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PRESSURE DROP AND SOLIDS DISTRIBUTION OF AIR–SOLIDS MIXTURE IN HORIZONTAL UNSYMMETRIC BRANCHES

Y. Morikawa, T. Kondo† and T. Hiramoto‡

Department of Mechanical Engineering for Industrial Machinery, Osaka University, Suita, Osaka, Japan

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Abstract—From the experimental results obtained under various combinations of branch angles the effects of branch angles, discharge ratios of air into the branched pipe and solid–air loading ratios on the pressure drop due to branching was considered. It was shown that the coefficients of additional pressure drop due to the solids, is proportional to solid–air loading ratios in the branched pipe and independent of branch angle of another branched pipe. The mass flow rate of coarse particles into the branched pipe is not controlled by the discharge ratios of air, and approximately determined by the ratio of the projected area of branched pipe on the plane vertical to the axis of the main pipe to the cross-sectional area of the main pipe.

1. INTRODUCTION

The pressure drop in branches, and solids distribution into the branched pipes are found in several papers. Experiments were performed on T-branch in horizontal and vertical planes (Lempp 1966) and on the symmetric Y-branch of various branch angles in horizontal plane (Morikawa *et al.* 1974). Using fine particles the solids distribution into the branched pipes of T-branch, Y-branch and cross-shaped branch was also treated (Maeda & Ikai 1976). Moreover, the behavior of air–solids mixture in a single or double T-branches was investigated (Morimoto *et al.* 1977).

The pressure drop and solids distribution into the branched pipes in the unsymmetric Y-branches in horizontal plane under various combinations of branch angles are treated here. From the experimental results the effects of branch angles, discharge ratios of air and particle–air loading ratios on the pressure drop were investigated. The relationship between solids distribution into the branched pipes and the geometric shape of the branch part was also considered.

2. EXPERIMENTAL APPARATUS

The experimental apparatus is shown schematically in figure 1. The pipe consisted of transparent plastic tube having an inside diameter of 41 mm. The inside surface of pipes was smooth. The discharge of air was measured by traversing calibrated Pitot tubes. Static pressures from the pressure taps, of which diameter was 0.8 mm, were let to a multi-tube manometer. The solids were supplied to the main pipe I through an electromagnetic feeder *a*. The rate at which the solids fell into air stream was controlled by adjusting the voltage. The air–solid two-phase flow entered cyclone separators *b* and *c*, and solids were separated here from the air stream.

Solid particles used in the experiment were nearly spherical polyethylene pellets with mean diameter of 1.1 mm and density of 920 kg/m^3. The mean air velocity in the main pipe I was held nearly constant at 22 m/s. The effects of branch angles, discharge ratios of air into the branched pipe and solid–air loading ratios on the pressure drop for the flow from pipe I to pipe II was measured. The solid–air loading ratios in the main pipe were less than 7.

3. COEFFICIENTS OF PRESSURE DROP IN THE BRANCH

The pressure drop in branch is defined as follows: In figure 1, the pressure taps *A* and *B* were selected in such positions that the flow was not affected by branch and solid feeder.

†Present address: Ishikawajima-Harima Heavy Industries Co., Tokyo, Japan.
‡Present address: Daifuku Machinery Works Ltd., Komaki, Japan.

Considering the energy balance of two-phase flow from pipe I to pipe II, the pressure drop Δp due to branching is expressed in the form

$$p_A + \frac{\rho_a}{2} v_1^2 = p_B + \frac{\rho_a}{2} v_2^2 + \lambda_1 \frac{l_1}{d} \frac{\rho_a}{2} v_1^2 + \lambda_2 \frac{l_2}{d} \frac{\rho_a}{2} v_2^2 + \Delta p \quad [1]$$

where p_A and p_B are static pressures at the positions A and B, ρ_a air density, d inner diameter of pipe, l_1 and l_2 the lengths of pipes in figure 1, v_1 and v_2 mean air velocities in pipe I and II, λ_1''' and λ_2 friction factors in pipe I and pipe II respectively.

The total pressure drop Δp is composed of pressure drop due to air flow alone Δp_a and the additional pressure drop due to solids Δp_s:

$$\Delta p = \Delta p_a + \Delta p_s. \quad [2]$$

Using the dynamic pressure in the main pipe I, the coefficients of total pressure drop in the branch are defined as

$$\zeta = \Delta p/(\rho_a v_1^2/2) \quad [3]$$

and the coefficients of pressure drop due to air flow alone are expressed

$$\zeta_a = \Delta p_a/(\rho_a v_1^2/2). \quad [4]$$

Further the coefficients of additional pressure drop due to solids are defined as

$$\zeta_s = \Delta p_s/(\rho_a v_2^2/2) \quad [5]$$

in which the dynamic pressure in pipe II is used. From these relations the following expression is obtained:

$$\zeta = \zeta_a + \zeta_s (Q_2/Q_1)^2 \quad [6]$$

where Q_1 and Q_2 are discharges of air in pipe I and II, respectively.

4. EXPERIMENTAL RESULTS AND CONSIDERATION

4.1 *Pressure drop of single-phase flow of air in the branch*

In order to obtain the additional pressure drop due to solids, the pressure drop of single-phase flow of air must be known. In spite of many investigations about the pressure drop of single-phase flow of air or water in branches, the works about the pressure drop concerning with unsymmetric Y-branch in figure 1 were scarcely found. Therefore the characteristics for this case were at first considered. Substituting the measured values of Δp_a into [4], the coefficients ζ_a are obtained.

Figures 2 and 3 represent the relations between ζ_a and Q_2/Q_1 for various combinations of θ_1 and θ_2. The values of ζ_a for $Q_2/Q_1 = 1.0$ are nearly equal to another. In figure 3 the values of ζ_a for $\theta_1 = 0$ are nearly independent of θ_2. In the case of the combinations ($\theta_1 = 0$, $\theta_2 = 60°$), ($\theta_1 = 0$, $\theta_2 = 90°$) and ($\theta_1 = 90°$, $\theta_2 = 90°$) the pressure drop is already known and the experimental results in figure 3 coincide well with those results. Expressing the coefficients of pressure drop in quadratic form of discharge ratio of air as

$$\zeta_a = a_0 + a_1(Q_2/Q_1) + a_2(Q_2/Q_1)^2 \quad [7]$$

the coefficients a_0, a_1 and a_2 are determined from the experimental results, which are shown in

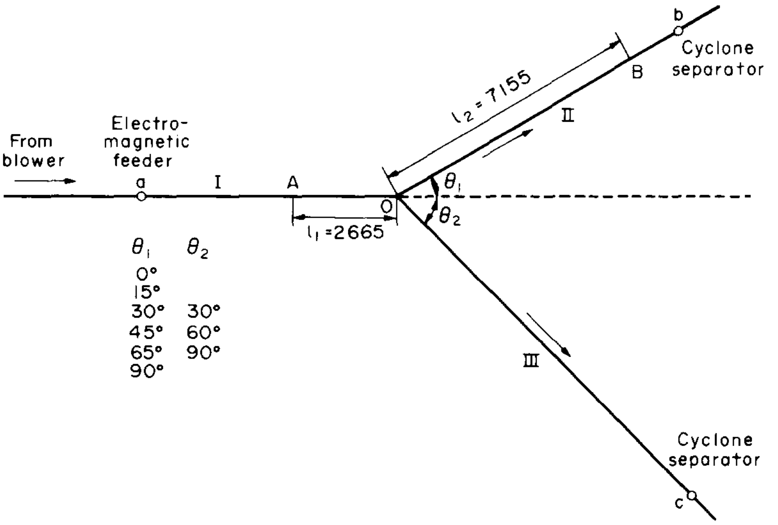

Figure 1. Experimental apparatus.

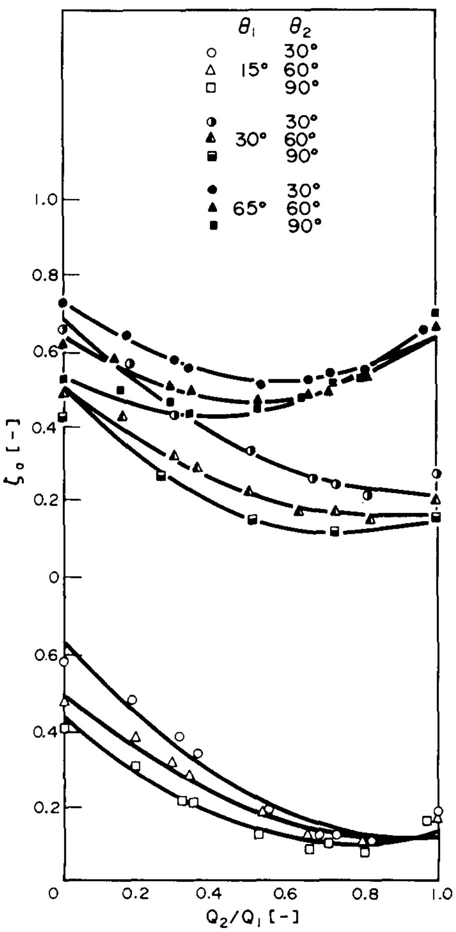

Figure 2.

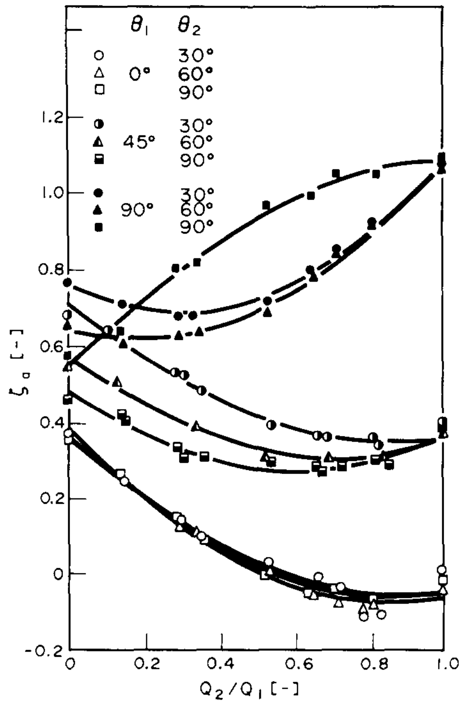

Figure 3.

Figure 2. Coefficient of pressure drop due to branching for air flow alone (θ_1 = 15°, 30°, 65°).

Figure 3. Coefficient of pressure drop due to branching for air flow alone (θ_1 = 0°, 45°, 90°).

Table 1. Values of coefficients a_0, a_1 and a_2 in [7]

θ_1	θ_2	a_0	a_1	a_2
	30°	0.375	−1.001	0.583
0°	60°	0.381	−1.049	0.607
	90°	0.370	−0.999	0.574
	30°	0.623	−1.122	0.627
15°	60°	0.507	−0.906	0.529
	90°	0.427	−0.885	0.549
	30°	0.692	−1.002	0.539
30°	60°	0.510	−0.820	0.487
	90°	0.504	−1.072	0.736
	30°	0.719	−0.868	0.516
45°	60°	0.579	−0.801	0.582
	90°	0.486	−0.714	0.590
	30°	0.734	−0.755	0.664
65°	60°	0.635	−0.698	0.706
	90°	0.534	−0.555	0.705
	30°	0.771	−0.503	0.826
90°	60°	0.645	−0.259	0.701
	90°	0.548	0.988	−0.427

table 1. The solid lines in figures 2 and 3 represent [7]. The pressure drop of single-phase flow for the branch used in the experiment has been thus made clear.

4.2 *Additional pressure drop in the branch due to solid particles*

Figures 4–8 show the coefficients of additional pressure drop ζ_s plotted versus solid–air loading ratio μ_2 in pipe II, i.e. the ratio of mass flow rate of solids G_{s2} to mass flow rate of air G_{a2} in pipe II. These values of ζ_s were calculated using [1], [2] and [5] with the experimental results.

In these results a significant difference is seen as below. The values of ζ_s for $Q_2/Q_1 = 0.72$ and 0.53 in figure 4 are negative and the other values of ζ_s in these figures are positive. In the case of negative values of ζ_s one would expect that the same phenomena as previous works (Maeda & Ikai 1973, Morimoto *et al.* 1977) should occur. At discharge ratios of $Q_2/Q_1 = 0.72$ and 0.53 for $\theta_1 = 0$ the air velocity behind the branch point decreases abruptly. In passing through the branch point the particles maintain, however, such velocity that they possessed in the main pipe, owing to large inertia of particles. Just behind the branch point the particle velocity is consequently larger than the air velocity. As a result the solids do work to air flow, by which the deceleration of solids is caused. In the case of $\theta_1 = 0$ and $Q_2/Q_1 = 1.0$, in figure 4, the values

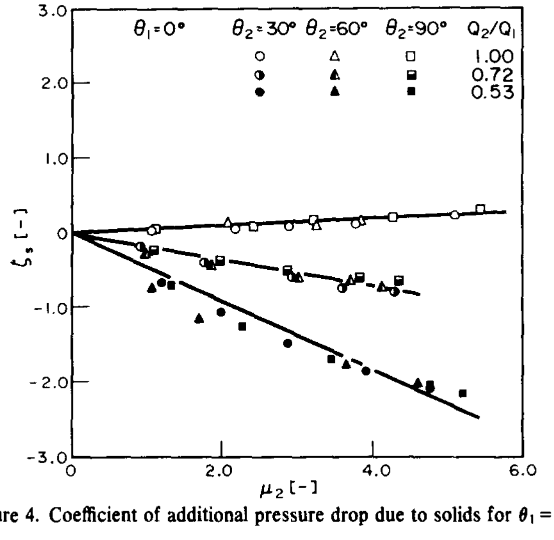

Figure 4. Coefficient of additional pressure drop due to solids for $\theta_1 = 0°$.

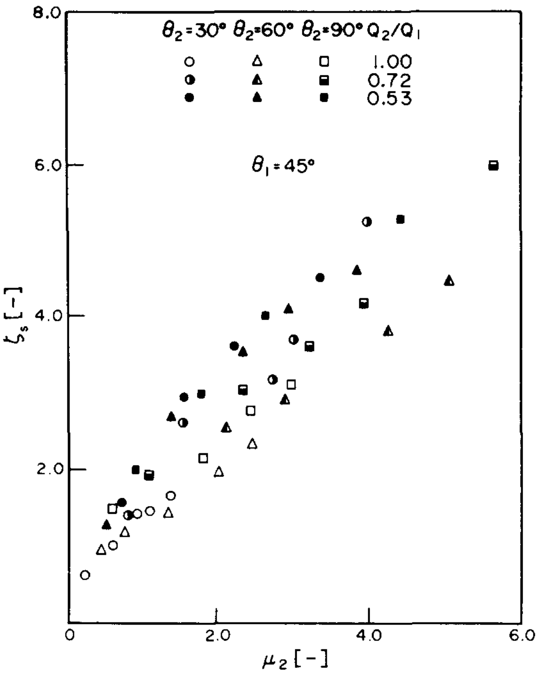

Figure 5. Coefficient of additional pressure drop due to solids for $\theta_1 = 30°$.

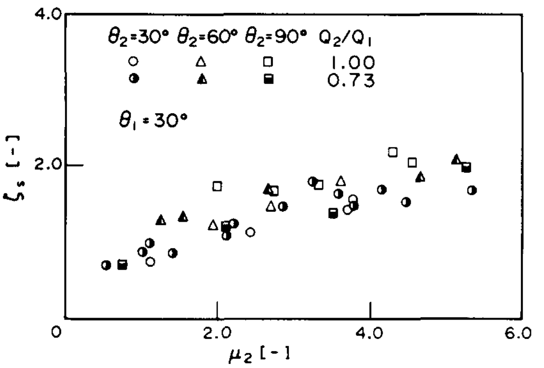

Figure 6. Coefficient of additional pressure drop due to solids for $\theta_1 = 45°$.

of ζ_s are very small in comparison to other cases, because the flow direction and velocity of particles in branch point are unchanged. Generally speaking, ζ_s increases with increasing solid–air loading ratio μ_2 in pipe II and depends upon the discharge ratios of air, but is independent of the branch angle θ_2.

4.3 *Solids distribution into the branched pipes*

The distribution of fine particles into the branched pipes depends on the discharge ratios of air (Lempp 1966; Maeda & Ikai 1976). On the other hand, the distribution of coarse particles are not controlled by the discharge ratios of air (Morikawa *et al.* 1974). The reason for the latter is as follows: the inertia of solid particles is greater than that of air, owing to greater density of particles than air density.

The experimental results of solids distribution are shown in figures 9–11. In these figures G_{s1} and G_{s2} are mass flow rates of solids in pipe I and II, and μ_1 is solid–air loading ratio in pipe I, i.e. the ratio of mass flow rate of solids G_{s1} to mass flow rate of air G_{a1} in the main pipe I. These figures indicate that the solids distribution into the branched pipe is independent of both Q_2/Q_1 and μ_1 as in the previous work (Morikawa *et al.* 1974).

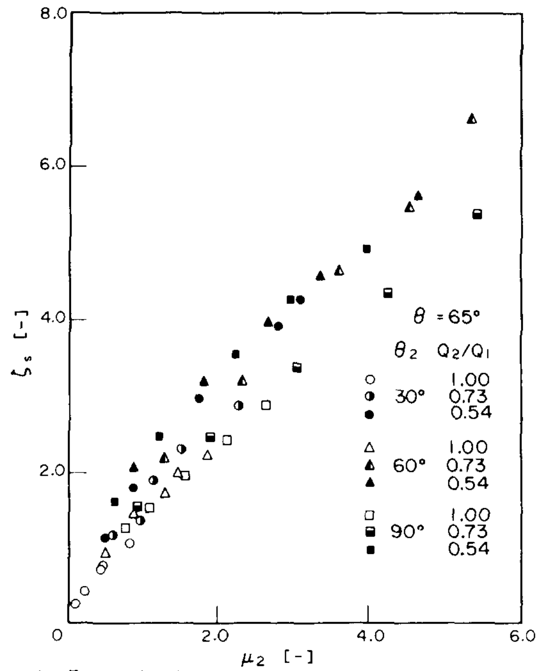

Figure 7. Coefficient of additional pressure drop due to solids for $\theta_1 = 65°$.

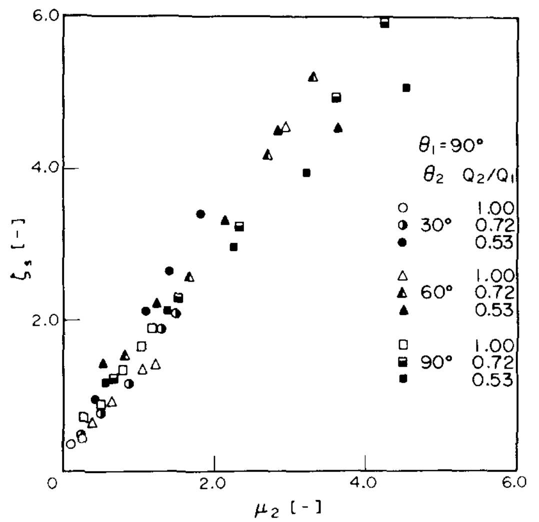

Figure 8. Coefficient of additional pressure drop due to solids for $\theta_1 = 90°$.

Referring to figures 9–11 the assumption is made that the solids distribution into the branched pipe II should depend on the projected area F_2 of pipe II at branch point on the plane vertical to the axis of the main pipe in figure 12. In figure 12 the area of surface OA is $(F_1/2)/\sin\{(\theta_1+\theta_2)/2\}$, where F_1 is cross-sectional area of pipe I. With this value the area F' of surface OB is represented as $F_1/2\{(\sin(\theta_1-\theta_2)/2)/\sin(\theta_1+\theta_2)/2)\}$. The area ratio F_2/F_1 is written therefore in the form

$$\frac{F_2}{F_1}=\frac{(F_1/2)+F'}{F_1}=\frac{1}{2}\left\{1-\left(\sin\frac{\theta_1-\theta_2}{2}\Big/\sin\frac{\theta_1+\theta_2}{2}\right)\right\} \qquad [8]$$

The ratio F_2/F_1 is thus determined only by the branch angles θ_1 and θ_2. The values of F_2/F_1 by [8] are shown in table 2. The solid lines in figures 9–11 represent [8]. Though the line designating area ratio deviates from the experimental values, one can expect that the solids distribution into the branched pipes should be determined approximately by the area ratio. As the result the

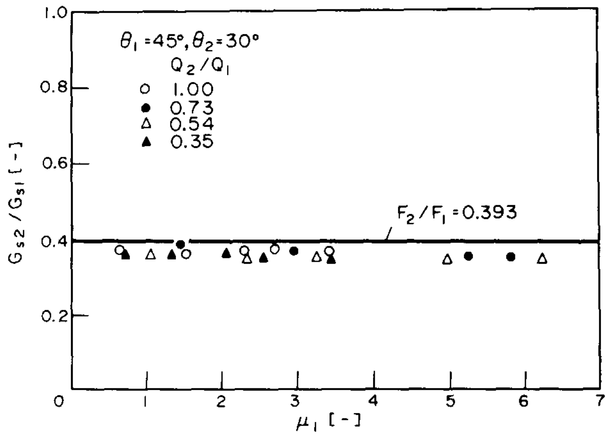

Figure 9. Solids distribution into the branched pipe for $\theta_1 = 45°$, $\theta_2 = 30°$ and $F_2/F_1 = 0.393$.

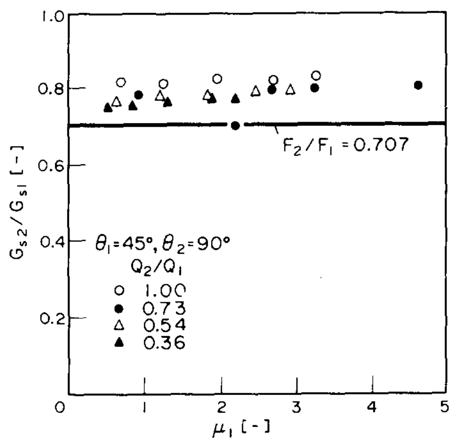

Figure 10. Solids distribution into the branched pipe for $\theta_1 = 45°$, $\theta_2 = 60°$ and $F_2/F_1 = 0.582$.

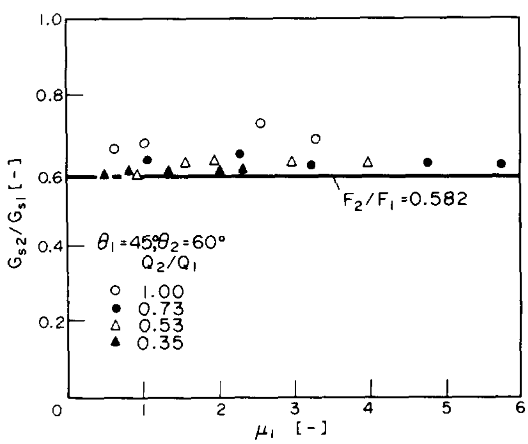

Figure 11. Solids distribution into the branched pipe for $\theta_1 = 45°$, $\theta_2 = 90°$ and $F_2/F_1 = 0.707$.

solids distribution into the branched pipes is shown in figure 13 as the function of F_2/F_1, which is independent of both solid–air loading ratio μ_1 and discharge ratio Q_2/Q_1.

5. CONCLUSION

From experimental results and the consideration of them the following information has been obtained about pressure drop and solids distribution of air–solid two-phase flow in the branching.

The coefficients of additional pressure drop for the flow from the main pipe I to the branched pipe II are independent of the branch angle of the branched pipe III and are shown as the function of both the branch angle and discharge ratio of air Q_2/Q_1. The coefficients of

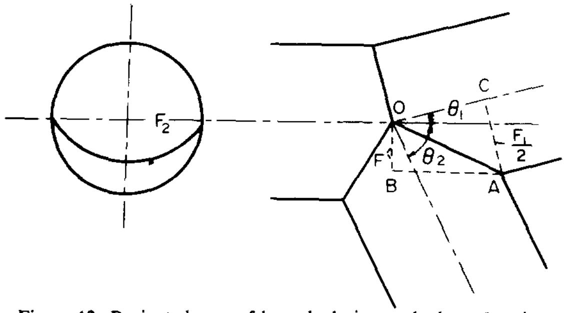

Figure 12. Projected area of branched pipe at the branch point.

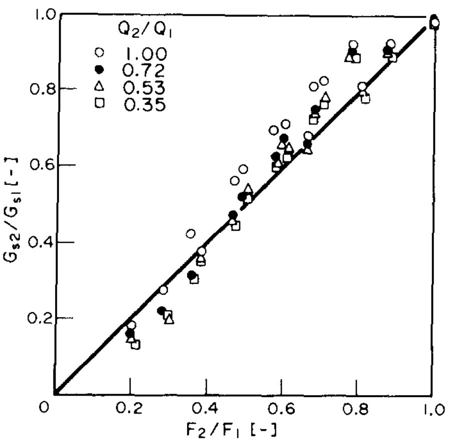

Figure 13. Relation between G_{s2}/G_{s1} and F_2/F_1.

Table 2. Values of F_2/F_1 for various combinations of branch angles

	θ_1	0°	30°	45°	65°	90°
$\frac{F_2}{F_1}$ θ_2	30°	1.0	0.5	0.393	0.296	0.211
	60°	1.0	0.683	0.582	0.475	0.366
	90°	1.0	0.789	0.707	0.611	0.5

additional pressure drop are proportional to the solid–air loading ratio in the branched pipe II.

For the solids size used in this experiment the solids distribution into the branched pipe is determined approximately by the geometric form at the branch point, i.e. by the combination of the branch angles θ_1 and θ_2, and independent of flow rate of solids in the main pipe and of discharge ratio of air.

These results should be useful in predicting the flow characteristics of air–solid two-phase flow in the branching.

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