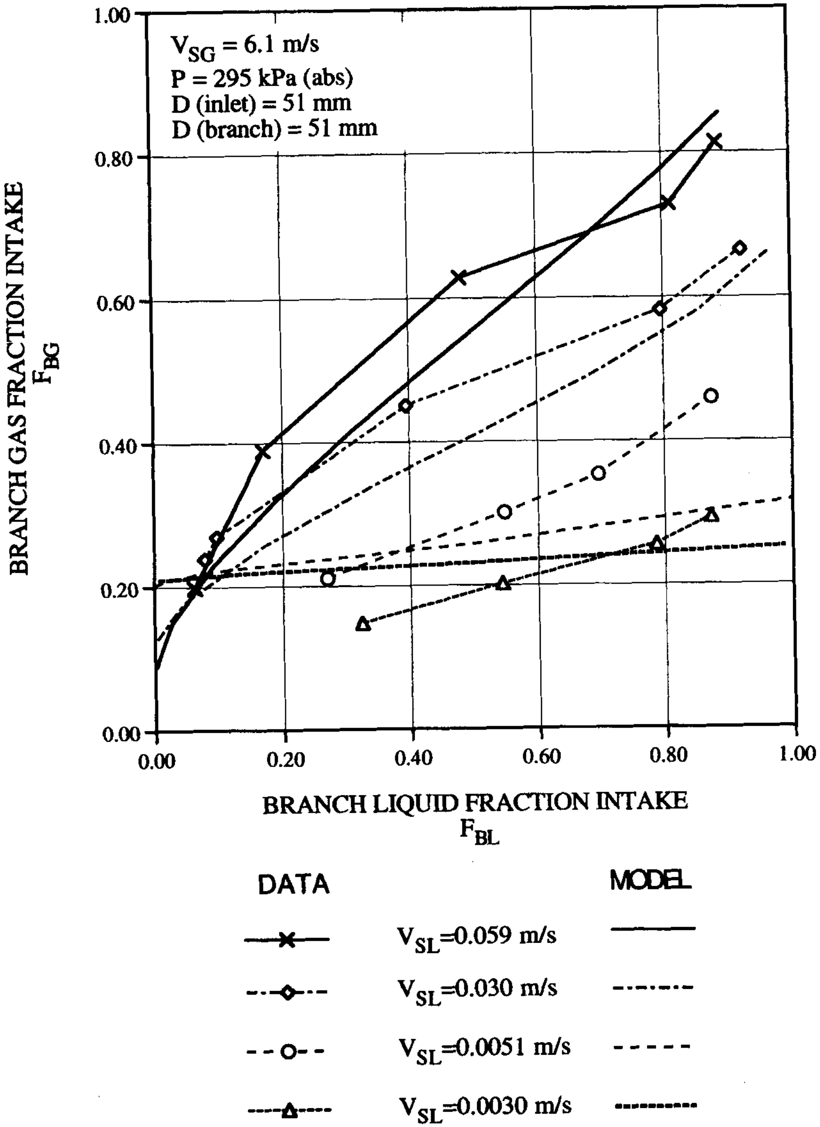

Figure 15. Comparision between the model and experimental data: branch arm horizontal

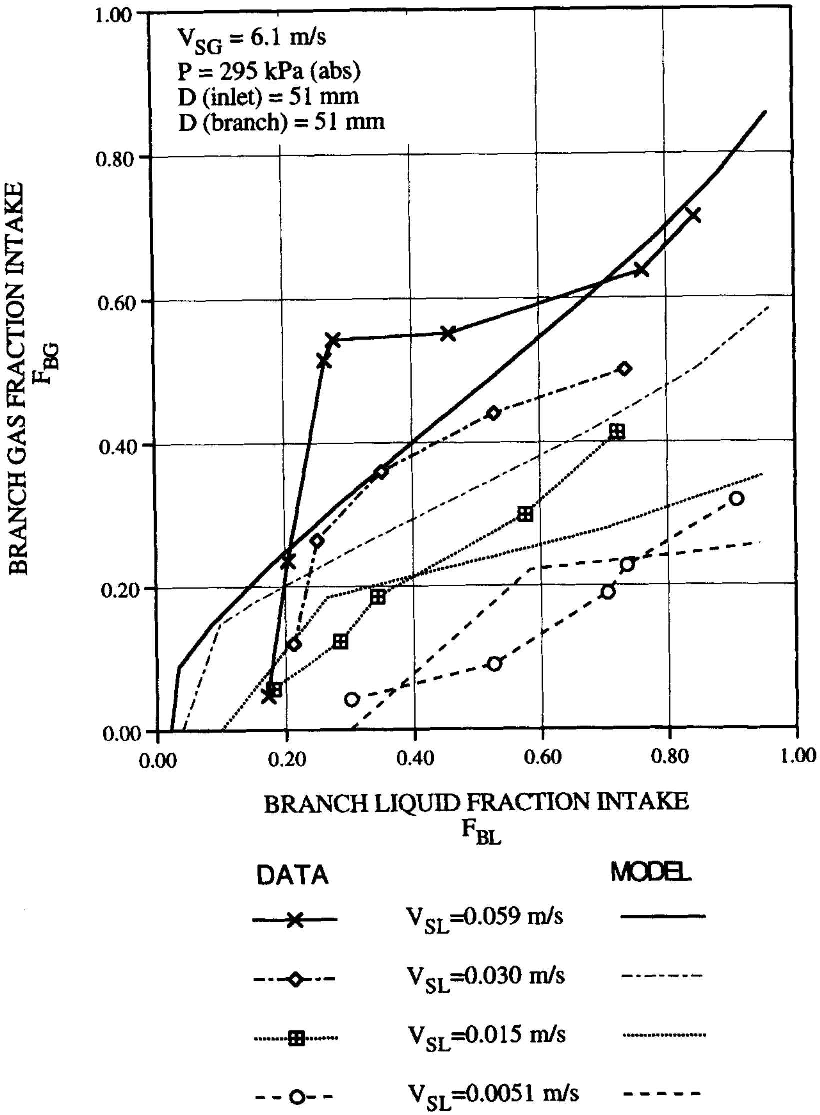

Figure 16. Comparision between the model and experimental data: branch arm 5 degrees downward.

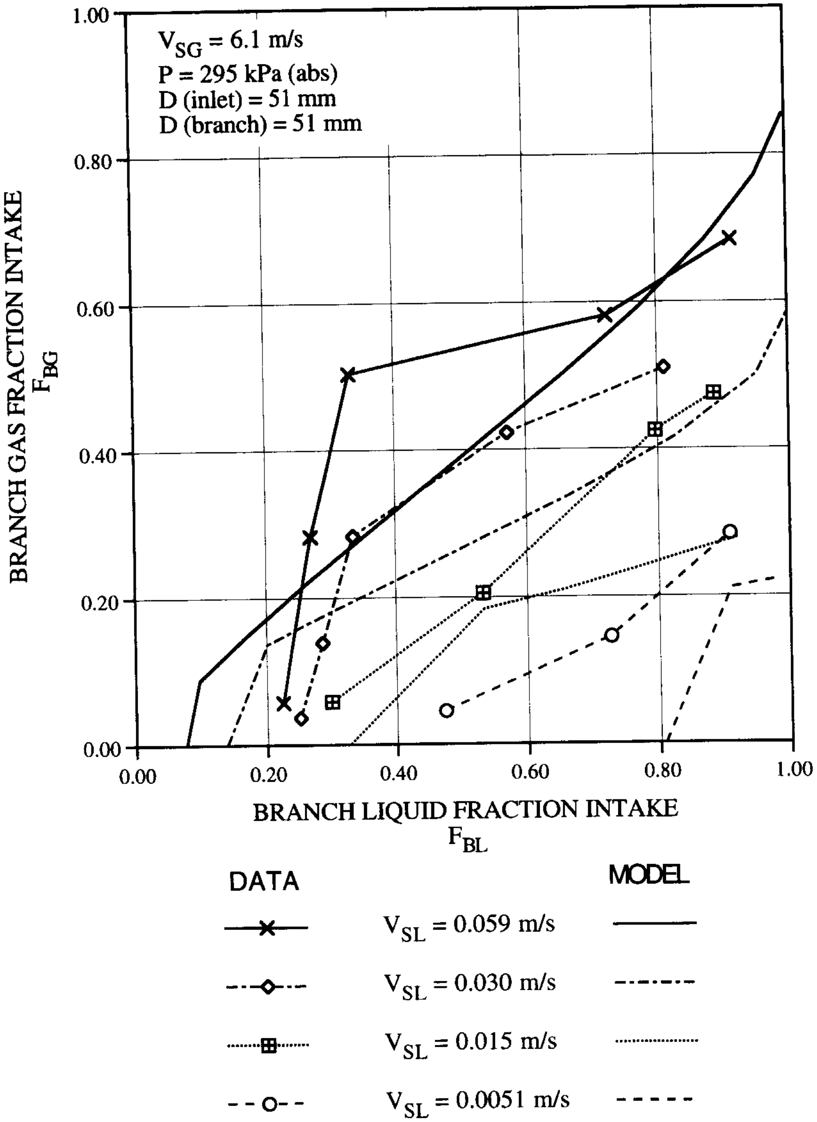

Figure 17. Comparision between the model and experimental data: branch arm 10 degrees downward.

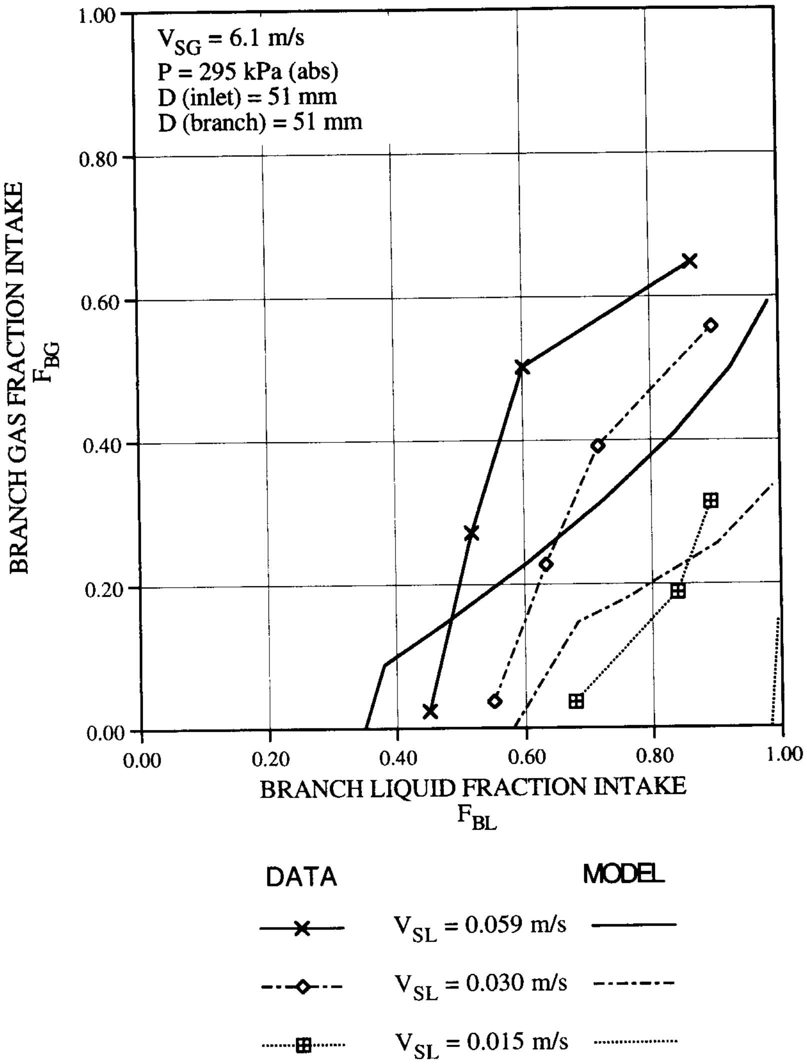

Figure 18. Comparision between the model and experimental data: branch arm 25 degrees downward.

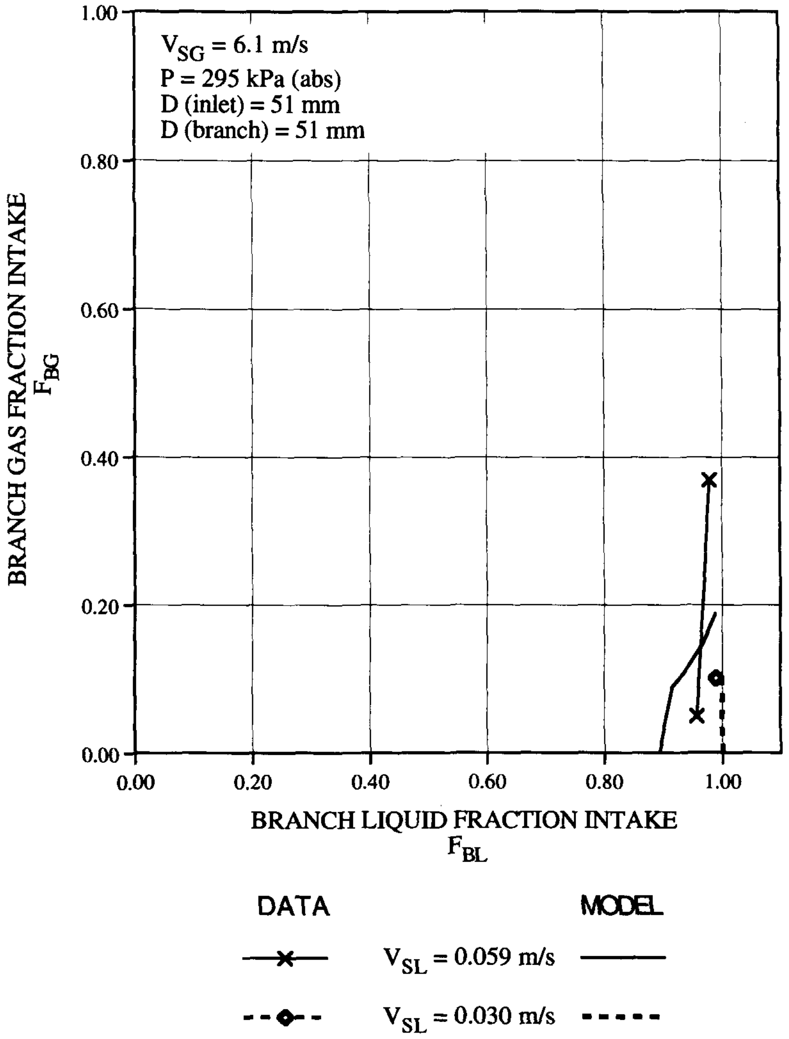

Figure 19. Comparision between the model and experimental data: branch arm 40 degrees downward.

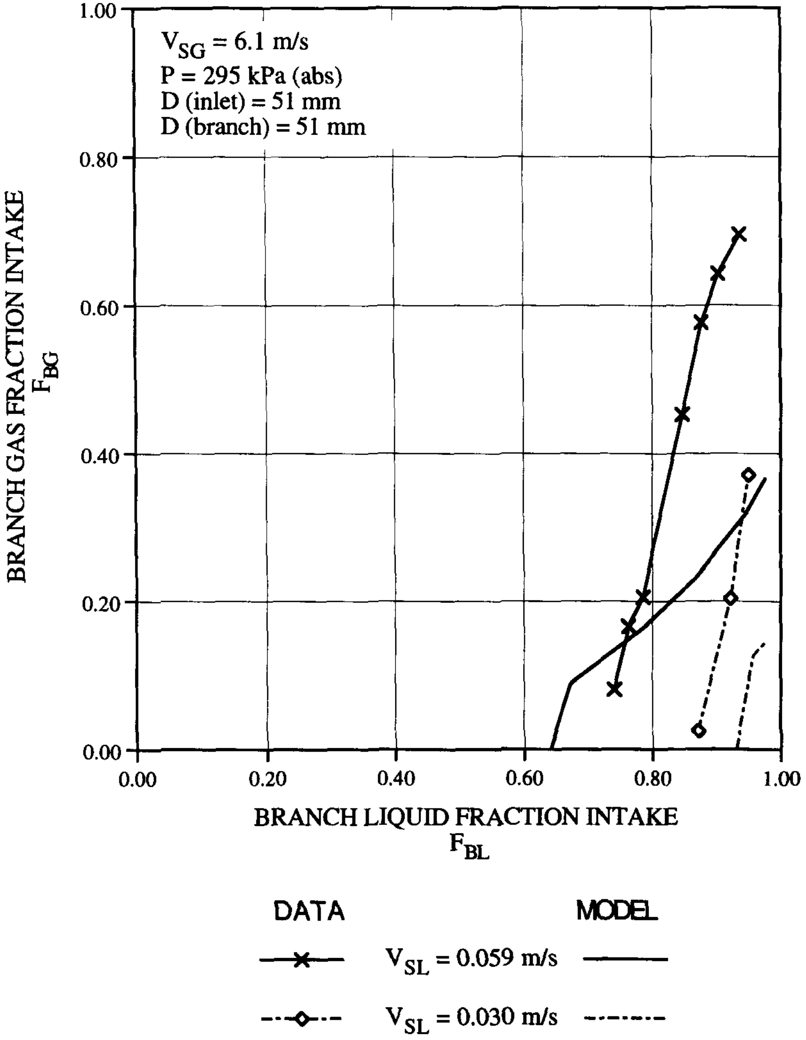

Figure 20. Comparision between the model and experimental data: branch arm 60 degrees downward.

experimental runs with $V_{SL} = 0.059$, 0.030, 0.015 and 0.0051 m/s are 0.095, 0.055, 0.030 and 0.011, while the measured results are 0.128, 0.084, 0.058 and 0.035, respectively. Therefore, it is necessary to use accurate liquid holdups for the model.

5. SUMMARY AND CONCLUSIONS

A theoretical and experimental investigation of two-phase flow splitting at a regular T-junction with an inclined side arm has been conducted. Experimental data were acquired for horizontal, upward inclinations and downward inclinations of the branch arm, with stratified wavy flow as the flow pattern upstream of the T-junction. The data show strong dependence of the splitting phenomenon on the orientation of the side arm. A mechanistic model was developed to predict the unequal splitting of the two phases of gas and liquid at the T-junction. The model is applicable for horizontal and all downward inclinations of the branch arm. Very good agreement was found between the model predictions and the experimental data.

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