DIVIDING STEAM-WATER ANNULAR FLOW IN T-JUNCTIONS WITH HORIZONTAL INLET AND DOWNWARDLY INCLINED BRANCH

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ABSTRACT

Experimental data on dividing steam-water two-phase annular flow in T-junctions having downwardly inclined branches was obtained. The experiments were performed under high inlet mass flux conditions which were not examined before. The data covered the inlet mass flux and inlet quality ranges: $600 < G_1 < 900$ kg/m^2.s and $0.02 < X_1 < 0.08$. The branch orientation was found to be a significant parameter affecting phase separation under the present test conditions. This is caused by the non-uniform angular distributions of the liquid film thickness associated with the horizontal inlet annular flow. The pressure changes of two-phase flow in the junction were closely correlated with the phase separation phenomenon. The effect of branch orientation on junction pressure changes was only important in the range of flow split ratio before total phase separation took place. The data on pressure rise in the run and pressure drop in the junction were correlated using simple models based on momentum and mechanical energy balance.

INTRODUCTION

The ability to predict the phase separation and pressure changes when two-phase flow is divided in a T-junction is of considerable importance in many applications in the power and process industries. However, our understanding and the data base on the subject remain rather incomplete.

Reported experimental and analytical studies have shown that phase separation and pressure distribution in T-junctions are complex functions of inlet flow regime, inlet quality, branch flow split ratio, conduit geometry etc.. Important experimental investigations on the subject are due to Collier (1976), Hong (1978), Henry (1981), Azzopardi and Whalley (1982), Saba and Lahey (1984), Seeger, Reimann and Muller (1986), Ballyk, Shoukri and Chan (1988), Rubel, Soliman and Sims (1988), McCreery and Banerjee (1990), Davis and Fungtamasan (1990). Comprehensive reviews of the topic are available by Azzopardi (1986), Lahey (1986) and recently by

Muller and Reimann (1991). Most of the existing experimental data on the subject were obtained from low pressure air-water flow divided in a horizontal branch. The effect of the branch orientation on phase separation was studied by only a few researchers in limited flow regimes. In referring to the experimental results, the subscripts 1, 2 and 3 will be used to describe the flow in the inlet, run and branch of the junction respectively.

The work presented herein is an extension of that reported by Ballyk et al (1986). The objective of this paper is to present recent data obtained on two-phase annular flow in T-junctions having horizontal inlet and downwardly inclined branches. The experiments were performed under operating conditions which were not examined before. Accordingly, it can enhances the current understanding of the phenomenon and contribute the existing data base on the subject. The inlet mass flux and inlet quality in the present investigation cover the ranges $600 < G_1 < 900$ kg/m .s and $0.02 < X_1 < 0.08$. The branch split ratio varies in the range $0.1 < G_3/G_1 < 1.0$ and branch downward angle was varied from $0^0 < \theta < 90^0$.

EXPERIMENTAL CONSIDERATIONS

The present investigation was performed on the steam-water two-phase flow loop of McMaster University illustrated schematically in figure 1. Preheated water and steam, from building supply, were mixed in the two-phase mixer. The mixture reached thermodynamic equilibrium through approximately 3 m of piping before entering the test section. The test sections used were T-junctions wherein the flow was split and passed from each downstream leg to condensers. The condensates were then metered and delivered back to an open storage tank. The entire loop is insulated to minimize heat losses with the exception of a 10 cm transparent section at the test section inlet for flow regime visualization. Three tests sections were used in the experiments each consisting of a horizontal tube with one branch tube at 90^0. The main tube for all test sections was made from 25.65 mm I.D. stainless steel tubing. The tests were carried out in horizontal inlet and downwardly inclined branches with 45^0 and 90^0 angles.

The thermodynamic equilibrium quality in the three legs of the T were evaluated from energy balances (at the two-phase mixer and condensers). The validity of the calculations were confirmed by checking mass and energy balances throughout the loop.

Within the test sections, the pressure distribution was measured by way of pressure taps in all three legs of the T. Five pressure taps were located in each of inlet and branch sections over approximately 600 mm. Due to slower flow development, the run contained up to fifteen pressure taps over approximately 2.4 m to ensure that a fully developed pressure profile was obtained. The void fraction in each leg at a location corresponding to fully developed pressure profile was measured.

PHASE REDISTRIBUTION RESULTS

In annular flow, substantial part of liquid is flowing as a thin liquid film along the tube wall. It is, therefore, expected that the liquid film in the main tube segment that is intercepted by the branch cross sectional area will be the first component to be extracted into the branch. At low branch flow, most of the branching flow is removed from the liquid film. Accordingly, under such condition, the branch quality is expected to be below that of the inlet flow. Increasing the branch flow, which corresponding to decreasing the branch downstream pressure, causes more vapour to be extracted through the branch raising the branch quality. It should be noted that increasing the branch flow is associated with a pressure rise through the junction run due to flow expansion. This adverse pressure rise yields an additional force which tends to drive the flow through the branch. Since the vapour phase in the inlet tube has lower axial momentum than the liquid phase, it tends to respond more readily to the decreasing pressure through the branch and the increasing pressure through the run. Accordingly, increasing the branch flow tends to result in increase in the branch flow quality. At a certain branch flow split ratio almost all of the inlet vapour will be extracted through the branch. This critical branch flow split ratio depends upon fluid dynamic parameters, e.g. inlet quality and mass flux, and the conduit geometrical parameters, e.g. the orientation of the branch, the diameter ratio of the branch to inlet etc.. When completed phase separation happens the T-junction functions like a phase separator.

Effect of branch orientation

Under horizontal annular inlet flow condition, the orientation of the branch has a significant influence on the redistribution of the two phases in the T-junction due to the non-uniform distribution of the liquid film caused by gravity effect. Unlike vertical annular inlet flow condition in which the effect of gravity on the angular distribution of liquid film can be neglected, in horizontal annular flow the liquid film is expected to drain toward the bottom of the pipe under the influence of gravitational forces resulting in a thicker film at the bottom. However, the liquid film is symmetrically distributed about a vertical plane passing through the axis of the tube.

Typical results showing the effect of branch orientation on phase redistribution is shown in figures 2a to 2d. The branch quality and mass flux are normalized with respect to inlet conditions, i.e. X_3/X_1 vs G_3/G_1. Equal phase distribution is represented by the horizontal line $X_3/X_1 = 1$, while complete vapour extraction is represented by the curve $X_3/X_1 = G_1/G_3$. The results for three branch orientation i.e. horizontal, 45^0 downward and 90^0 downward under various inlet flow condition are presented. In the range of the present experimental study, the results show significant effect of branch orientation on phase separation. It is clear that the horizontal branch causes the most severe phase separation condition. For the same inlet condition, the results show that rotating the branch downward from the horizontal orientation results in lower branch quality through the entire range of flow split ratio. The maximum normalized branch quality is also reduced. Moreover, the flow split ratio at which equal phase distribution and complete vapour extraction occur is moved to higher value with increasing the downward rotation of the branch.

The observed trends are caused by the asymmetrical distribution of the liquid film in the annular inlet flow having very thin film at the top with increasing thickness toward the bottom. By downward rotation of the branch, more liquid becomes readily available for extraction resulting in higher liquid content in the branch flow at any given flow split ratio.

Effect of inlet flux and quality

The results showed clearly that, independent of branch orientation, the inlet mass flux has very little effect on the phase separation phenomenon. This can be shown by comparing the data in figures 2c and 2d obtained for the same inlet quality, $X_1 = 2\%$, and for mass flux of 600 and 900 $kg/m^2.s$ respectively. This trend is consistent with earlier data published on the literature.

It is also interesting to note that the effect of inlet quality on phase redistribution is dependent on branch orientation. This effect can be inferred from the results shown in figures 2a, 2b and 2c which were obtained at a constant mass flux, $G_1 =$ 600 $kg/m^2.s$, for various inlet qualities. For a horizontal branch, an increase in inlet quality results in reduction of the peak phase separation ratio and increase in the flow split ratio at which complete phase separation is encountered. This caused by the increase in the thickness of the liquid film available for extraction as the liquid film will tend to be more uniform with increasing vapour velocity, i.e. increasing inlet quality. However, as the liquid film thickness at the bottom decreases with increasing quality, less liquid becomes available for extraction. Accordingly, the effect of inlet quality is reversed for the 90^0 downward branch, i.e. the peak branch quality ratio increase with increasing inlet quality.

JUNCTION PRESSURE CHANGES

Pressure changes in a T-junction can be modeled by both momentum and mechanical energy balance. When a flow is divided in a T-junction the deceleration of the fluid causes a reversible pressure rise in the run and branch conduit due to Bernoulli effect. However, previous studies have shown that the irreversible pressure drop is much lower than Bernoulli type reversible pressure recovery in the run, as a result there is a net pressure rise in the run conduit and the axial pressure recovery is usually modeled based on momentum balance. Studies also indicated that the irreversible pressure drop is much higher than reversible pressure rise in the branch, accordingly there is a net pressure drop in the branch conduit which is always modeled based on mechanical energy balance. The following assumptions were made to simplify the analysis through out this report.

i. The inlet flow is divided discontinuously into two streams just before the T junction.

ii The static pressure is assumed uniform across any flow channel and the velocities are parallel to the conduits wall. Consequently the momentum flux coefficient and kinetic energy flux coefficient equal unit.

Single-phase flow

Applying the momentum equation and mechanical energy equations to model the run pressure rise and the branch pressure drop respectively, it can be shown that for single-phase flow [see Collier (1976)]

$$(\Delta P_{2-1})_j = K_{12}\rho(u_1^2-u_2^2) \tag{1}$$

$$(\Delta P_{1-3})_j = \frac{\rho}{2}(u_3^2-u_1^2)+K_{13}\frac{\rho u_1^{\,2}}{2} \tag{2}$$

where ΔP_{2-1} and ΔP_{1-3} are the run pressure rise and branch pressure drop respectively. K_{12} is known as the run momentum correction factor, which accounts for the indeterminant axial momentum carried out of the control volume by the branching flow, K_{13} is the mechanical energy loss coefficient due to the dissipation in the T-junction. The experimental measurement of (ΔP_{2-1})$_j$ and (ΔP_{3-1})$_j$ are obtained by extrapolating the fully developed pressure profile in the conduits to the junction centre line. Single phase run momentum correction factor K_{12} and branch energy loss coefficient K_{13} obtained in the present work and calculated from eqn. (1) and (2) are plotted against branch flow split ratio shown in figure 3a and 3b. The present data shows that for high enough inlet mass flux K_{12} and K_{13} are unique functions of branch flow split ratio G_3/G_1. Consequently the empirical correlation of K_{12} and K_{13} obtained by Ballyk Shoukri and Chan(1988) are used in present investigation:

$$K_{12} = 0.704-0.320(\frac{G_3}{G_1})-0.028(\frac{G_3}{G_1})^2 \tag{3}$$

$$K_{13} = 1.081-0.914(\frac{G_3}{G_1})+1.050(\frac{G_3}{G_1})^2 \tag{4}$$

Two-phase flow

Simplification of the momentum and mechanical energy equations for two-phase flow in a T-junction can be achieved by assuming homogeneous or separated flow. Besides the assumptions applied to single-phase flow, the following additional assumptions are applied for two-phase flow in the junction.

i. thermal equilibrium exists between the phases.

ii. the pressure changes in the junction are small relative to the absolute pressure of the system.

iii. uniform void fraction across the piping conduits.

Axial Pressure Recovery. A comprehensive survey of the open literature has shown that the axial pressure recovery can be modelled by applying axial momentum balance on a control volume centred at the junction as was shown by Pierre and Glastonbury (1972), Fouda and Rhodes (1974), Collier (1976) and Ballyk, Shoukri and Chan (1988). Assuming separated flow, the axial momentum balance yields:

$$(\Delta P_{2-1})_j = P_2-P_1 = K_{12s}(\frac{G_1^2}{\rho_{m1}}-\frac{G_2^2}{\rho_{m2}}) \tag{5}$$

where K_{12s} is the two-phase separated momentum correction factor and ρ_m is the momentum density.

$$\rho_m = [\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}]^{-1} \tag{6}$$

Several separated two-phase momentum correction factors have been suggested by different researchers for a T-junction with horizontal branch. Fouda and Rhodes (1974) recommended that K_{12s} = 0.533. Madden and St Pierre (1969) and Ballyk, Shoukri and Chan (1988) showed that K_{12s} = 1.0 for T-junctions having a horizontal branch under annular inlet flow conditions.

The two-phase separated momentum correction factor K_{12s} calculated from the present data is plotted against the branch flow split ratio in figures 4a and 4b for the T-junctions with the branch downwardly inclined by 90^0 and 45^0 respectively. Physically K_{12s} is the correction factor which account for the momentum flux taken off by branch flow. For a horizontal branch, Ballyk et al (1988) showed that K_{12s} equals to unity, which indicates that the axial momentum flux carried by the branch is insignificant. In the case of downwardly oriented branches more water is extracted into the branch due to gravitational forces. A part of the axial momentum flux will be taken off the control volume. Consequently the axial momentum correction factor should be smaller than that of horizontal branch junction. Present investigation shows that K_{12s} = 0.42 for 90^0 downward branch and K_{12s} = 0.78 for 45^0 downward branch respectively.

Branch pressure drop. Mechanical energy equation was used to model branch pressure drop in T-junctions by most of the previous researchers. In mechanical energy equation based models when two-phase flow is divided in T-junction the branch pressure change consists of two parts i.e. reversible pressure change due to Bernoulli effect and irreversible pressure loss due to mechanical energy dissipation,

$$(\Delta P_{1-3})_j = (\Delta P_{1-3})_{rev} + (\Delta P_{1-3})_{irr} \tag{7}$$

There are several mechanical energy equation based models available which can be used to predict branch pressure drop. Saba and Lahey (1982) expressed $(\Delta P_{1-3})_j$ with separated flow model:

$$(\Delta P_{1-3})_j = \frac{\rho_{h3}}{2}(\frac{G_3^2}{\rho_{e3}^2} - \frac{G_1^2}{\rho_{e1}^2}) + K_{13}\frac{G_1^2}{2\rho_{m1}} \tag{8}$$

where ρ_e and ρ_m is energy and momentum densities defined as:

$$\rho_e = [\frac{x^3}{\alpha^2\rho_g^2} + \frac{(1-x)^3}{(1-\alpha)_2\rho_l^2}]^{-0.5} \tag{9}$$

$$\rho_m = [\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}]^{-1} \tag{10}$$

In homogeneous flow model eqn.(8) becomes:

$$(\Delta P_{1-3})_j = \frac{\rho_{h3}}{2}(\frac{G_3^2}{\rho_{h3}^2} - \frac{G_1^2}{\rho_{hl}^2}) + K_{13}\frac{G_1^2}{2\rho_{hl}} \tag{11}$$

Reimann and Seeger (1986) recommend another homogeneous model as:

$$(\Delta P_{1-3})_j = \frac{\rho_{h3}}{2}(\frac{G_3^2}{\rho_{h3}^2} - \frac{G_1^2}{\rho_{hl}^2}) + K_{13}\frac{G_1^2}{2\rho_{hl}}\frac{\rho_{h3}}{\rho_{hl}} \tag{12}$$

Ballyk, Shoukri and Chan (1988) suggested a separated flow model based correlation:

$$(\Delta P_{1-3})_j = \frac{\rho_{h3}}{2}(\frac{G_3}{\rho_{e3}^2} - \frac{G_1^2}{\rho_1^{*2}}) + K_{13}\frac{\rho_{h3}G_1^2}{2\rho_1^{*2}}\Phi_{tp} \tag{13}$$

where the two-phase multiplier Φ_{tp} is determined empirically and the equivalent inlet density ρ_1^* is defined as:

$$\rho_1^* = [\frac{x_1^2 x_3}{\alpha_1^2\rho_g^2} + \frac{(1-x_1)^2(1-x_3)}{(1-\alpha_1)^2\rho_l^2}]^{-0.5} \tag{14}$$

The present experimental data of 90^0 and 45^0 downward branch, reduced by Saba and Lahey separated model of eqn. (8) are shown in figure 5. When the branch flow split ratio is higher more than 40% eqn.(8) can predict the measured values. It appears that equation (8) is able to predict the branch pressure drop well only in the range of complete vapour extraction. The predictions of the homogeneous model using eqn.(11) is presented in figure

6. Again, the homogeneous model appears to predict the observed data at high flow split ratios. As discussed previously total phase separation happens when branch flow split ratio is in the range of 0.4 to 0.8 for the 90^0 and 45^0 downward branch T-junction. Figure 5 and 6 illustrate that both the separated and homogeneous flow models presented by Saba and Lahey can be used to predict branch pressure drop as long as total phase separation is achieved.

The predictions using Reimann and Seeger's homogeneous flow model of eqn.(12) is presented in figure 7. This model also can correctly predict branch pressure drop only in the range of flow split where total phase separation takes place. However Reimann and Seeger's model is in better agrement with the present data than Saba and Lahey's model. It should be mentioned that the irreversible part of these models can be expressed as the irreversible energy loss of liquid phase times a two-phase flow multiplier:

$$(\Delta P_{1-3})_{irr} = K_{13}\frac{G_1^2}{2\rho_l}\phi_{tp} \qquad (15)$$

where the two-phase multiplier Φ_{tp} is:

$$\phi_{tp} = \frac{\rho_l}{\rho_{ml}}$$ Saba & Lahey separated model

$$\phi_{tp} = \frac{\rho_l}{\rho_{hl}}$$ Saba & Lahey homogeneous model

$$\phi_{tp} = \frac{\rho_l \rho_{h3}}{\rho_{hl}^2}$$ Reimann & Seeger homogeneous model

It is interesting to note that in the homogeneous model of Reimann & Seeger, the two-phase multiplier is equivalent to the product of Saba & Lahey's two-phase multiplier and a correction factor ρ_{h3}/ρ_{h1} which involves the effect of branch phase separation. After this correction the accuracy of predicted results is greatly improved. The above shows that the key issue to model branch pressure drop is to find a more realistic two-phase flow multiplier which can successfully predict the effect of branch phase separation.

Intuitively it makes sense that the two-phase multiplier Φ_{tp}

should be a function of inlet flow regime, inlet quality X_1, inlet pressure P_1, branch flow split ratio G_3/G_1 and the geometry configuration of the T junction. All these parameters have strong influence on phase separation in the junction. Consequently two-phase flow multiplier is closely correlated with junction phase separation. A semi-empirical natured model has suggested by Ballyk, Shoukri and Chan (1988) as shown in eqn.(13) in which the effect of inlet quality was incorporated.

Equation (13) was used to obtain the two-phase multiplier Φ_{tp} using present data. The results are shown in figure 8. The data presented in this figure was empirically correlated by the following expression:

$$\Phi_{tp} = 0.603+3.193(\frac{G_3}{G_1})+14.210(\frac{G_3}{G_1})^2+10.354(\frac{G_3}{G_1})^3-20.730(\frac{G_3}{G_1})^4 \qquad (16)$$

A comparison of the branch pressure drop calculated by this correlation and experimental measurement is presented in figure 9. Good agreement is shown.

CONCLUSION

Detailed experimental data on dividing steam-water annular flow in T-junctions having horizontal inlet and downwardly inclined branches were obtained. The branch orientation was found to be a significant parameter affecting phase separation under a horizontal annular inlet flow condition when the quality was less than 10%. This effect of branch orientation on phase separation is caused mainly by the non-uniform thickness distribution of the liquid film in the inlet tube; typical of horizontal annular flow. The results showed that, in general, downward rotation of the branch results in less vapour extraction as the liquid film available for extraction is thicker. The inlet mass flux was found to have no effect on the phase separation phenomenon. However, the inlet quality has a pronounced effect. Changing the inlet quality effects the liquid film thickness distribution and accordingly affects the phase separation phenomenon.

The data on pressure changes through the junction were correlated using simple models based on momentum and mechanical energy balance. The run pressure recovery data was correlated using momentum balance. The momentum correction factor was found to depend on branch orientation. The branch pressure drop was correlated using mechanical energy based model and a two-phase multiplier which was found to be independent of branch orientation.

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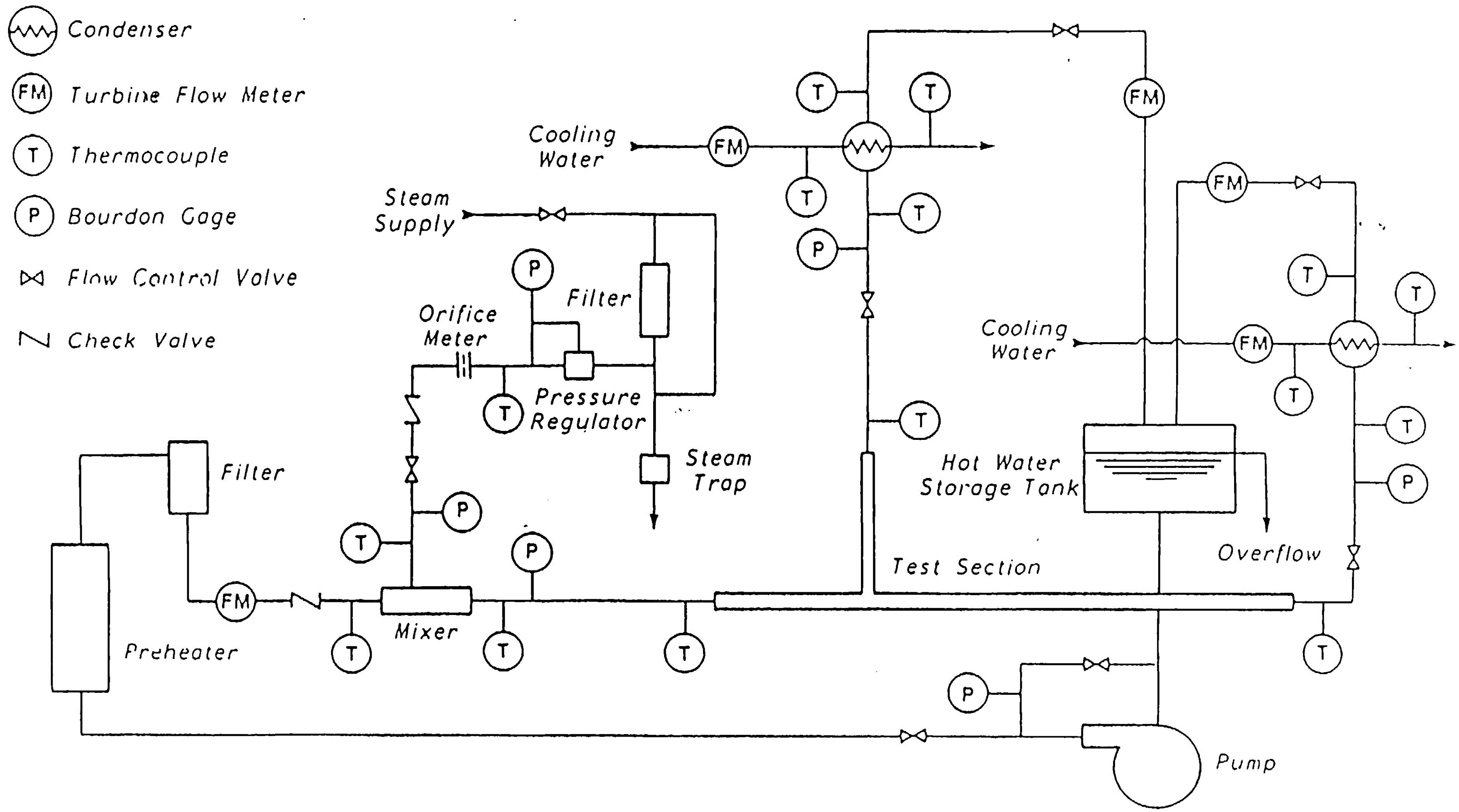

Fig. 1. Steam-water two-phase experimental loop.

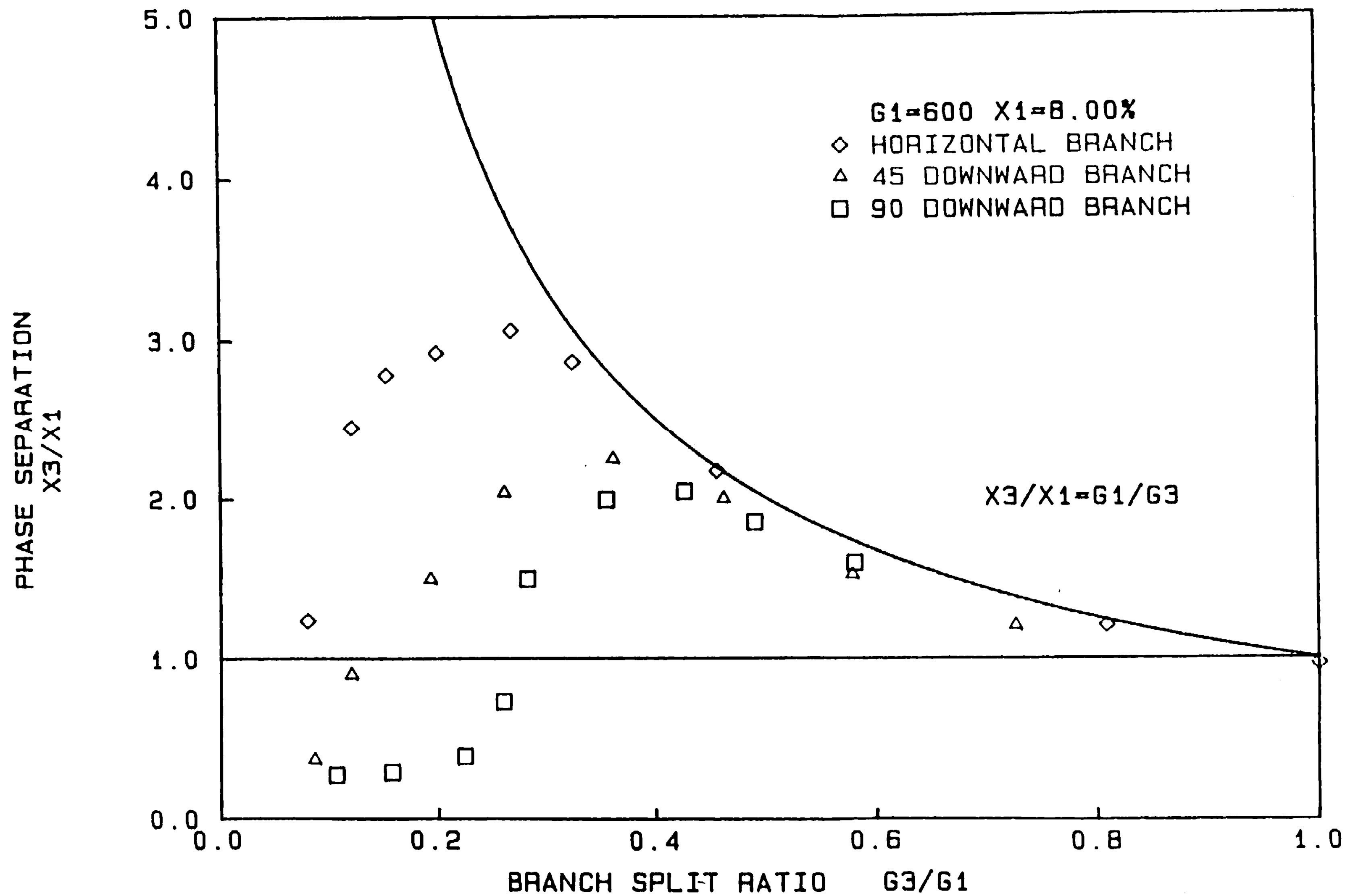

Fig.2A. Effect of branch orientation on phase separation.
(G_1 = 600 kg/m^2.S, x_1 = 8.0%)

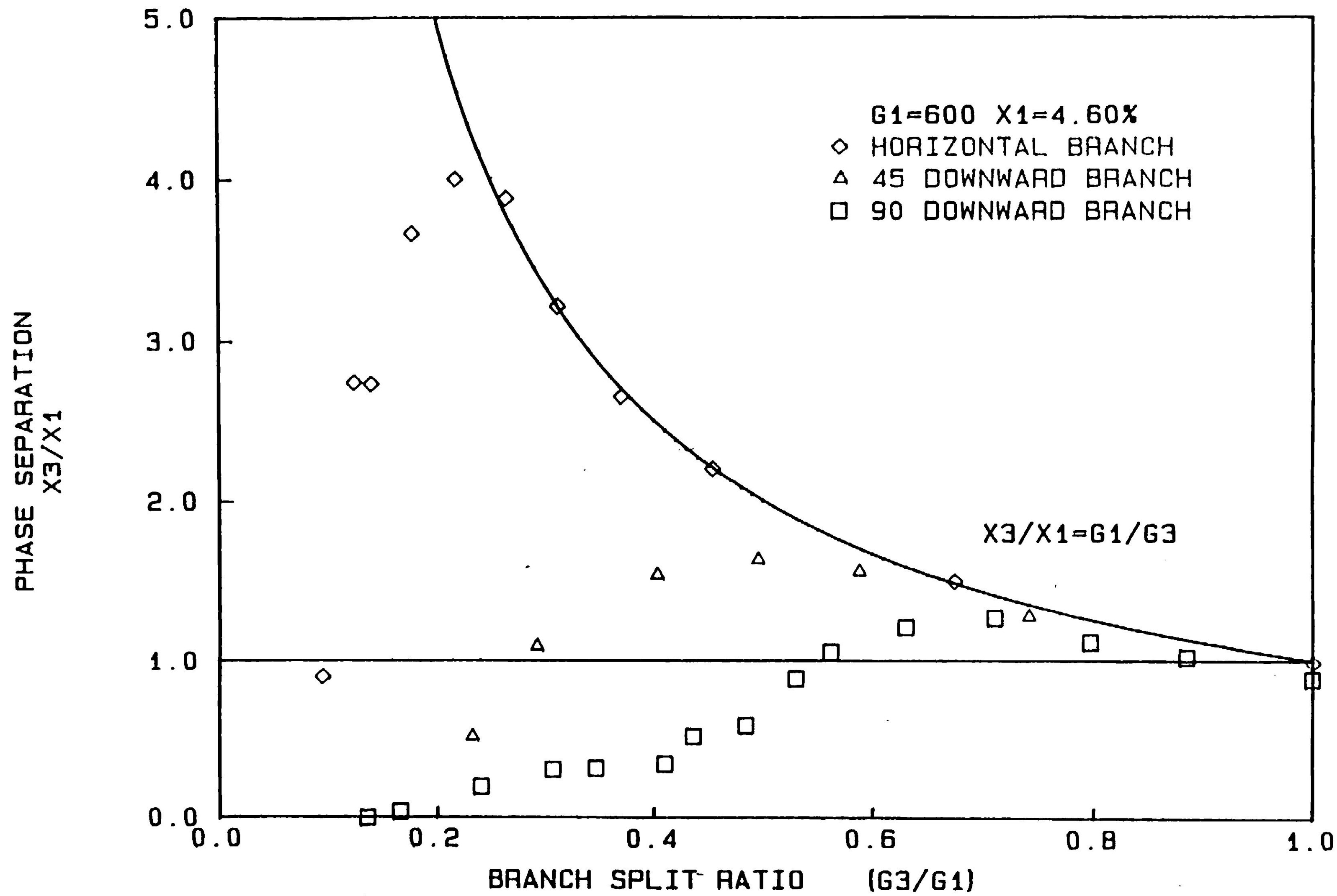

Fig.2B. Effect of branch orientation on phase separation.
(G_1 = 600 kg/m^2.S, x_1 = 4.6%)

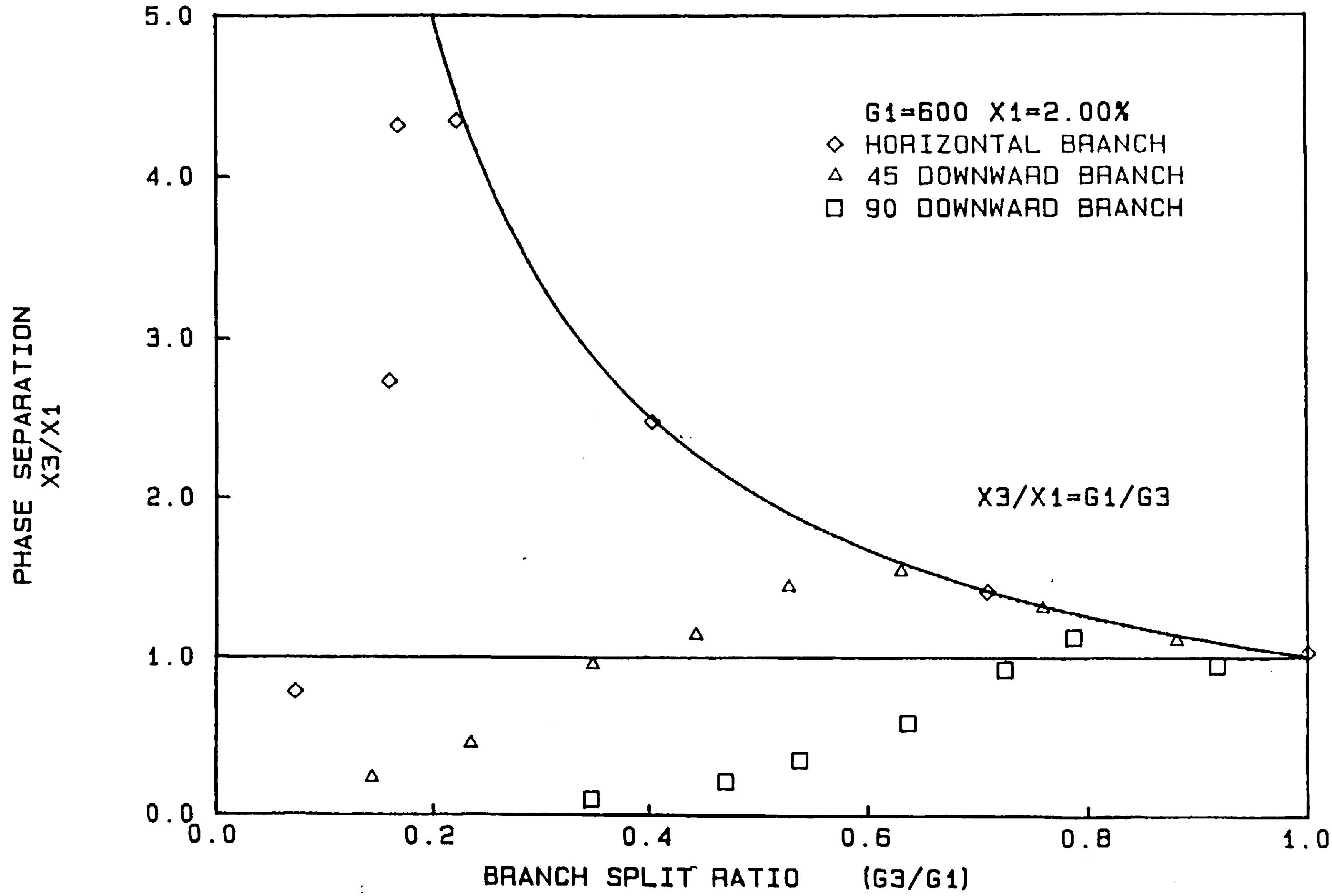

Fig.2C. Effect of branch orientation on phase separation.
(G_1 = 600 kg/m^2.S, x_1 = 2.0%)

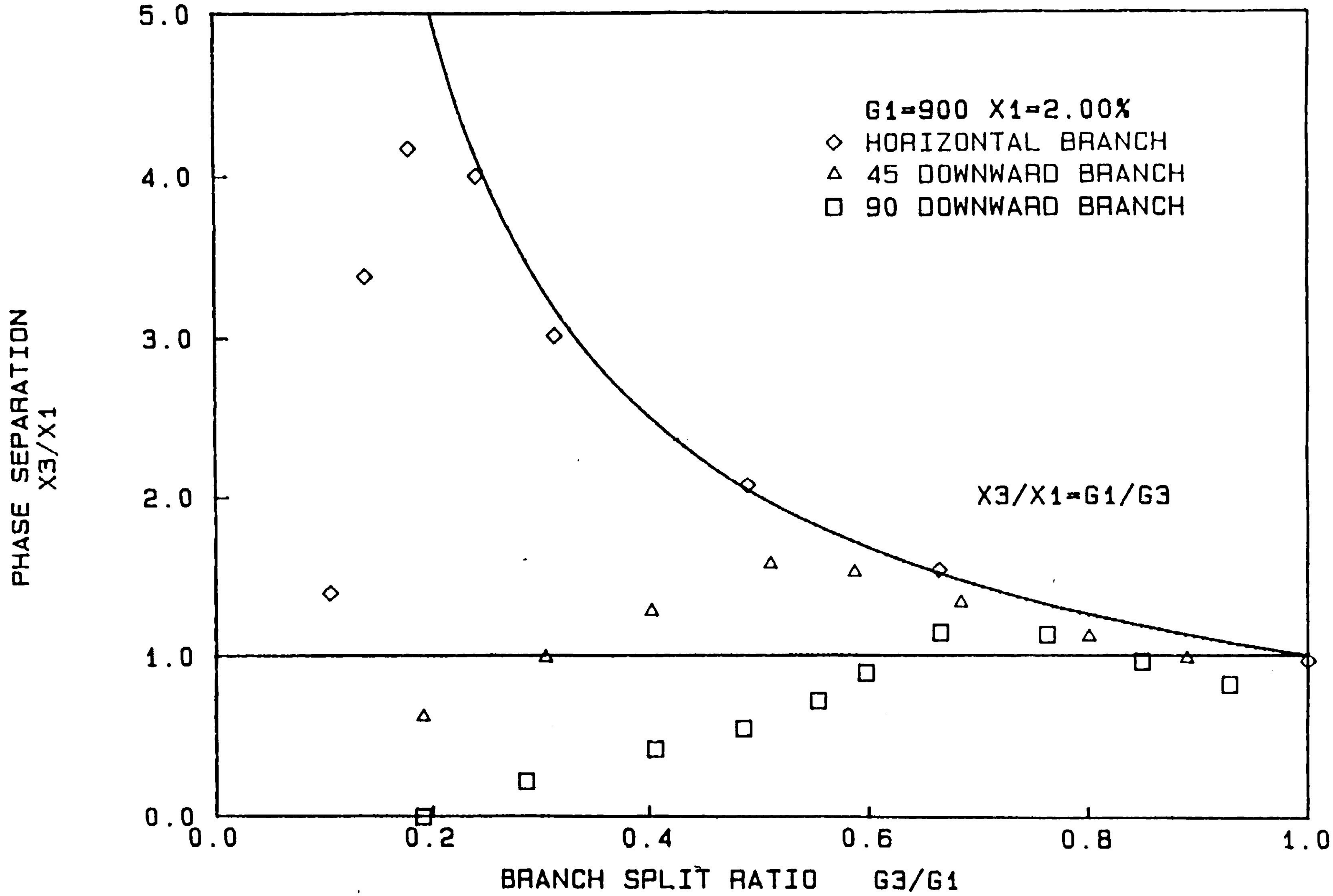

Fig.2D. Effect of branch orientation on phase separation.
(G_1 = 900 kg/m^2.S, x_1 = 2.0%)

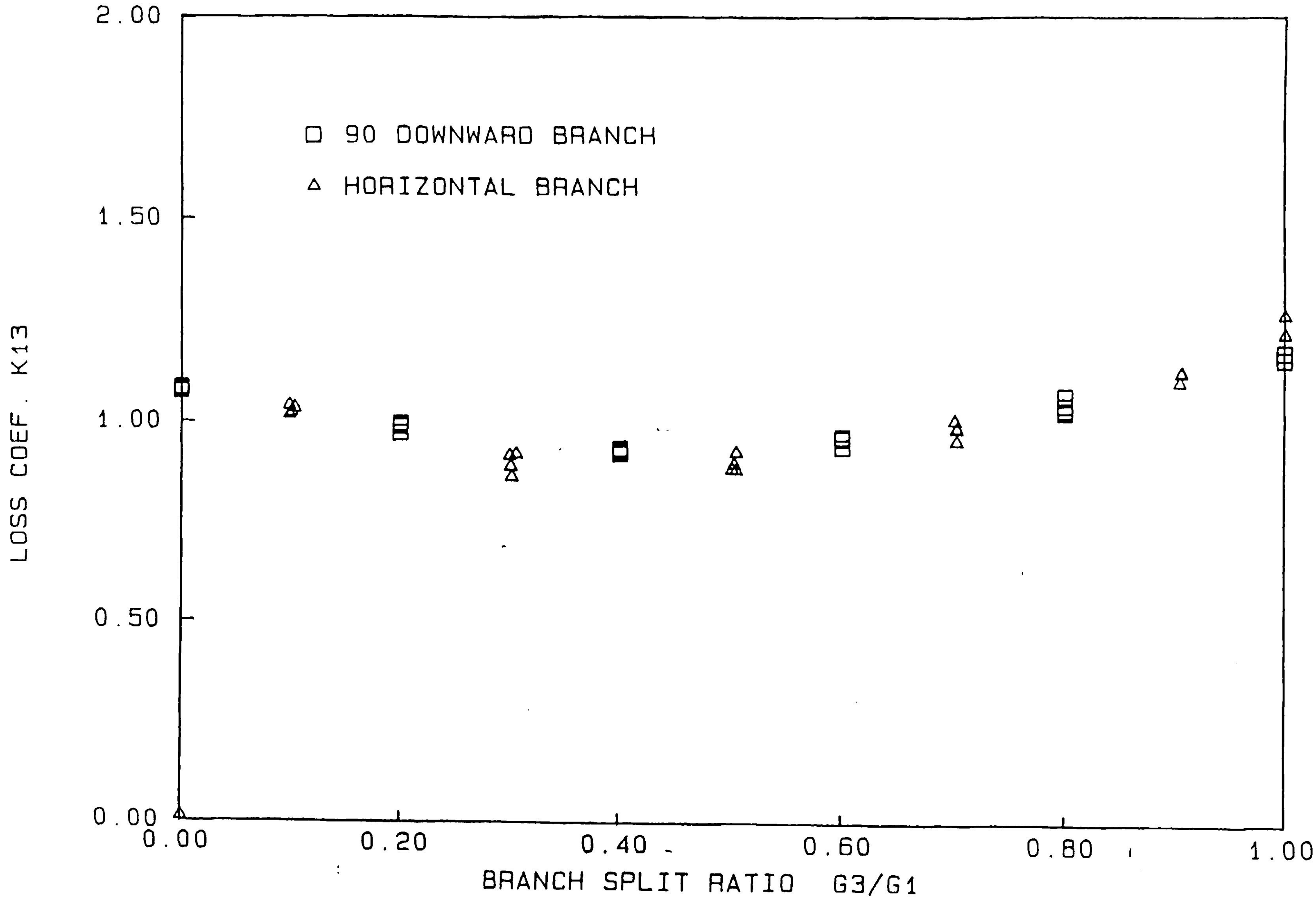

Fig.3A. Effect of branch orientation on sigle-phase branch energy loss coefficient.

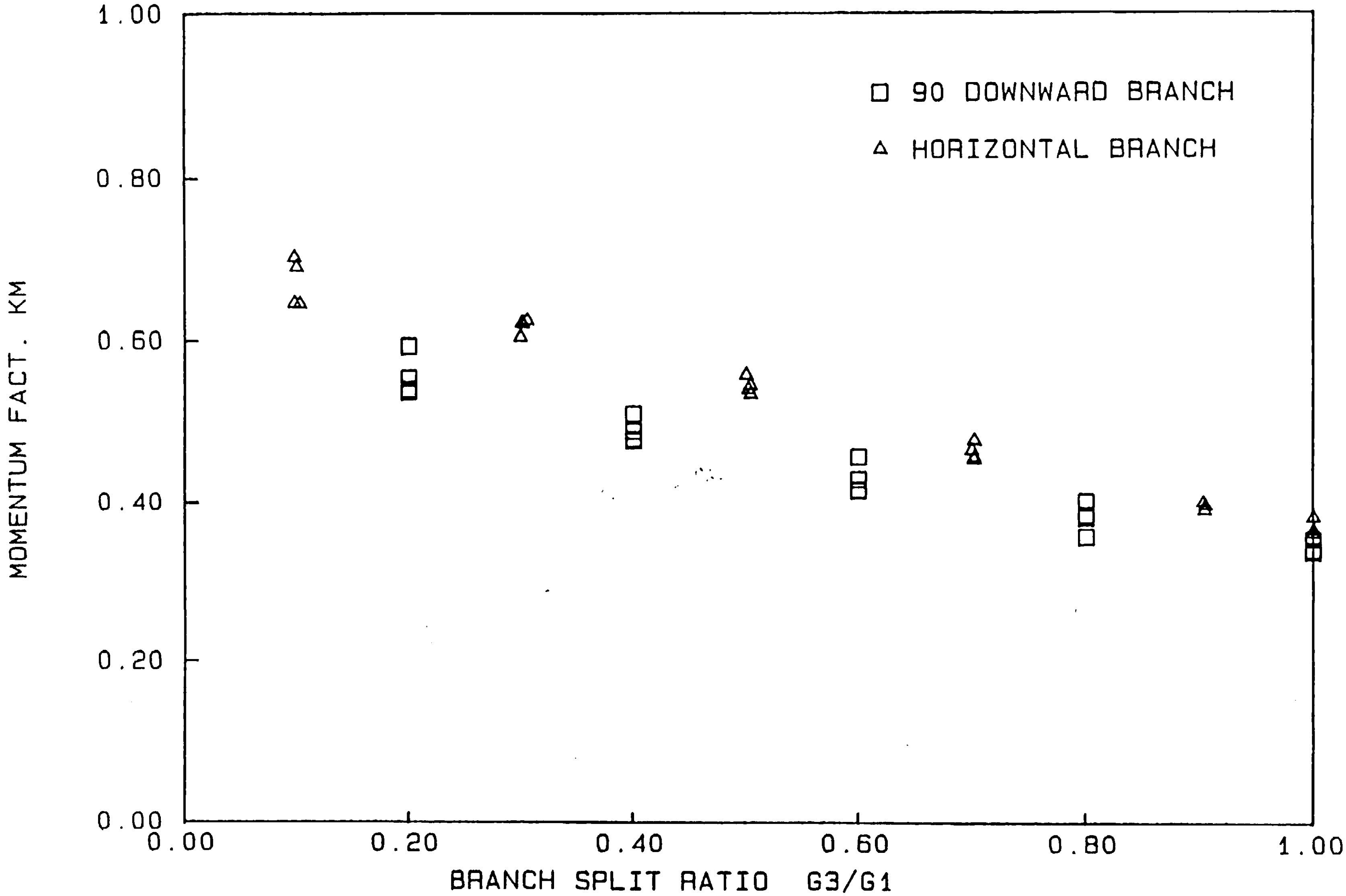

Fig.3B. Effect of branch orientation on sigle-phase momentum correction factor.

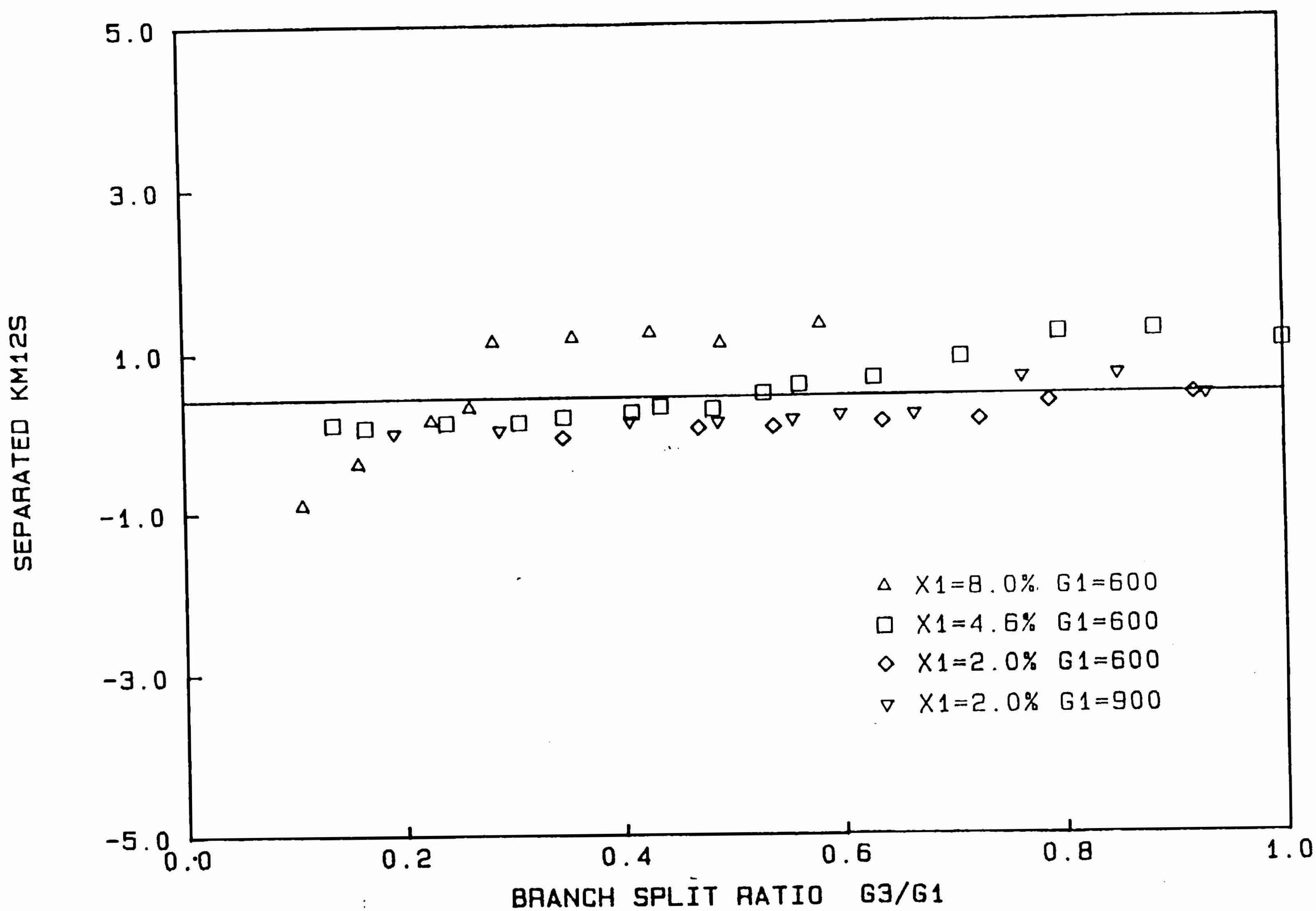

Fig.4A. Run momentum corrector factor in 90^{o} downward branch junction.

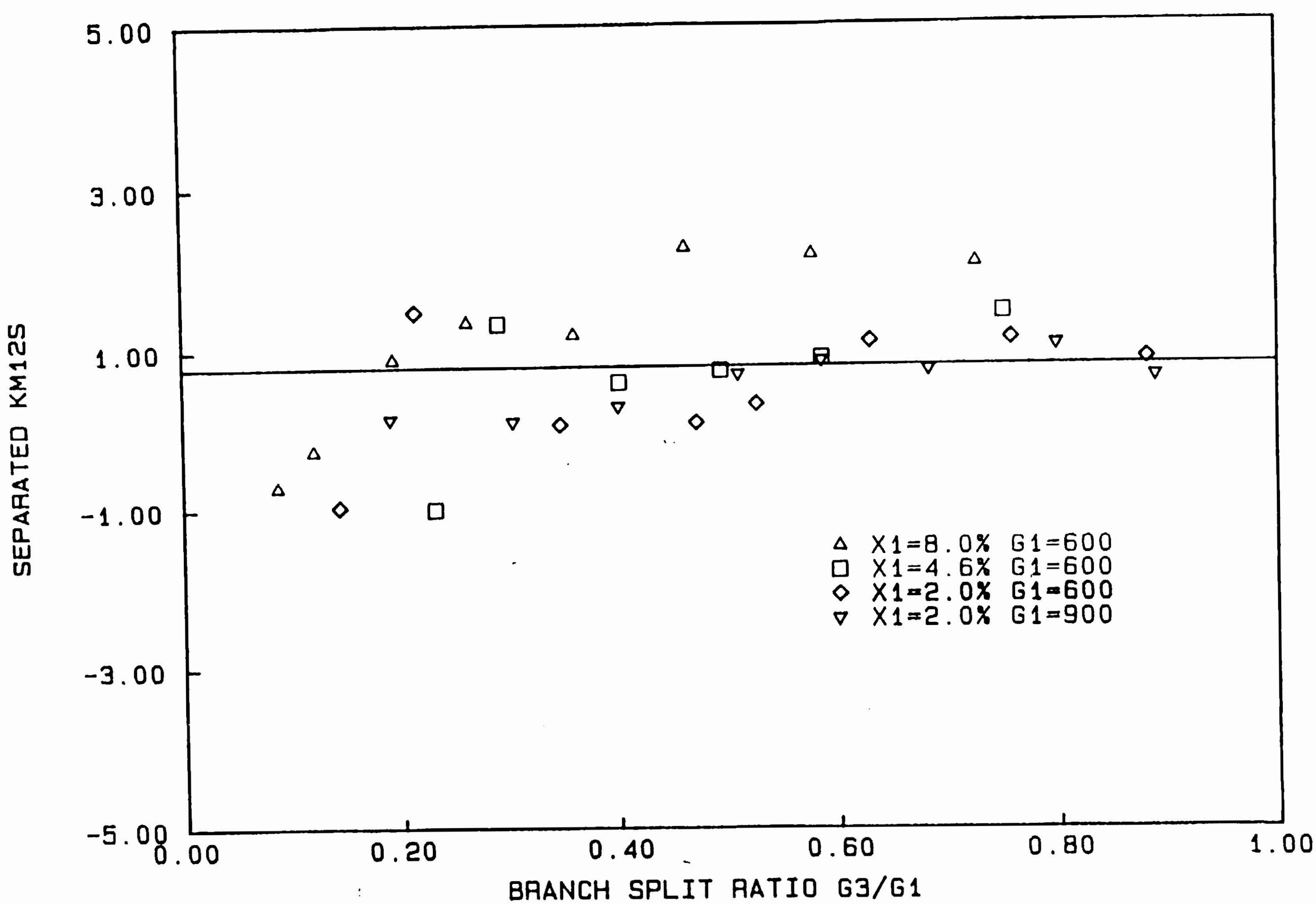

Fig.4B. Run momentum corrector factor in 45^{o} downward branch junction.

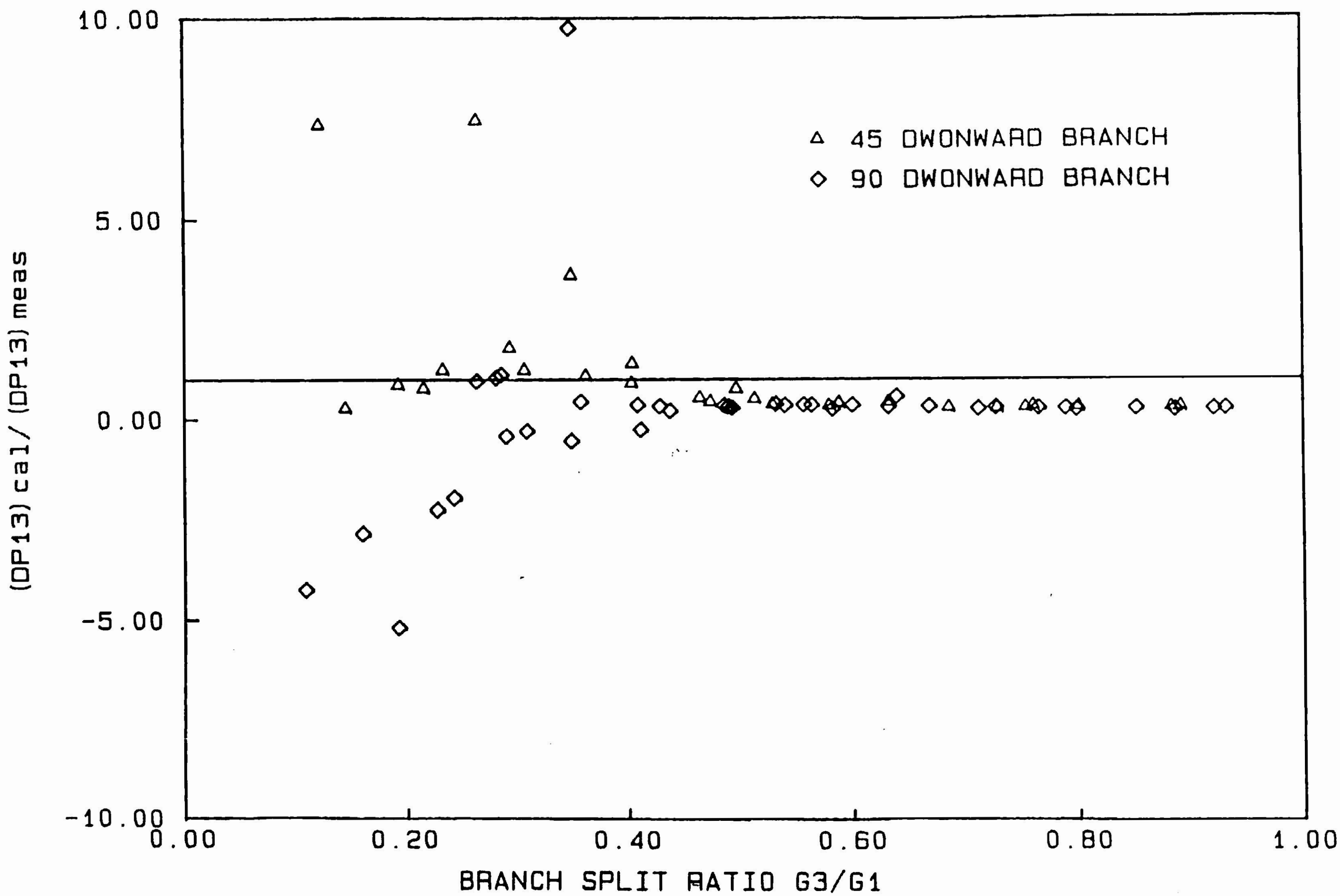

Fig.5. Comparison of branch pressure drops predicted by Saba & Lahey's separated model with experimental measurement.

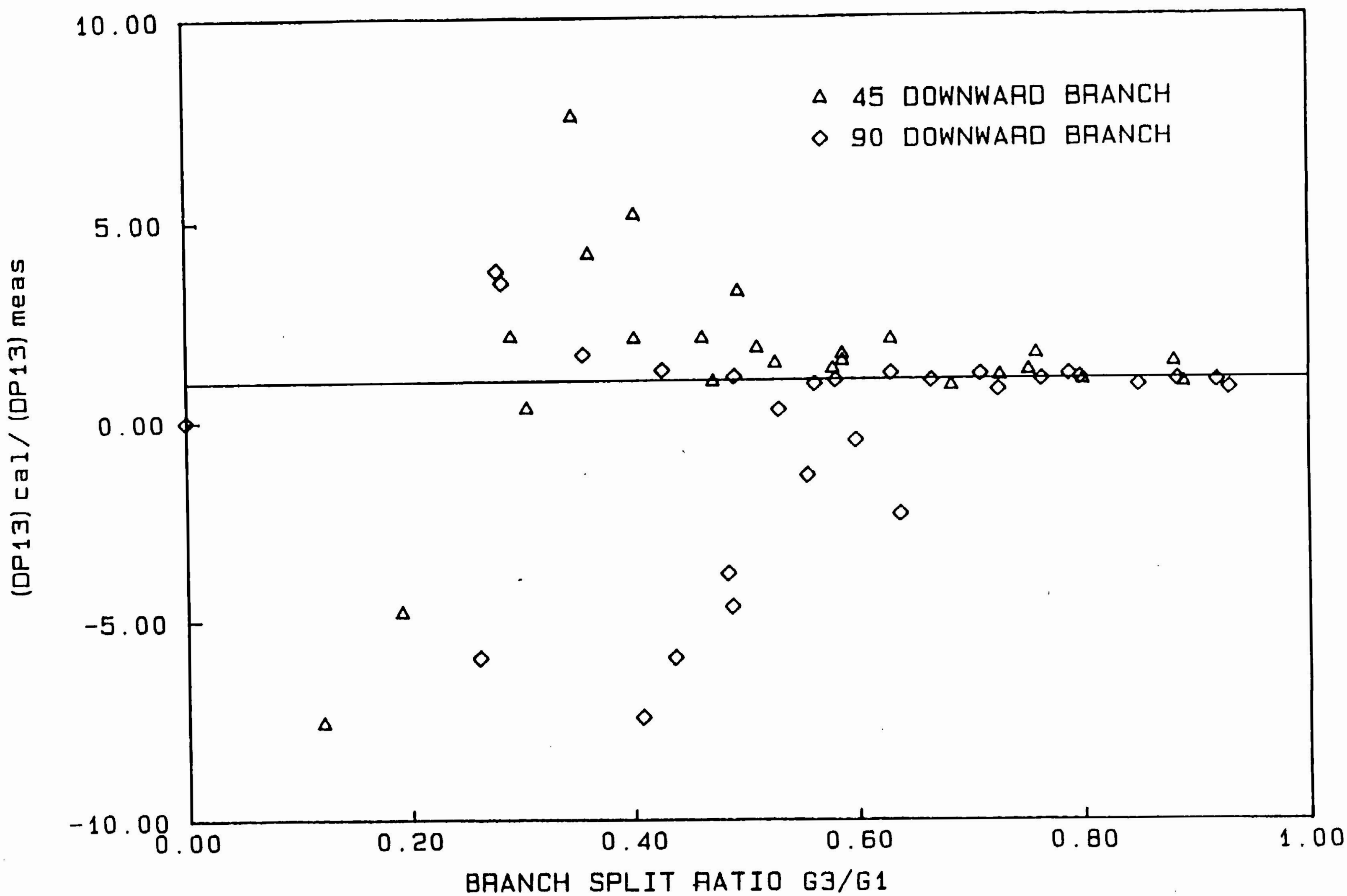

Fig.6. Comparison of branch pressure drops predicted by Saba & Lahey's homogeneous model with experimental measurement.

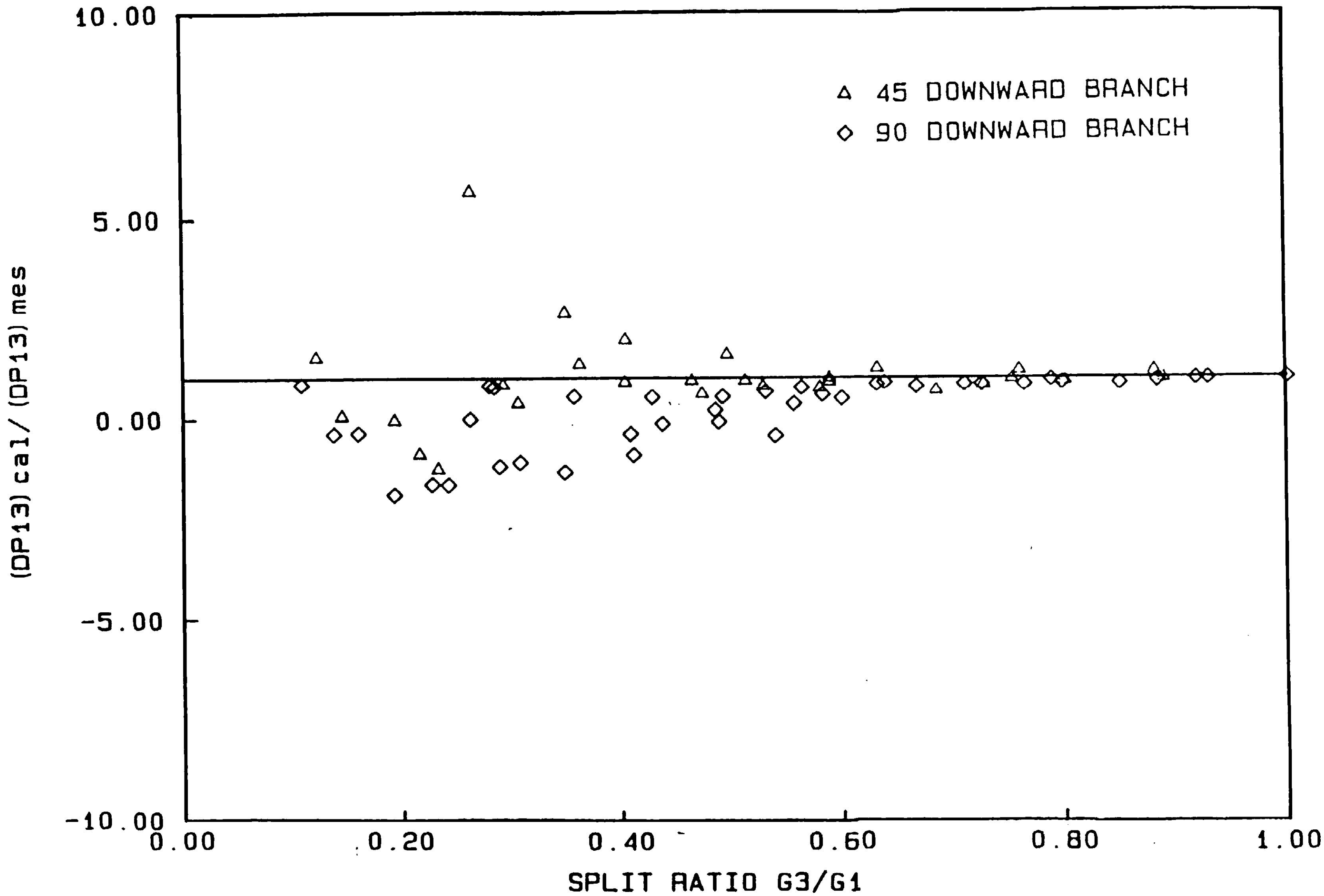

Fig.7. Comparison of branch pressure drops predicted by Reimann & Seeger's homogeneous model wiht experimental measurement

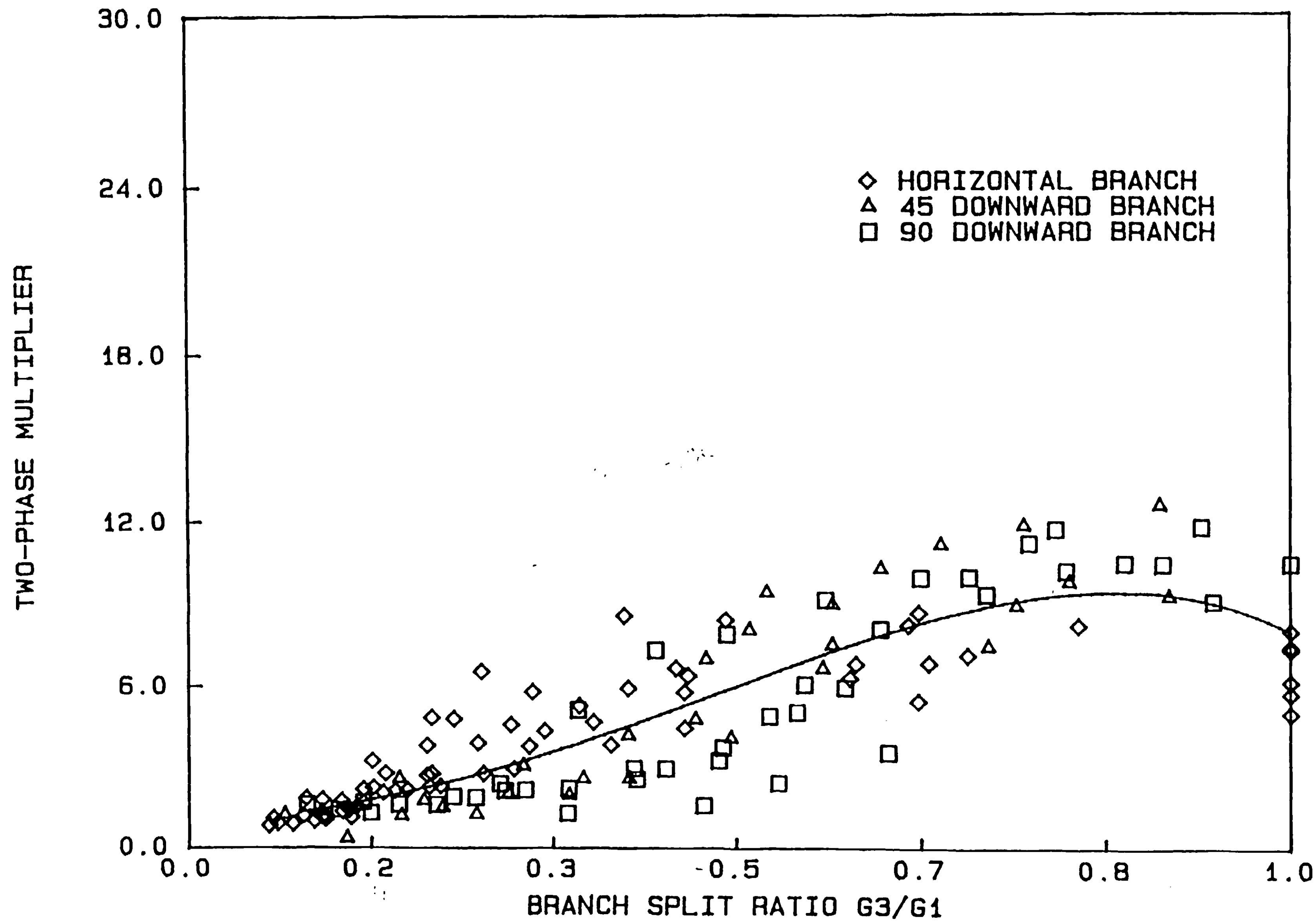

Fig.8. Two-phase multiplier as a function of branch flow split ratio.

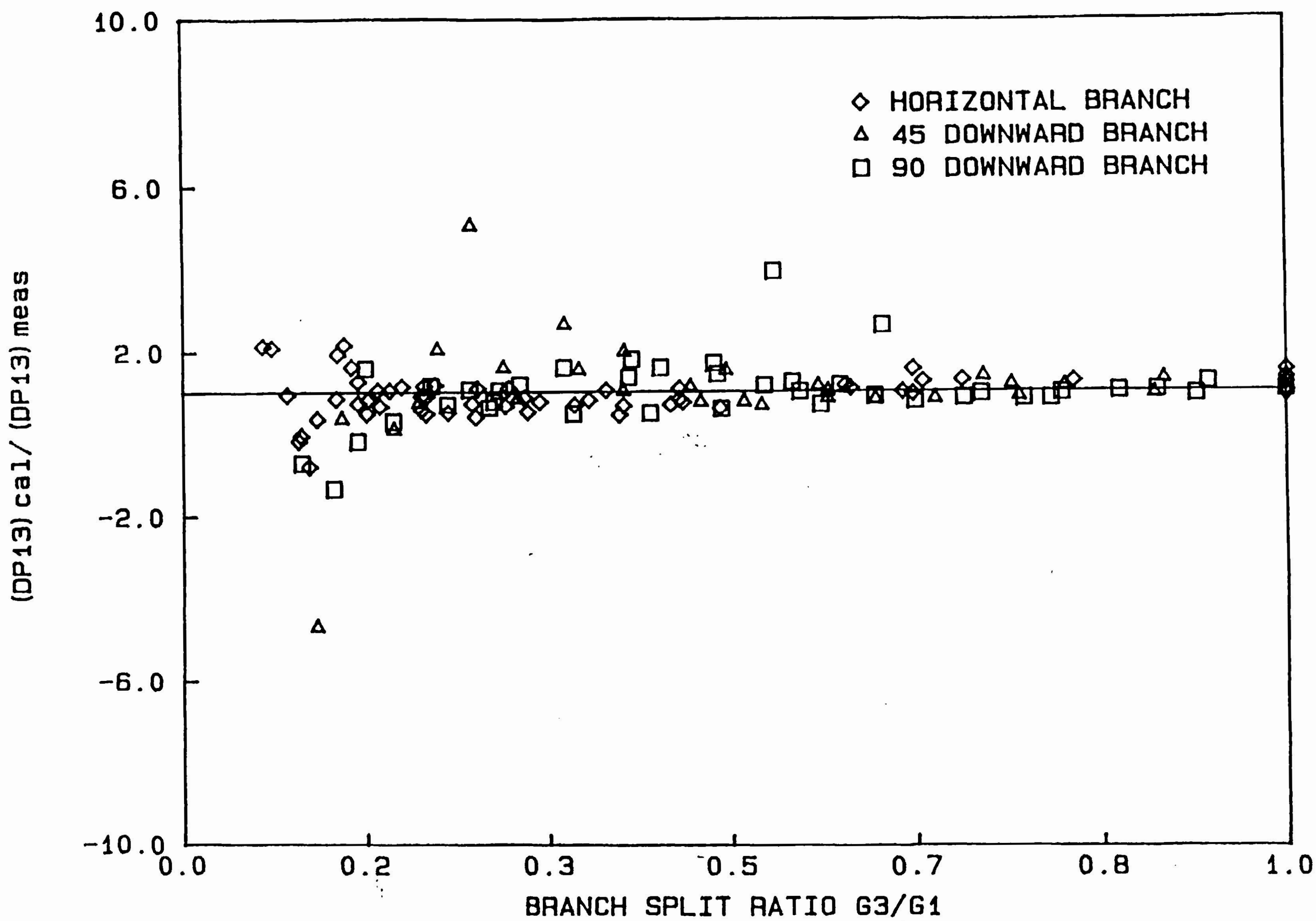

Fig.9. Comparison of branch pressure drops calculated by Ballyk-Shoukri correlation and experiment measurement.