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A UNIFIED MODEL FOR STRATIFIED–WAVY TWO-PHASE FLOW SPLITTING AT A REDUCED T-JUNCTION WITH AN INCLINED BRANCH ARM

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Abstract—Stratified–wavy two-phase flow splitting at a reduced T-junction with an inclined branch arm has been investigated experimentally and theoretically. Experimental data have been acquired with the reduced branch arm inclined at horizontal, downward inclination angles of −5°, −10°, −25°, −40° and −60° and upward inclination angles of 1°, 5°, 10°, 20°. The data reveal that for the case of a downward branch arm configuration the high gas velocity in the reduced branch arm and the gravity effects tend to increase the liquid flowing into the branch, as compared to the horizontal case. For upward inclinations of the branch arm, gravity forces tend to reduce the liquid flow into the branch. Comparison between published experimental data for a regular tee and the present data for a reduced tee for the different inclination angles is also presented.

A unified model has been developed for the prediction of the splitting phenomenon for the horizontal, upward and downward orientations of the reduced branch arm. The model is based on the momentum balance equations applied for the separation streamlines of the gas phase and liquid phase. Comparison between the model predictions and experimental data shows good agreement with respect to the general trend and shape of the splitting curves and reasonable agreement with respect to the absolute values. © 1997 Elsevier Science Ltd.

Key Words: splitting, stratified flow, T-junction, inclined reduced branch

1. INTRODUCTION

Pipe tees are common features in pipeline networks, oil field flow lines and refinery streams to divide or combine flows. When two phases flowing in a pipe encounter a T-junction, phase redistribution takes place between the run and the branch arms. The liquid phase splits rarely in the same ratio as the gas phase. 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. As a result of this preferential liquid flow, there is a change of composition or even flow pattern in the branch and run arms. This unpredictable nature of splitting of the two phases between the branch and the run arms is complicated due to the large number of variables that influence it. Some of the factors that influence the splitting behavior are the 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.

Although branching conduits are a common feature in pipeline networks in various industries such as oil and gas, chemical processing and the nuclear industry, little attention has been paid towards analyzing this problem until the 1970s. In the past two decades, relevance of this problem to various industrial applications and better understanding of two-phase flow have resulted in a significant amount of experimental work and analytical studies in this area. However, most of the work done in the past was on regular T-junctions with a horizontal branch arm. Though the tees encountered in the industry are seldom regular and horizontal, very little work has been done on reduced tees with an inclined branch arm. A summary of the pertinent studies on T-junctions with an inclined branch arm follows.

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†Now with Schlumberger Dowell.

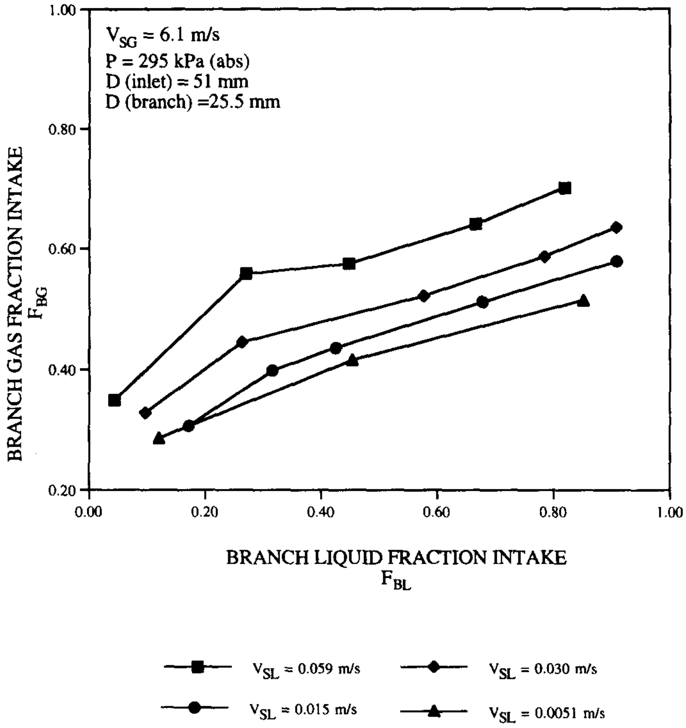

Figure 1. Experimental results for splitting ratios: reduced T-branch arm horizontal.

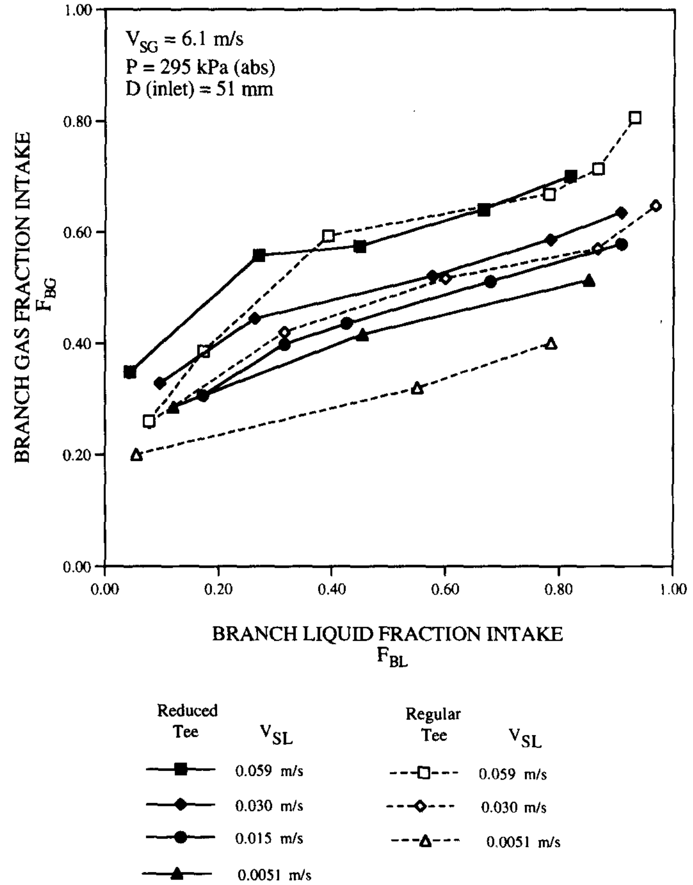

Figure 2. Comparison of reduced tee data and regular tee data for horizontal branch arm.

1.1. *Studies on regular tees*

Most of the previous researchers on T-junctions have concentrated on tees with a horizontal branch arm. A complete list of the studies conducted on regular tees with a horizontal branch arm is presented by Penmatcha (1993), Ashton (1993) and Penmatcha *et al.* (1996). Following is a summary of the studies conducted on regular tees with an inclined branch arm.

Seeger *et al.* (1985) performed phase separation experiments for a horizontal inlet tee and three side tarm orientations: horizontal, upward vertical and downward vertical. In a subsequent paper, Seeger *et al.* (1986) presented empirical correlations for the liquid flow splitting under the above three orientations of the branch arm. Reimann and Seeger (1986) reported the pressure distribution in the run and branch arm. Data were collected with air–water and steam–water flow in a T-junction with equal diameters and horizontal, upward vertical and downward vertical branch arms. A correlation was developed to predict the pressure drop at the branch and run arms. The authors concluded that the results of the model were unsatisfactory for vertical upward orientation of the branch arm. Ballyk and Shoukri (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 different sizes of the branch arm and three orientations were studied. The three orientations included horizontal, 45° downward and 90° downward.

Penmatcha (1993) conducted an investigation of two-phase flow splitting at a downward inclined T-junction. Experiments were conducted on air–water flow through a 50.1 mm regular T-junction under stratified–wavy flow pattern conditions at the inlet. A mechanistic model based on separation streamlines was developed. The model gives very good predictions for horizontal and downward inclined branch. Ashton (1993) conducted a similar study for upward inclinations of the branch

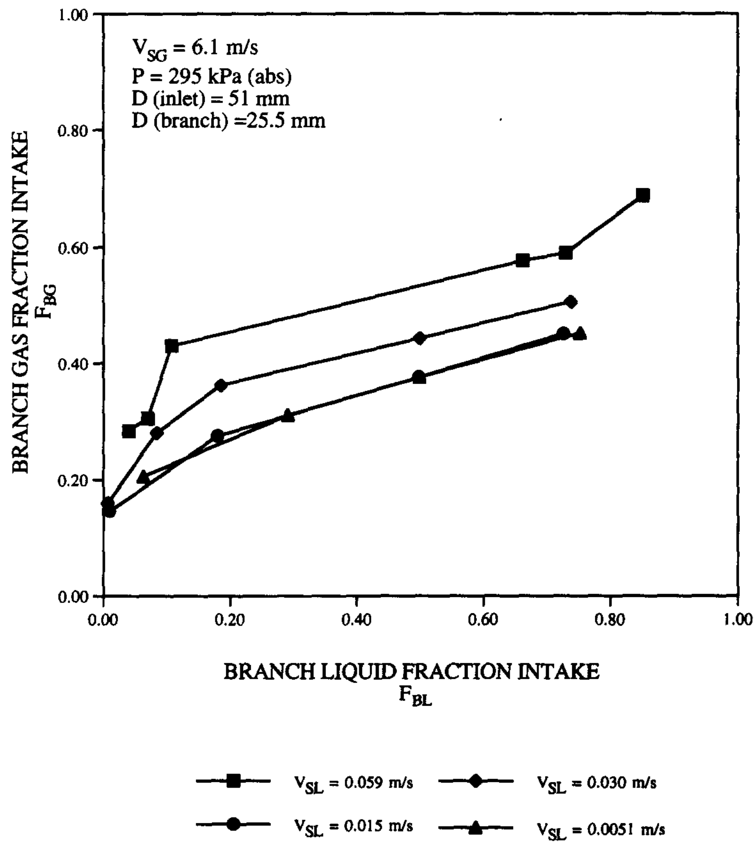

Figure 3. Experimental results for splitting ratios: branch arm −5° downward.

arm. His proposed model does not predict the threshold gas fractions well, however reasonable agreement was found between the data and the model.

1.2. *Studies on reduced tees*

Two-phase flow splitting at a reduced T-junction with a horizontal branch arm was studied by Shoham *et al.* (1989). Both stratified–wavy and annular flow patterns upstream of the T-junction, were studied. They conducted the experiments with air–water mixtures on a 50.8 mm sharp edged reduced tee with a branch to inlet diameter ratio of 0.5. A mechanistic model was developed which gave reasonable predictions when compared to their experimental data.

Azzopardi *et al.* (1990) studied two-phase flow at a horizontal T-junction with a reduced diameter branch arm under stratified–wavy and annular flow conditions. The data obtained were compared with the Shoham *et al.* (1989) model. The effect of side arm orientation and downstream geometry on stratified–wavy and annular flow has been studied by Azzopardi and Smith (1992). A horizontal main pipe with horizontal and vertically upward oriented side arms were 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.

Ganguly (1994) studied the pressure distribution in horizontal regular and reduced T-junctions. It was observed that the pressure drop is higher in the case of reduced tee compared to the regular tee case. Also, the pressure rise in the run arm due to Bernoulli's effect was observed in all the experiments.

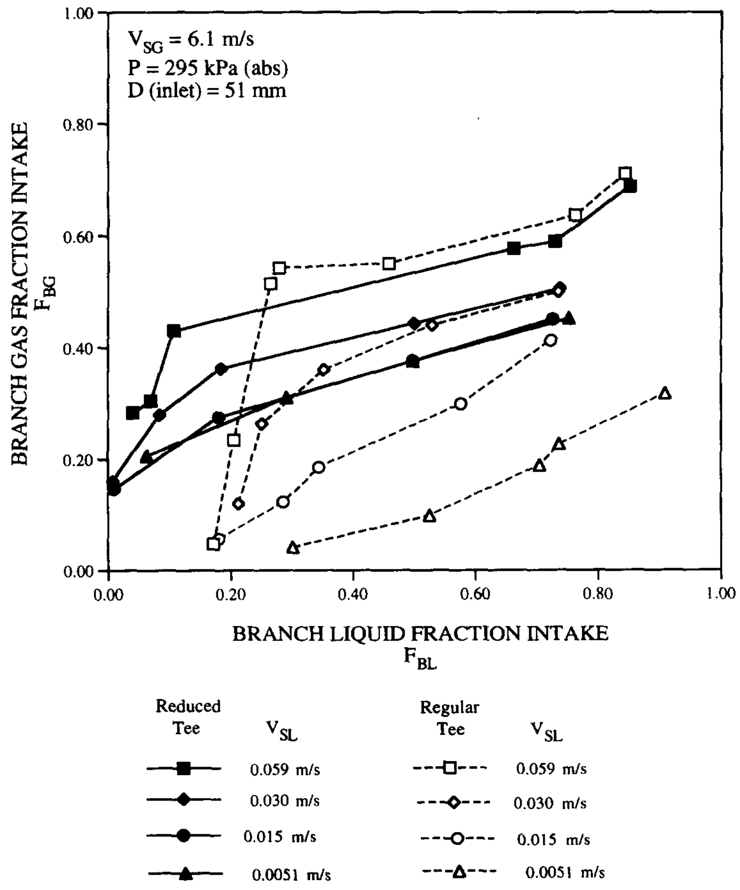

Figure 4. Comparison of reduced tee data and regular tee data for branch arm −5° downward.

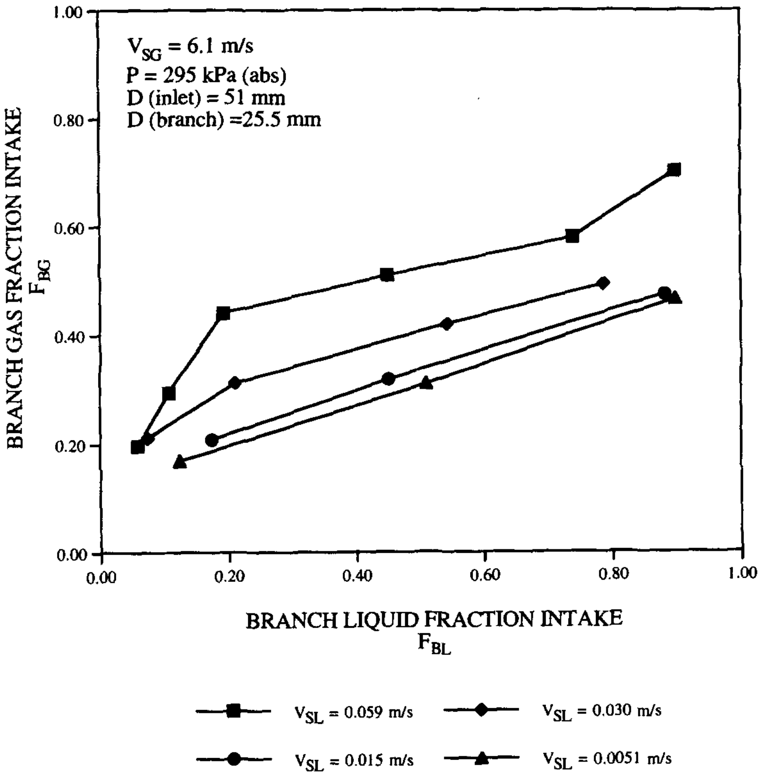

Figure 5. Experimental results for splitting ratios: branch arm −10° downward.

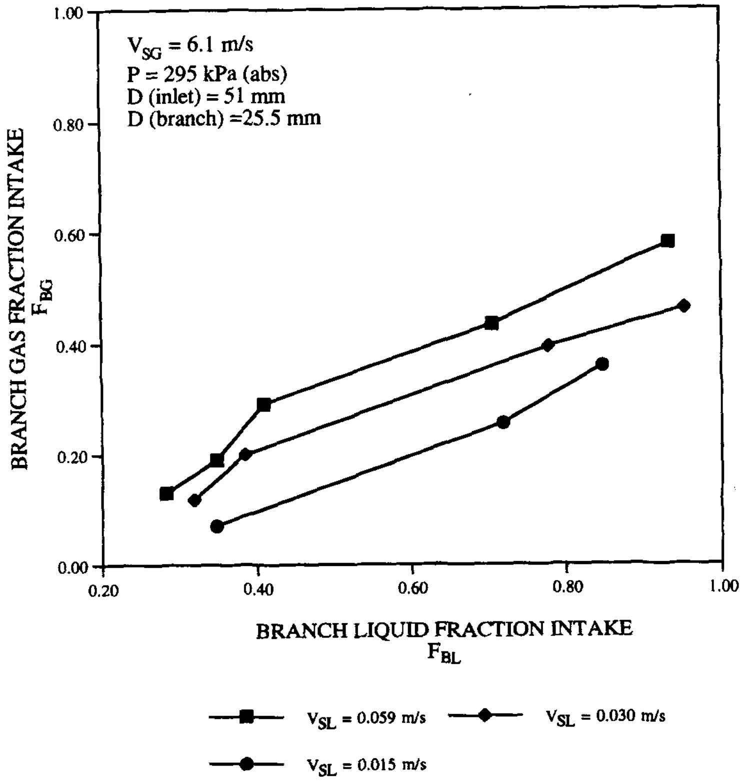

Figure 6. Experimental results for splitting ratios: branch arm −25° downward.

It is obvious from the literature review that there is a lack of both systematic experimental data and pertinent theories for two-phase splitting in non-horizontal reduced tees, for the entire range of branch arm inclinations. This provides the scope for the present study. It is the objective of this paper to study stratified–wavy two-phase flow splitting at reduced tees with a horizontal inlet but an inclined branch arm. The entire range of branch arm inclination angles are considered. A unified mechanistic model is developed to predict the gas and liquid splitting ratios for all orientations of the branch arm including horizontal, upward and downward.

2. EXPERIMENTAL PROGRAM

2.1. *Test facility*

Details of the experimental test facility are given by Penmatcha *et al.* (1996). The same facility is utilized in this study, except that a new reduced tee was installed instead of the regular tee used previously (Marti 1995).

The reduced tee is constructed of clear PVC R-4000 with the inlet and run arm diameters of 50.8 mm and a 25.4 mm branch arm. 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. At a distance of 76.2 mm from the center of the tee, the first of six pressure taps, 3.18 mm in diameter, was drilled in each arm. The next two pressure taps were drilled 76.2 mm apart with the remaining three separated by 177.8 mm. 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

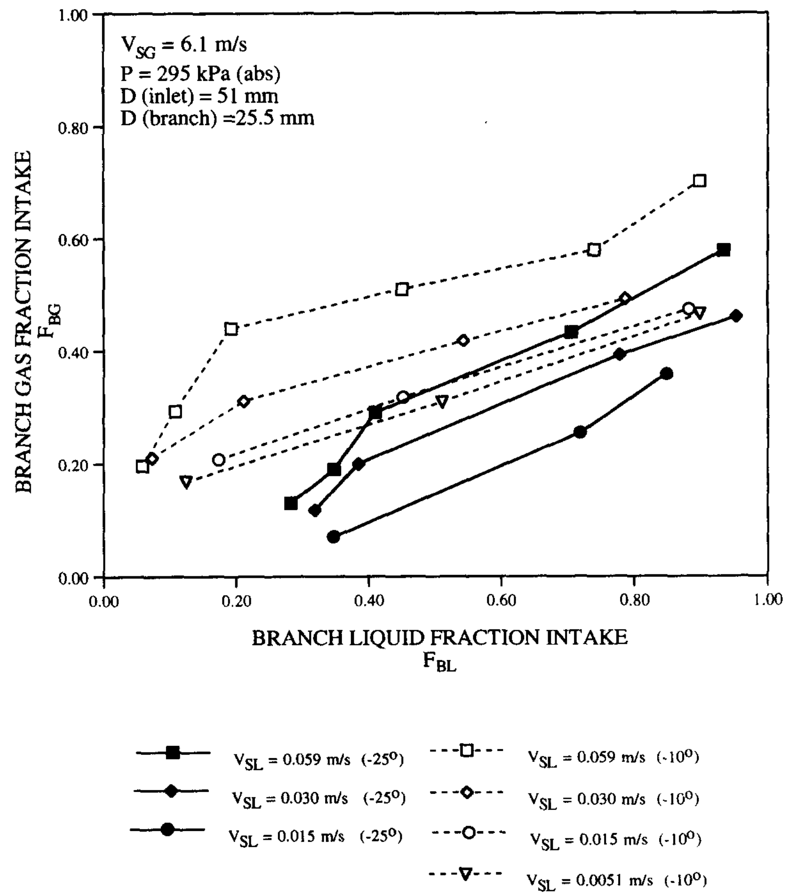

Figure 7. Comparison of experimental results for branch arm −10 and −25° downward.

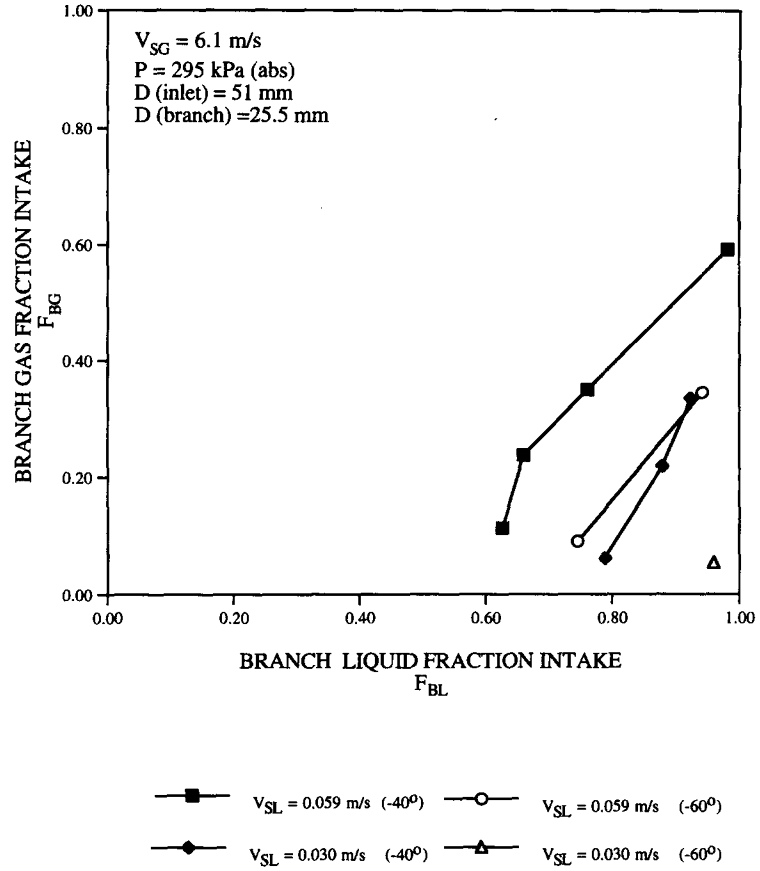

Figure 8. Experimental results for splitting ratios: branch arm −40 and −60° downward.

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 branch arm is attached.

2.2. *Experimental data*

All the experimental flow splitting runs were carried out under stratified–wavy flow conditions. A total 135 experimental runs were conducted. The pressure at the reduced T-junction was maintained at 295 kPa absolute for all the experimental runs. Data were acquired with the branch arm at horizontal, −5°, −10°, −25°, −40° and −60° downward inclinations and 1°, 5°, 10° and 20° upward inclinations. The average superficial velocity of the gas phase is fixed at $V_{SG} = 6.1$ m/s. 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 ratio of the branch to run gas flow rates, and measuring the resulting splitting ratio of the liquid phase between the branch and run arm. This procedure was repeated for each inclination angle. It was found that when the branch arm's downward inclination was increased to −60°, almost all the liquid was diverted into the branch arm. Also, when the branch arm is inclined upward beyond 20°, similar trend in the splitting ratios was observed for all higher inclination angles. As a result, the data were acquired for downward inclinations from horizontal to −60° and for upward inclinations to 20°.

The splitting mechanism can be understood by considering the dominant forces controlling the physical phenomenon. These forces can be enumerated as follows.

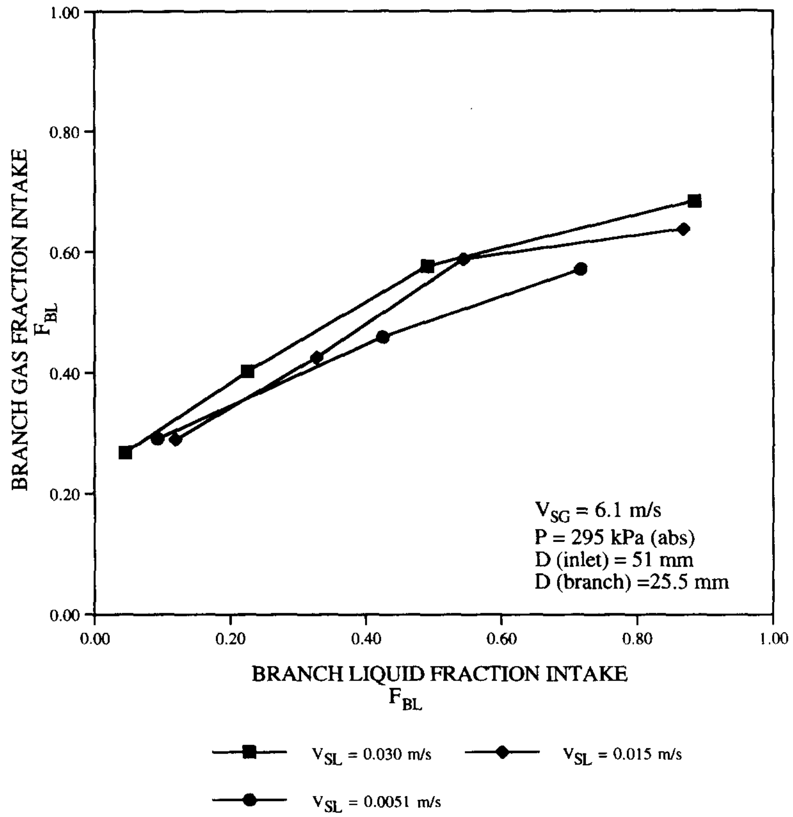

Figure 9. Experimental results for splitting ratios: branch arm 1° upward.

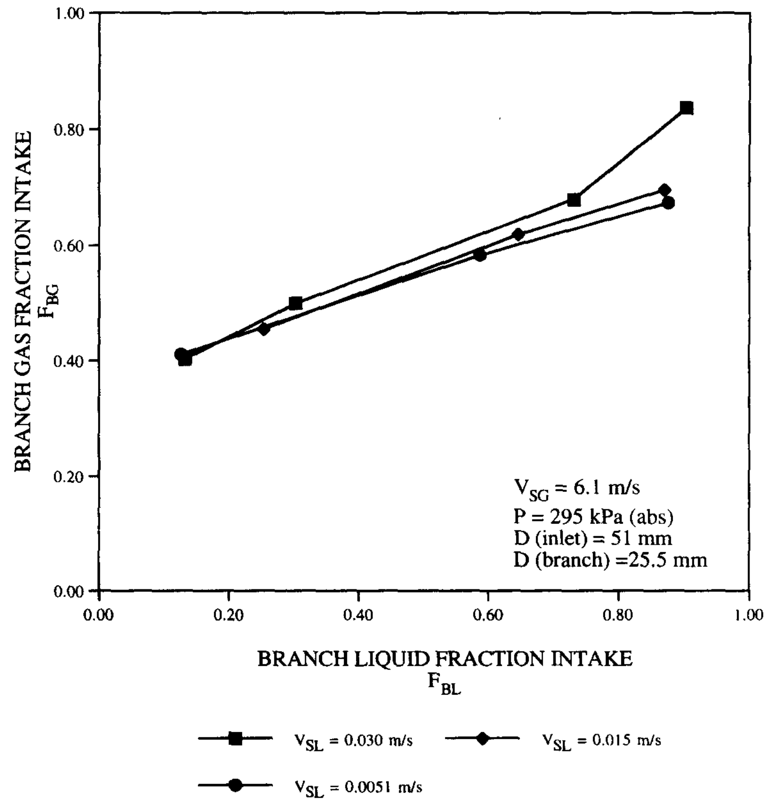

Figure 10. Experimental results for splitting ratio branch arm 5° upward.

2.2.1. *Gravity forces.* The gravity forces on the liquid phase tend to act in favor of the liquid flowing into the branch arm as the branch arm is inclined downward, and act against the liquid phase flowing into the branch arm for upward inclinations. This effect is observed in the case of regular tee as well as reduced tee. Another effect which has to be considered in the case of a reduced tee is the elevation difference between the liquid level in the inlet conduit and the branch arm opening. The liquid phase has to 'climb-up' to reach the branch arm opening in order to be diverted into the branch arm. This effect is important in the case of horizontal and upward inclinations of the branch arm.

2.2.2. *Inertial forces/travel time effect.* The axial momentum of the liquid phase tends to make the liquid flow in the axial direction, and bypass the branch arm opening. Although this effect is observed in both regular and reduced tee configurations, it is more pronounced in the case of reduced tee for the following reason: The travel time, or the time available to divert the liquid to flow into the branch arm instead of flowing straight into the run arm, is shorter for reduced tee as the branch arm opening is smaller. As a result more liquid bypasses the branch arm opening. The liquid that could not enter the branch hits the pipe wall downstream of the tee opening and continues to flow into the run arm.

2.2.3. *Pressure drop at the T-junction.* Pressure drop at the T-junction in the case of a reduced tee is higher than that of a regular tee. For the same gas fraction intake into the reduced branch arm, the gas velocity into the branch increases significantly, creating a higher pressure drop. For instance, if the branch arm diameter ratio is 2:1 for regular and reduced branch, respectively, the gas velocity in the branch arm for the reduced tee case increases fourfold for the same fraction

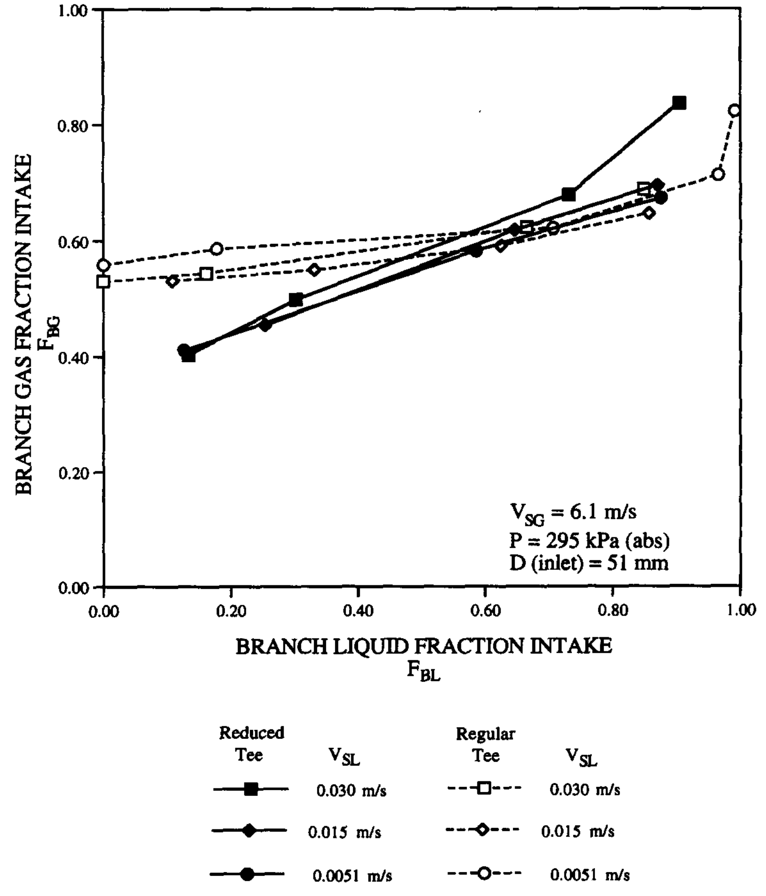

Figure 11. Comparison of reduced tee data and regular tee data for branch arm 5° upward.

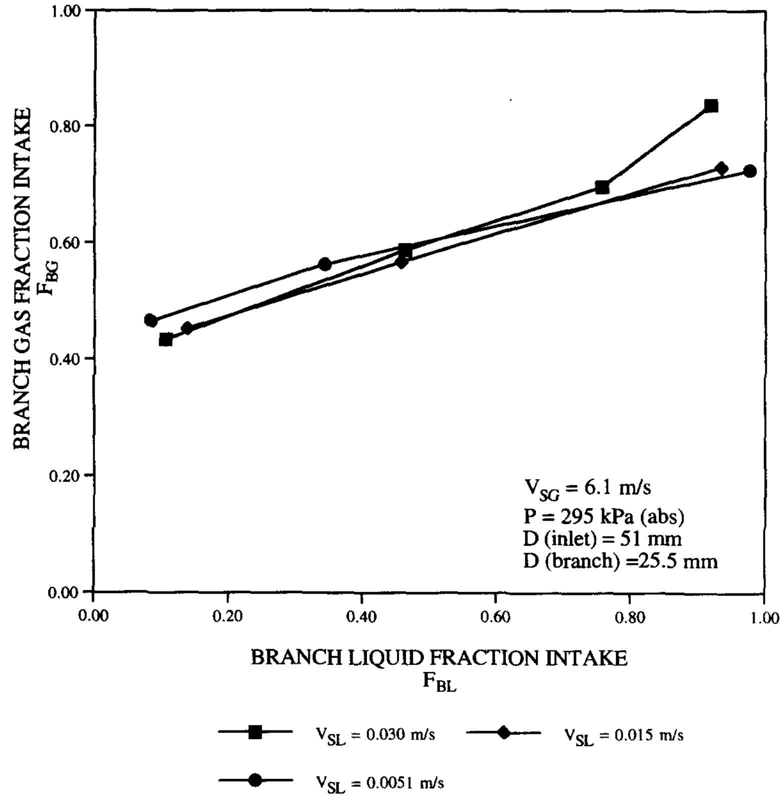

Figure 12. Experimental results for splitting ratios: branch arm 10° upward.

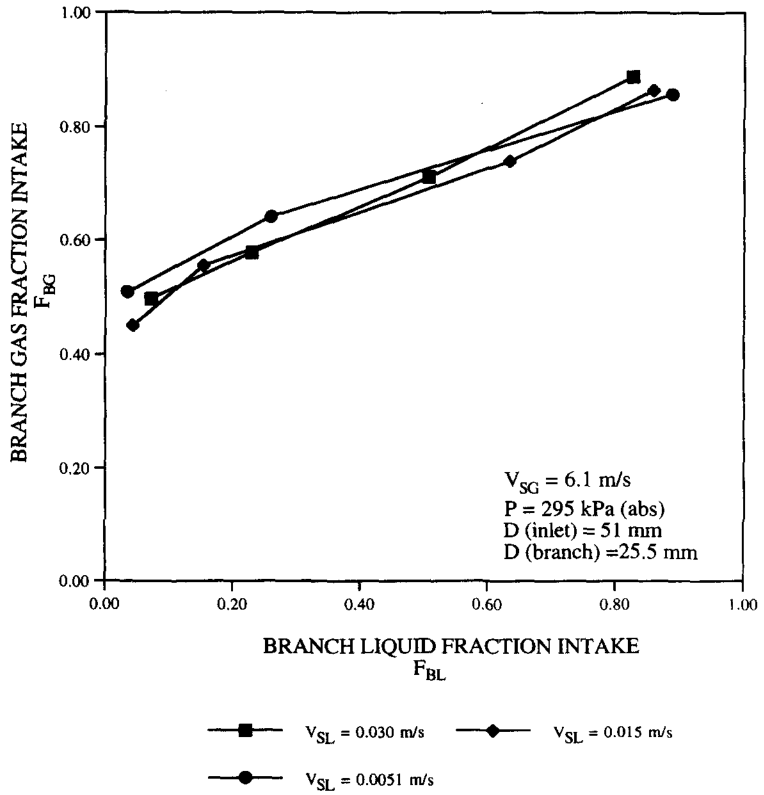

Figure 13. Experimental results for splitting ratios: branch arm 20° upward.

of gas diverted. This increase in pressure drop tends to act in favor of the liquid flowing into the branch. The high gas velocity and high pressure drop created cause more liquid to flow into the branch arm for the case of reduced tee.

As mentioned before, the flow pattern upstream of the T-junction is stratified–wavy flow. The flow pattern in both the run and branch arms are observed to be stratified–wavy flow for all the downward inclinations. For the upward inclination angles, at high branch gas fraction intakes, the flow pattern in the branch arm is annular flow, while at low gas fraction intakes the observed flow pattern is stratified–wavy. The run arm flow pattern is stratified–wavy flow for all cases. Note that for the case of a regular tee, for upward inclinations of the branch arm, periodic slug flow was observed for all flow conditions.

Analysis of the data for the various inclination angles of the branch arm and comparison to the regular tee case follows.

2.3. *Horizontal branch arm*

Figure 1 shows the experimental results obtained for the reduced tee with the branch arm in the horizontal position. The results for the reduced and regular tee configurations for horizontal branch arm are compared in figure 2. At low gas fraction intakes the elevation effect and the inertial forces dominate the splitting behavior, causing less liquid to flow into the reduced branch arm as compared to the regular tee. At higher gas fractions, because of very high gas velocities in the branch, the pressure drop in the branch arm increases so much that it tends to dominate the other

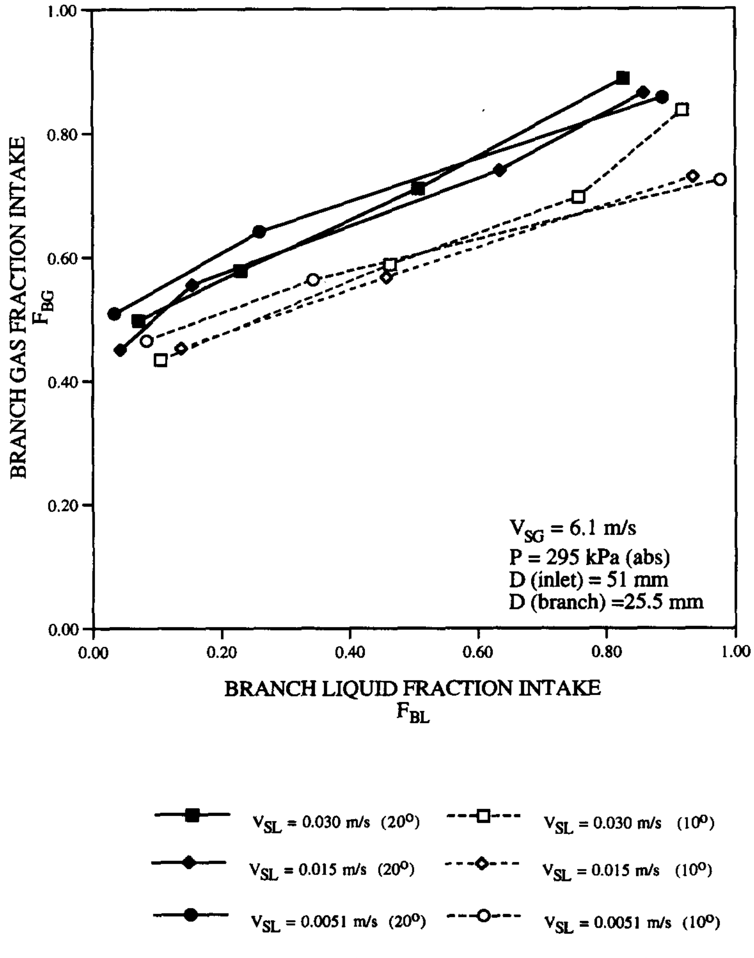

Figure 14. Comparison of experimental results for branch arm 10 and 20° upward.

two forces causing an equal amount of branch liquid fraction intake for reduced and regular tee cases for a particular gas fraction intake.

2.4. *Downward inclined branch arm*

As the branch arm is inclined downward, more liquid is diverted into the branch arm as compared with the horizontal branch arm case. Figures 3–8 show the experimental results for −5°, −10°, −25°, −40° and −60° downward inclinations of the branch arm. Figure 4 compares regular and reduced tee data for −5° downward case. Similar trend, as described above for the horizontal case, is observed between the regular and the reduced tee configurations. At low gas fraction intakes, the branch liquid fractions are less for the reduced tee as compared to the regular tee. At higher gas fractions the regular and reduced tee have almost equal branch liquid fraction intakes for a particular gas fraction intake. As explained before, for a reduced tee, at low gas fractions

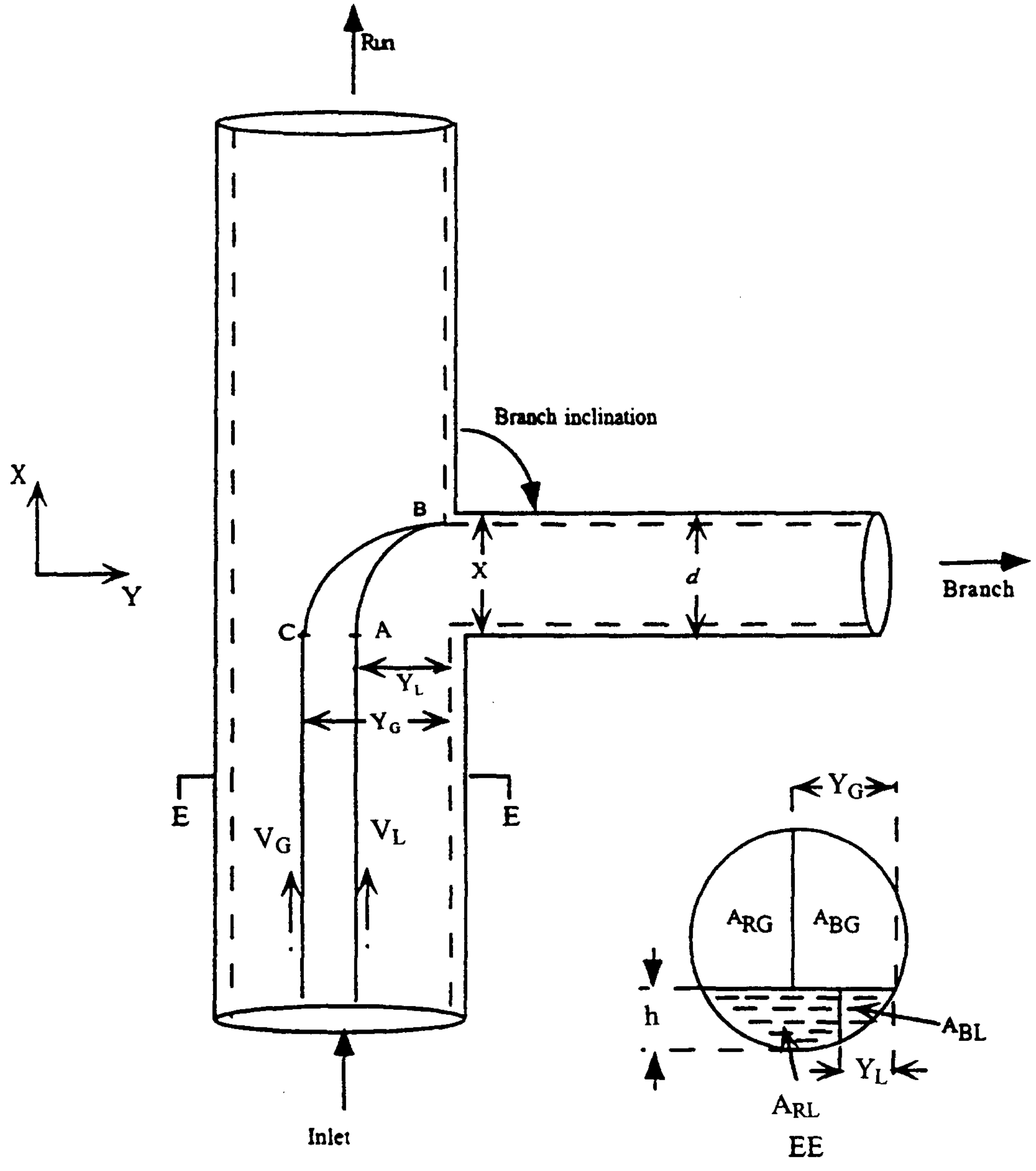

Figure 15. The physical model for gas–liquid flow splitting at a reduced tee.

the travel time effect and the inertial forces dominate, while at high gas fractions the pressure drop created by high gas velocities in the branch arm becomes important in diverting liquid into the branch arm.

Experimental data for −10° and −25° downward are compared in figure 7. More liquid is diverted for the −25° case, as compared to the −10° case. As the branch arm is inclined further downward, more and more liquid is diverted into the branch arm for the higher downward inclinations. At −60° almost all of the liquid is diverted into the branch arm resulting in an almost complete phase separation. Thus, no additional data for further inclination angles were taken.

2.5.1. Upward inclined branch arm

Experimental results for 1°, 5°, 10° and 20° upward inclinations are shown in figures 9–14. The results show similar trend throughout the change in inclination angles. As can be seen, a minimum amount of gas (threshold gas fraction) has to be diverted into the branch before any liquid can be diverted. As the inclination angle is increased the required threshold gas fraction also increases. Another important feature observed in all upward inclinations is that, the splitting ratios become independent of the liquid velocities.

Figure 11 compares the experimental results for 5° upward inclination for the regular and reduced tees. The comparison shows that at low gas fractions, more liquid is diverted into the branch in the reduced tee case, as compared to regular tee. At high gas fractions both configurations

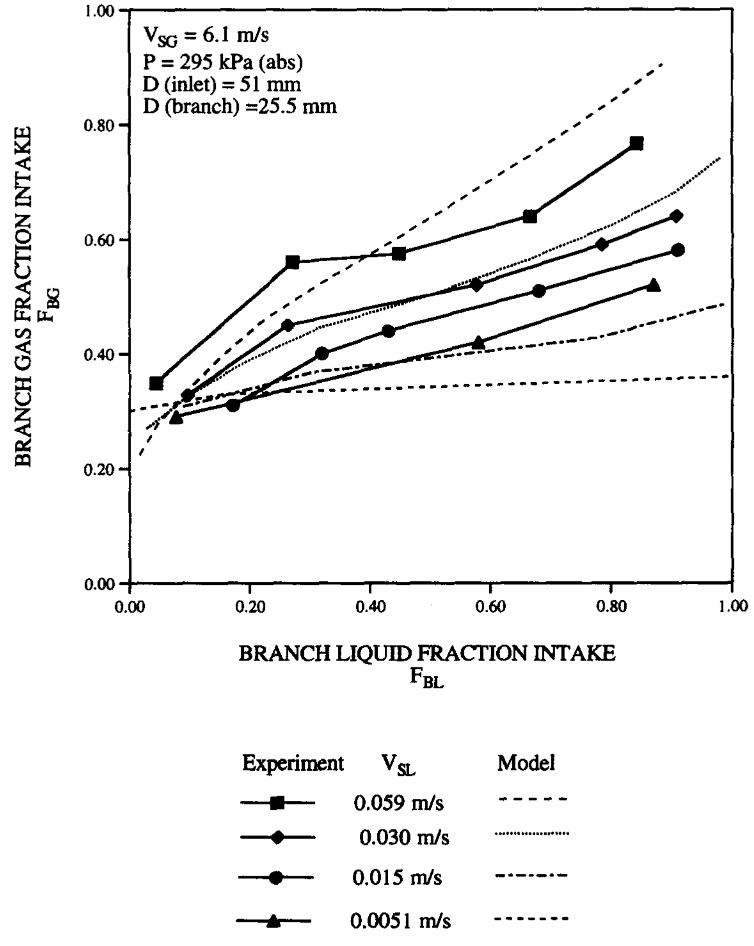

Figure 16. Comparison between the model and experimental data: branch arm horizontal.

receive almost equal amount of liquid in the branch for a particular gas fraction. This can be explained as follows: in the case of reduced tee, due to higher gas velocities, the pressure drop at the tee is higher than that of the regular tee. The pressure drop dominates the gravity and inertial forces in reduced tees more than for the case of regular tees. Thus, more liquid flows into branch, at low gas fractions. At higher branch gas fractions, the combination of the gravity, pressure drop and inertial forces seem to be equal for regular and reduced tee causing almost equal amount of liquid to be diverted into the branch, for both cases, for a particular superficial liquid velocity.

Experimental data for 10° and 20° are compared in figure 14. It can be seen that less liquid goes into the branch at higher inclinations for the same gas fraction intake. If the branch arm inclination is increased further, it is expected that similar trend would continue. For these conditions the reduced tee acts as a separator.

3. MODELING

The present model for the reduced tee configuration is an extension of the model developed by Penmatcha *et al.* (1996) for a regular tee for downward inclinations of the branch arm. Figure 15 shows the flow system at dynamic equilibrium, in which the gas and liquid phases split unevenly at a T-junction. It is assumed that the fluid particles in both the phases travel along streamlines. As shown in figure 15, 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,

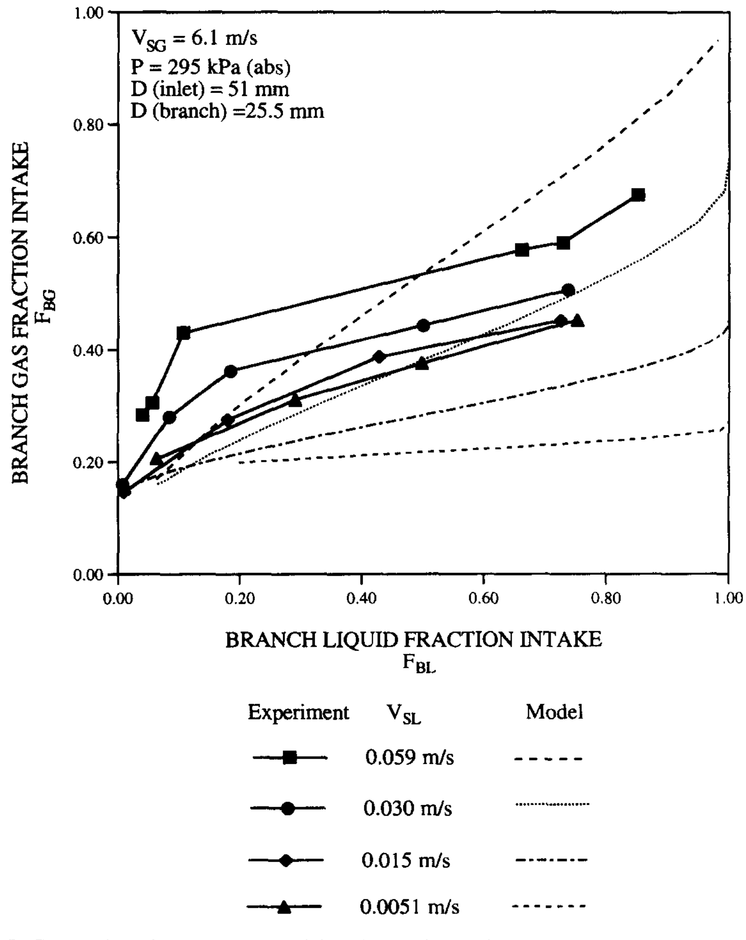

Figure 17. Comparison between the model and experimental data: branch arm −5° downward.

cannot reach it and hence hit the pipe wall at the rear end of the branch opening and, thus, will flow straight into the run arm.

A 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 streamline approach was used by previous investigators such as McCreery (1984), Shoham *et al.* (1987), Hwang *et al.* (1988) and Penmatcha *et al.* (1996). AB is the dividing streamline for the liquid phase, while CB is the dividing streamline for the gas phase, as shown in figure 15. 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 is diverted into the branch, and that on the left side goes straight into the run arm. Note that the separation streamlines are not the same for the gas and the liquid phases.

The objective of the model is to develop a method to predict the fraction of liquid diverted into the branch, F_{BL}, for a given gas fraction intake into the branch, F_{BG}. This is carried out for a given branch to inlet diameter ratio and a given inclination angle of the branch arm, θ. As the branch gas fraction intake is known, the pressure gradient created at the branch arm to accomplish this can be calculated. The same pressure gradient acts also on the liquid phase.

The gravity force acting on the liquid, which can be calculated from the inclination of the branch arm, is divided into two terms. The first part accounts for the inclination of the branch arm (which is called the gravity term hereafter). The second part accounts for the elevation difference between the bottom of the inlet pipe and the bottom of the branch arm opening, which the liquid has to 'climb-up' (which is called the elevation term hereafter) before it

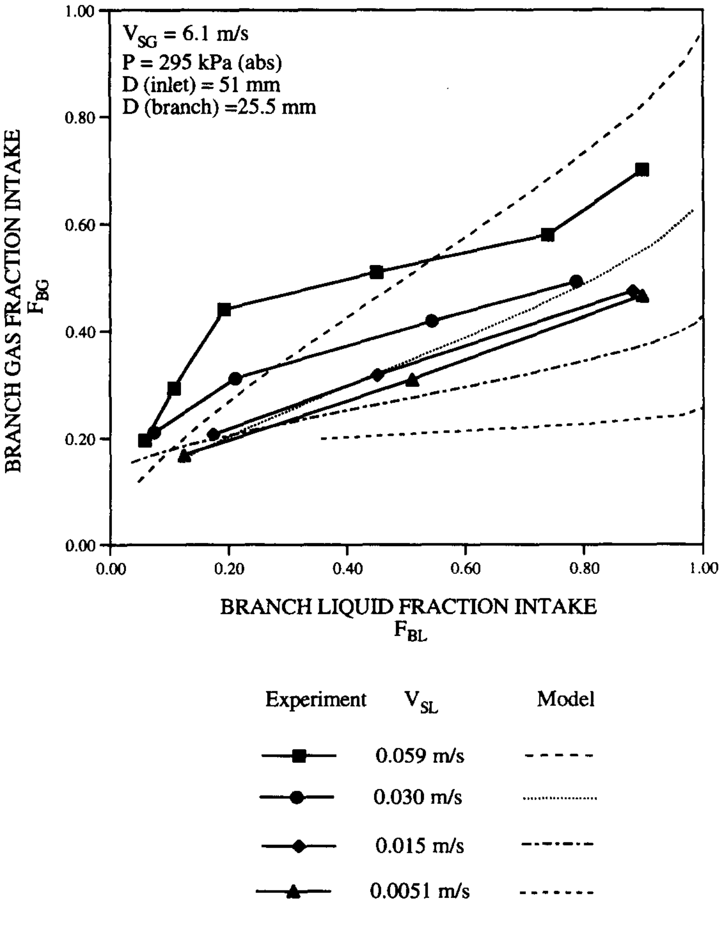

Figure 18. Comparison between the model and experimental data: branch arm −10° downward.

can be diverted into the branch. Both the gravity and elevation terms for the gas phase can be neglected. However, for the liquid phase these terms cannot be neglected. The horizontal branch arm is a special case in which the gravity term will become zero, but the elevation term remains. For upward inclinations of the branch arm, both the gravity and the elevation terms have to be accounted. For all downward inclinations of the branch arm the effect of the elevation term is neglected as it is not the dominant factor affecting the liquid split. 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 the gas fraction intake, 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. The required geometrical equations are given in appendix A. 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,

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

where P is the pressure, Y is the radial distance, ρ is the density, g is the acceleration due to gravity, V is the velocity, t is the time and z is the elevation difference between the bottom of the inlet pipe

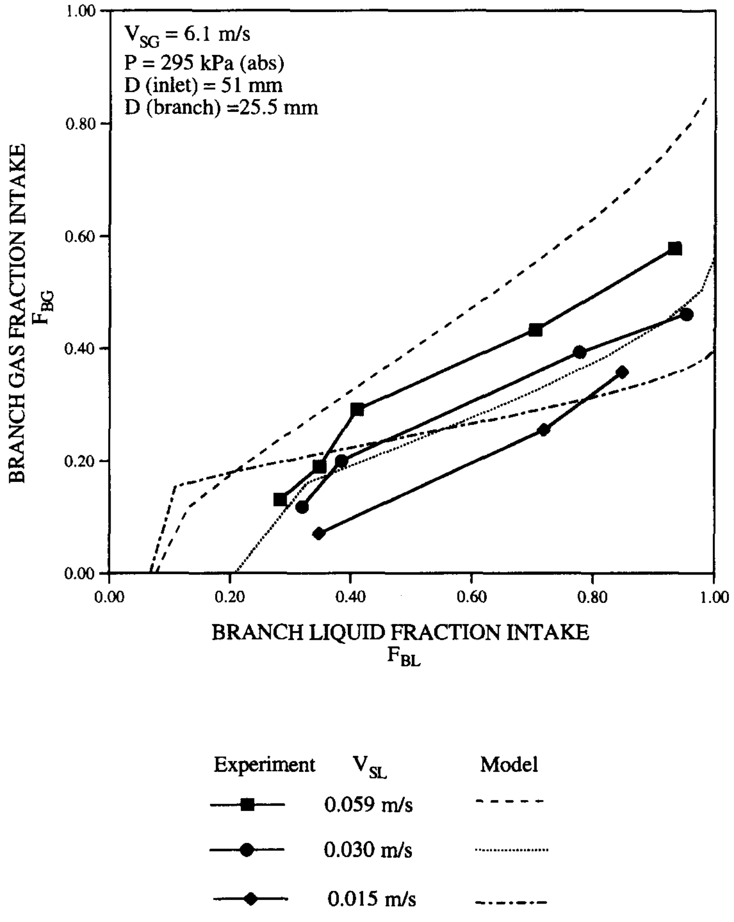

Figure 19. Comparison between the model and experimental data: branch arm −25° downward.

and the bottom of the branch arm opening. The subscript G denotes the gas phase. The inclination angle of the branch arm, θ, is positive upward and negative downward. Since the gravity term and elevation 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.

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

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

where ΔP_{G} is the pressure drop between the points C and B in the Y direction. The axial distance traveled by the gas fluid element from C to B is X_{G} and t_{G} is the time taken to accomplish this. We can also write

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

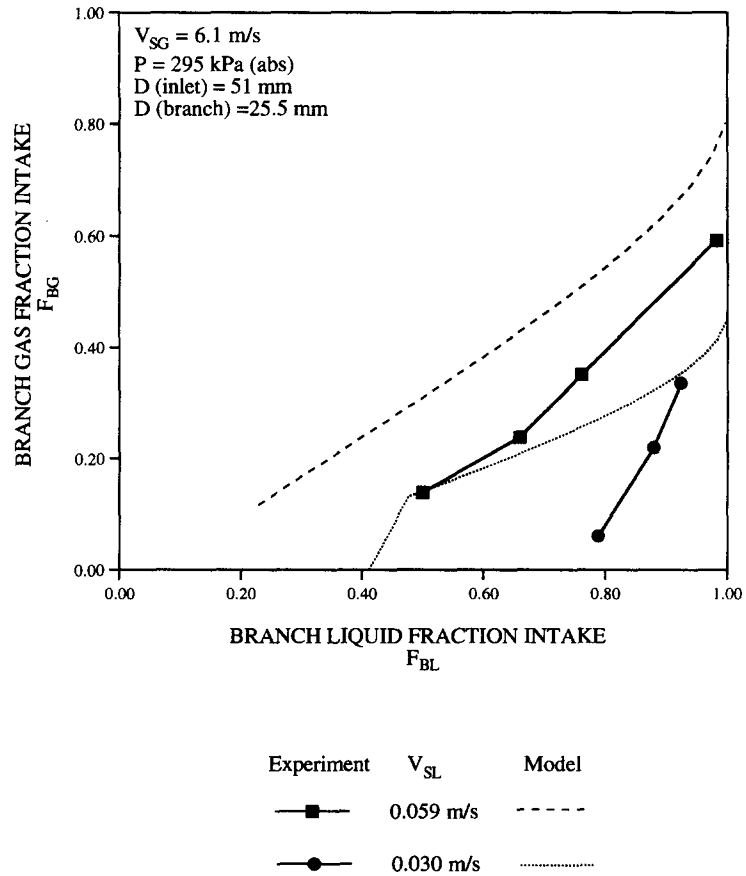

Figure 20. Comparison between the model and experimental data: branch arm −40° downward.

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

$$Y_G = \frac{a_{RG} t_G^2}{2} = \frac{V_{GB}}{2} \frac{X_G}{V_G}. \qquad [5]$$

Rearranging [5], yields

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

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

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

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,

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

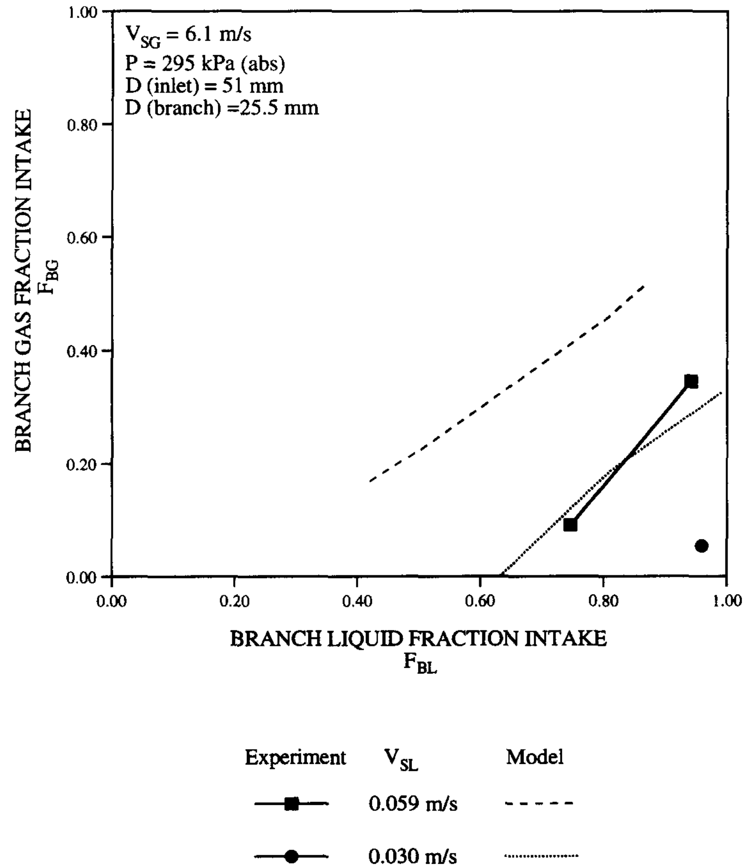

Figure 21. Comparison between the model and experimental data: branch arm −60° downward.

The subscript L in the above equation denotes the liquid phase. 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 $\partial P/\partial Y$ is constant, and since $V_{LA} = 0$, integrating [8] from A to B gives

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

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

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

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

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

and

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

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

$$\left(\frac{2\rho_L V_L^2}{X_L^2}\right) Y_L^2 + \left(\frac{\Delta P_G}{Y_G} + \rho_L g \sin\theta\right) Y_L + \rho_L g z = 0. \qquad [13]$$

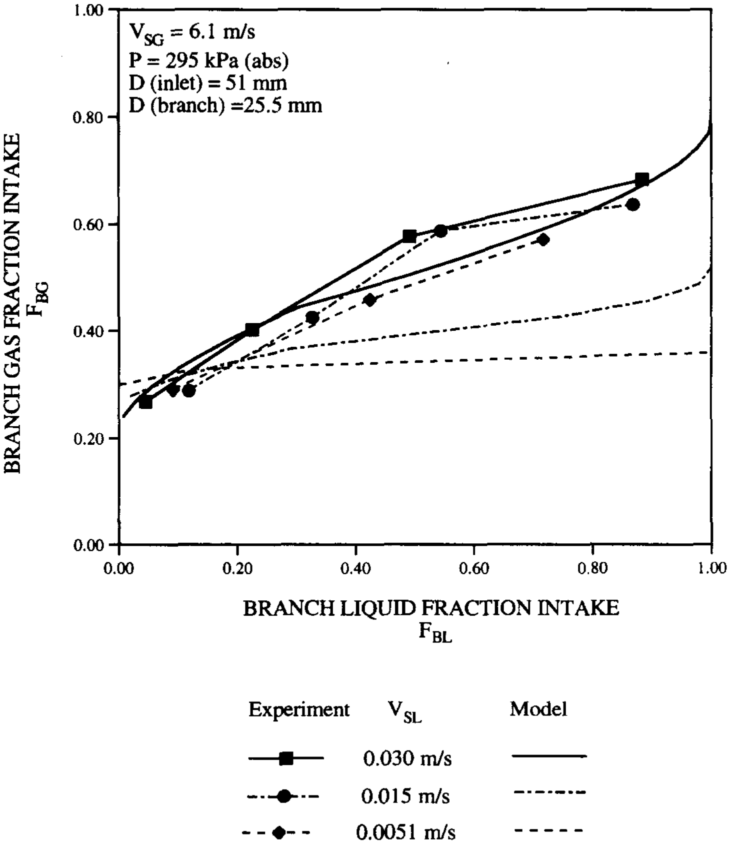

Figure 22. Comparison between the model and experimental data: branch arm 1° upward.

ΔP_G in [13] can be substituted from [7]. The axial distance traveled by the fluid phases is taken as follows: For downward inclinations of branch arm, at high liquid velocities, $X_G = X_L = d$, and at low liquid velocities $X_G = X_L = \frac{d}{2}$. For horizontal and upward inclinations, for all liquid velocities, $X_G = X_L = \frac{d}{2}$, where d is the diameter of the branch arm.

Another value that needs to be calculated is the elevation difference between the bottom of inlet pipe and the branch arm opening, z. This value changes according to the inclination of branch arm. From geometrical calculations, [14] can be arrived at for the value of z. As can be seen, it is a function of inlet diameter, branch diameter and inclination of the branch arm

$$z = \frac{D}{2} + \frac{D}{2}\sin\theta - \frac{d}{2}\cos\theta. \qquad [14]$$

Using the above values for X_G and X_L, and [14] for z, Y_L can be evaluated from [13]. Once Y_L is determined the fraction of liquid diverted into the branch, F_{BL}, can be calculated using the geometrical relationships given in appendix A.

4. RESULTS AND DISCUSSION

The results obtained from the proposed model are compared with the experimental data in figures 16–25. 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

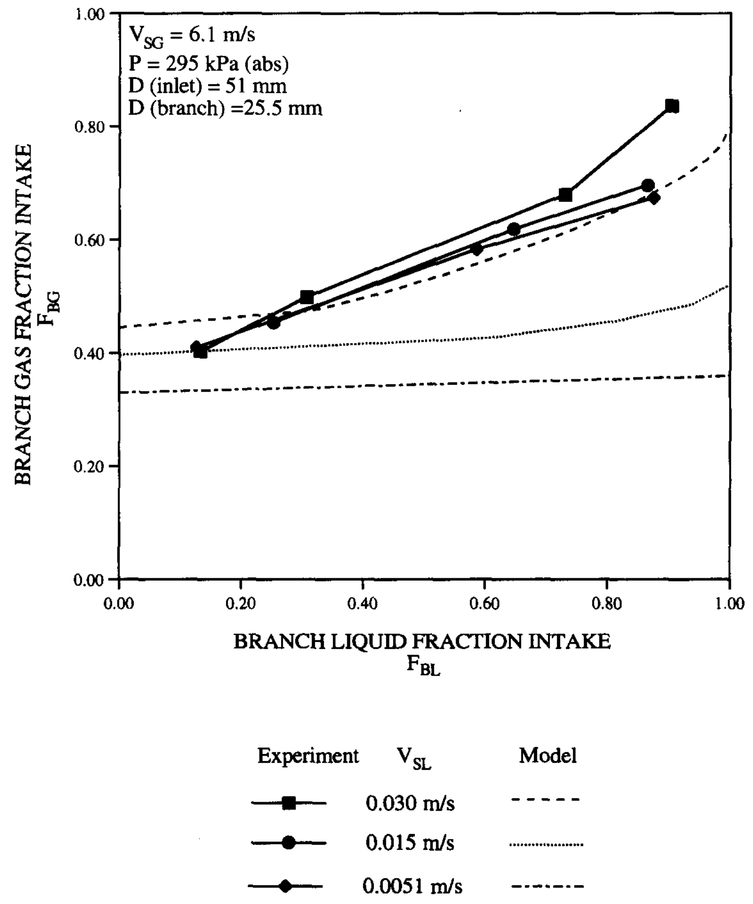

Figure 23. Comparison between the model and experimental data: branch arm 5° upward.

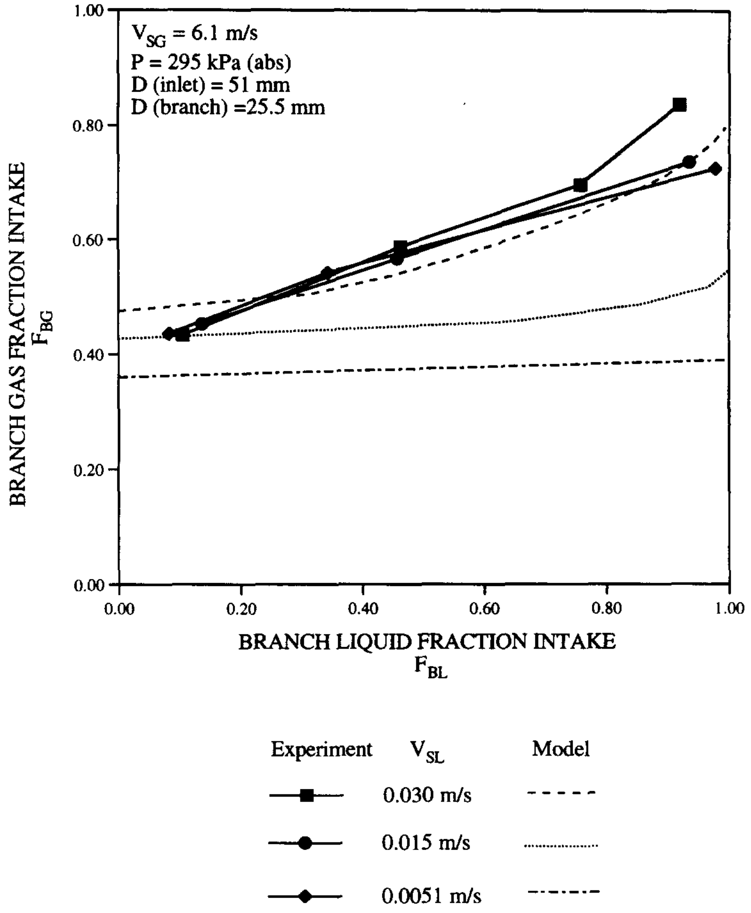

Figure 24. Comparison between the model and experimental data: branch arm 10° upward.

very close to the experimental data, both for the horizontal branch arm and for all the downward inclinations of the branch arm. The model predictions are good for all upward inclinations of the branch arm. Model predictions observed for both upward and downward inclinations show better agreement with the experimental data for high superficial liquid velocities (greater than 0.030 m/s).

5. SUMMARY AND CONCLUSIONS

A theoretical and experimental investigation of stratified–wavy flow splitting at a reduced T-junction with an inclined branch arm has been conducted. Experimental data were acquired for horizontal, upward and downward inclinations of the reduced branch arm. The data shows a strong dependence of the splitting phenomenon on the orientation of the branch arm. A unified mechanistic model for stratified–wavy two-phase flow splitting at a reduced junction was developed to predict the unequal splitting of the two phases at the T-junction. The model is applicable for horizontal and all downward and upward inclinations of the branch arm. The model shows good agreement with the experimental data with respect to the general trend and shape of the splitting curves where as with respect to the absolute values the agreement was fair. Branch threshold gas fraction predictions of the model agree very well with the experimental results for all upward inclinations. The model should be applicable for moderate ratios of branch to inlet diameter.

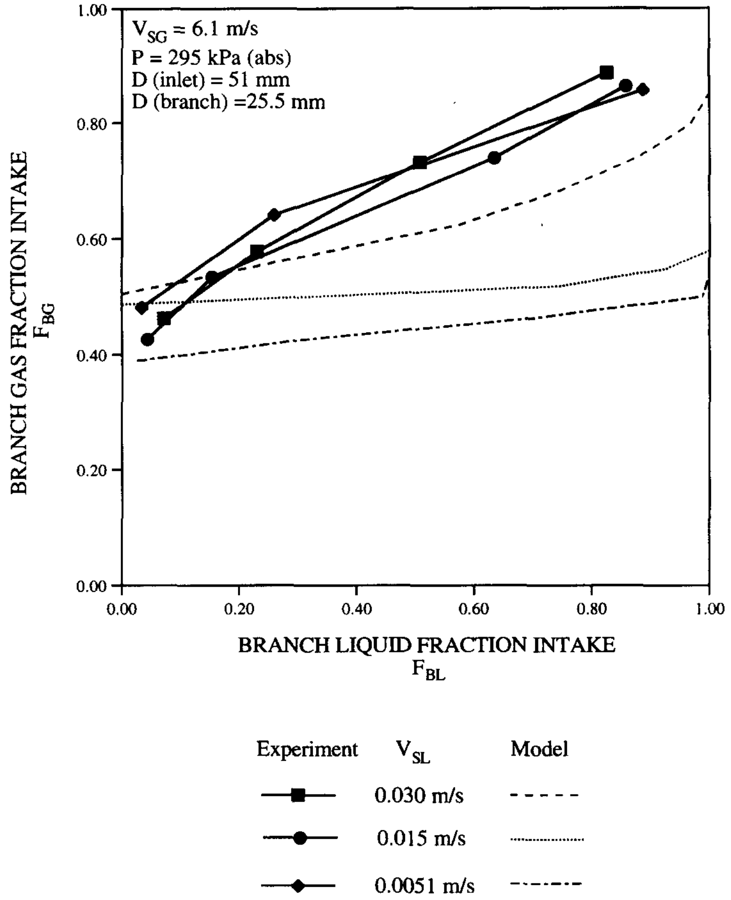

Figure 25. Comparison between the model and experimental data: branch arm 20° upward.

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APPENDIX A

The calculation of F_{BG} or F_{BL}, when Y is given, is outlined here. The geometrical relationships are shown in figure A1. From the holdup measured, the liquid level h in a circular pipe can be calculated.

Therefore,

$$S_I = D\sqrt{1-\left(2\frac{h}{D}-1\right)^2},$$

$$b = \frac{1}{2}(D - S_I),$$

$$a = Y + b,$$

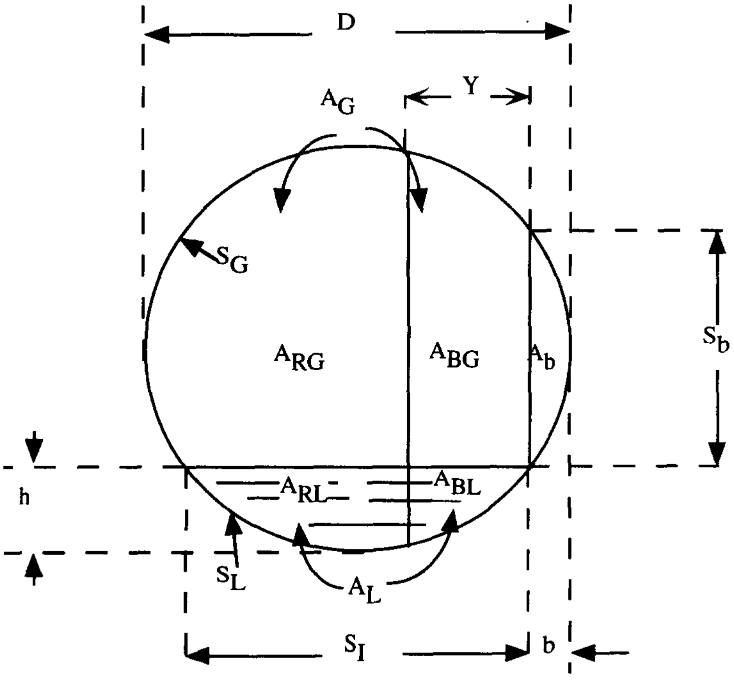

Figure A1. Geometrical relationships.

$$A_L = A_{RL} + A_{BL} = \frac{1}{4}D^2\left[\pi - \cos^{-1}\left(2\frac{h}{D} - 1\right) + \left(2\frac{h}{D} - 1\right)\sqrt{1 - \left(2\frac{h}{D} - 1\right)^2}\right],$$

$$A_B = A_{BG} + A_{BL} = \frac{1}{4}D^2\left[\pi - \cos^{-1}\left(2\frac{a}{D} - 1\right) + \left(2\frac{a}{D} - 1\right)\sqrt{1 - \left(2\frac{a}{D} - 1\right)^2}\right],$$

$$A_b = \frac{1}{4}D^2\left[\pi - \cos^{-1}\left(2\frac{b}{D} - 1\right) + \left(2\frac{b}{D} - 1\right)\sqrt{1 - \left(2\frac{b}{D} - 1\right)^2}\right],$$

$$S_b = D\sqrt{1 - \left(2\frac{b}{D} - 1\right)^2}.$$

So,

$$A_{BL} = \frac{1}{2}[A_B - (a - b)S_b - A_b],$$

$$A_{BG} = A_B - A_{BL},$$

$$F_{BG} = \frac{A_{BG}}{A_G},$$

$$F_{BL} = \frac{A_{BL}}{A_L}.$$

In the physical model, if $Y = Y_G$, then F_{BG} is calculated using the above method, or if $Y = Y_L$, then F_{BL} is calculated using the above method.