ANALYSIS OF GAS - SOLID FLOW THROUGH DIFFUSERS

Part I : Theoretical Analysis

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Abstract:

This paper presents a theoretical investigation of compressible non - equilibrium gas - solids flows through diffusers of different geometries. A well established approach to the theory of compressible gas- solids flow, based on one - dimensional flow model, is used in the theoretical treatment. The assumption that the solid particles and the gas are in equilibrium; which usually used by previous investigators; is not used here, so the existence of velocity and temperature differences between the two phases necessitates a numerical solution of the governing equations. The flow properties such as; flow pressure, velocity and temperature of the gas and velocity and temperature of the solids were found to depend on the values of solids loading ratio, solids material density, particle diameter and diffuser angle.

1. INTRODUCTION

Flows in which solid particles are suspended in a gas stream arise in a variety of situations. A few of these are pneumatic conveying of granular solids, abrasive or crosive jets, pulverized fuel jets as applied to boilers and gas turbines, the nozzles of solid fuel rocket engines and the ingestion of sand by an air-intake-system air craft turbine which is responsible for blade erosion.

The performance of the turbo- jet or ram- jet power instellation depends to a large extent on the performance of the air-intake-system of which the subsonic diffuser is an important part. Most of previous investigations have been made on gas flow subsonic diffuser,[1-4] . Considerable literature exists on the flow of gas-solids mixtures at low velocities and the subject has been extensively reviewed by Torobin and Gauvin [5] . The recently increased interest in the field of gas-solids flows through nozzles has followed the use of metallic fuel constituents in rocket engines, and theories for the one-dimensional, compressible flow of gas-solids mixtures have been presented by Kliegel [6], Rudinger [7], Warda [8], and Hultberg and Soo [9]. Mobbs, et.al [10], studied the effect of initial velocity and temperature lags on the flow behaviour of a gas-solid suspension in a convergent - divergent nozzle, under subsonic and choked flow conditions.

In this presentation, theoretical investigations on subsonic gas - solid flow diffusers with total expansion angle of 10^0,20^0,25^o and 30^o are presented. The influence of solids mass loading ratio, particle material density and particle diameter are also examined.

1.1 Nomenclature

A	Diffuser cross - sectional area
a	Pure gas speed of sound
B	A constant in equation (5)
C_d	Particle drag coefficient
C_p	Specific heat of the gas at constant pressure
C_s	Specific heat of the solids
d	Particle diameter
J	Temperature lag parameter
K	Velocity lag parameter
K_g	Gas conductivity
L	Total length of diffuser
m_g	Mass rate of flow of gas
m_s	Mass rate of flow of solids
Nu	Particle Nusselt number
Pr	GAS Prandtl number
P	Pressure
R	Gas constant
Re	Particle Reynolds number
s	Distance in the downstream direction
T_g	Gas temperature
T_o	Mixture stagnation temperature
T_s	Solids temperature
u	Gas velocity
v	Solid particle velocity

X	Solids to gas mass flow ratio, (m_s/m_g)
ρ_g	Gas density
ρ_p	Density of solid particles
ρ_s	Distributed solids density
u	Gas viscosity

Suffix

1	Conditions at inlet to diffuser

2. THEORETICAL ANALYSIS

2.1. Basic Assumption

The assumptions on which the analysis is based are as follows;

1- The flow is one-dimensional and steady

2- The gas is a perfect gas with a constant composition

3- The particles are spherical, smooth and of constant density and specific heat

4- The particles do not interact and are uniformly distributed. Brownian motion of the particles does not contribute to the pressure of the system

5- The flow is adiabatic with no mass transfer between the flow and its surroundings or between the two phases

6- The temperature of a particle is uniform through-out owing to its high thermal conductivity (compared to that of the gas)

7- The volume occupied by particles is small enough to be neglected

8- Thermal energy exchange between solids and gas occurs by convection

9- Drag forces are the only forces accelerating or decelerating the particles

2.2. Governing Equations

With the above assumptions and referring to Fig (1), the equations governing the flow and energy transfer in the diffuser are:

Gas continuity: $m_g = \dot{\rho}_g . A . u$ (1)

Solids continuity: $m_s = \rho_s . A . v$ (2)

Gas equation of state : $P = \rho_g . R . T_g$ (3)

Overall momentum equation:

$$m_g(u_1 + Xv_1) - m_g(u + Xv) + P_1A_1 - PA + \tfrac{1}{2}\,(P_1 + P)(A - A_1) = 0 \qquad (4)$$

Overall energy equation :

$$C_pT_g + u^2/2 + X(v^2/2 + C_sT_s) = (C_p + XC_s)\,T_o = B/2 \qquad (5)$$

Particle momentum equation :

$$dv/ds = 3/4\ .\ C_d.\rho_g.\ (u-v).|u-v|\ /\ (\rho_p.d.v) \qquad (6)$$

Particle heat transfer equation :

$$dT_s/ds = 6.Nu.K_g.(T_g - T_s)/\ (\rho_p.C_s.v.d^2) \qquad (7)$$

Now , let

$$Z = m_g(u_1 + Xv_1) + (P_1A_1) + \tfrac{1}{2}\,P_1(\ A - A_1)$$

and,

$$Y = 2A\ /\ (\ A + A_1)$$

Combining equations (1) , (3) and (4) and eliminating T_g by use of equation (5), gives the following expression for the gas velocity;

$$u = \frac{-H \pm \sqrt{H^2 + 2FN}}{F} \qquad (8)$$

where,

$$H = \frac{Y\ Z}{m_g.R} - \frac{XYv}{R}$$

$$F = 2(\ 1/2C_p - Y/R)$$

$$N = \frac{B - X(\ v^2 + 2\ C_s\ T_s)}{2\ C_p}$$

The ± sign in equation (8) indicates that two values of u are possible. The proper value is selected so that the solution is for subsonic flow through diffuser.

2.3. Particle drag coefficient and Nusselt number

The following approximation to the "standard drag curve", used by Mobbs, et.al. [10] ,will be used here.

$C_d = 24\ /Re$ for $Re < 0.1$

$C_d = (24 + 0.379\cdot\ Re^{0.67})/Re$ for $0.1 < Re < 500$

$C_d = 2.63\ /\ Re^{0.26}$ for $500 < Re < 1000$

$C_d = 0.44$ for $Re > 1000$

Where,

$$Re = \rho_g.(\ u - v\ ).d\ \ /\ \ u$$

The Nusselt number was taken according to, [10] as follows;

$$Nu = 2 + 0.459\ Re^{0.55}.\ Pr^{0.33}$$

Where, Pr is the gas Prandtl number , taken to be 0.7 throughout.

2.4. Specification of diffuser inlet conditions

The temperature and velocity lags are defined by the parameters;

$$J = (T_s - T_o)/(T_g - T_o) \qquad (9)$$

and

$$K = v/u \qquad (10)$$

These parameters were originally introduced by Kliegel [6] in a constant fractional lag analysis of nozzle flow and by Mobbs, et.al. [10] in a convergent - divergent nozzle flow.

In order to specify the inlet conditions of diffuser, it is assumed that the gas - solid mixture is expanded, from the mixture stagnation temperature T_o ,i.e. with a constant overall energy flow rate. If X,J,K and T_o are fixed, the overall energy equation can be used to determine the gas temperature T_g for any value of the gas mass flow rate. The gas velocity and remaining gas parameters can then be determined from the equations of gas continuity and state. The solids velocity and temperature are determined from Eqs (9) and (10).

2.5. Diffuser profile and choice of solid

The computer program was arranged so that any area profile could be used provided it can be expressed as a function of the axial distance from the diffuser inlet. Two particle materials, were used in the present work. These were polystyrene and glass spheres, which usually used in the practical work.

2.6. Method of computations.

Eqs (6) and (7) were integrated, in the first instance; over a step length; starting from one step after the known inlet conditions, to obtain the solids velocity and temperature at each step. This integration was carried out using a 4 th order 5- stage Runge- Kutta - Merson method. New values of the remaining gas parameters can then be calculated from Eqs (1),(3) and (5), and the process repeated.

3. RESULTS AND DISCUSSION

The computed results show the variation of gas velocity, gas temperature, pressure, solids velocity and solids temperature along the diffuser axis.

3.1. An investigation of the effects of varying the solids loading ratio.

Fig (2) shows this investigation, where the following assumptions were taken during the computation; T_o= 300 k°, ρ_p= 1060 kg/m^3 (polystyrene), d= 250 μ, C_s= 1340 J/kg.k°, m_g=0.120 kg/s., the initial value of K and J were kept constant and equal to 0.95 and the dry air was used as the gas phase. From this figure it can be seen that, the variations of pressure and temperature increase when the solids added to the air and the variations of gas velocity and solid velocity decrease with an increase in the amount of solids in the mixture. These trends result from the particle drag and heat transfer being increased because there are a large number of particles present at the higher solids loading.

3.2. An investigation of the effect of varying the diffuser total angle.

Fig (3) shows the variation of pressure, gas temperature, solid temperature, gas velocity and solid velocity along the diffuser axis, for 10°,20°, 25° and 30° diffusers. It is assumed that X = 0.6 and that all other coditions are the same as in Fig (2).

From this figure it can be seen that, the flow properties are affected by the design value of diffuser angle. The 30° diffuser has a heighst value of thermal stresses than the other diffusers. The variations of gas temperature and solid temperature are increase, while the gas velocity and solid velocity are decrease along the diffuser axis with an increase of diffuser angle. This may be due to an increase of the variation of flow area.

3.3. An investigation of varying the solids material density.

In order to investigate the effect of varying the solids material, the polystyrene powder is assumed to be replaced by glass spheres in the calculations. The glass sphere was chosen as the alternative solid phase to facilitate comparisons between the results obtained from the two types of powders, and also because the glass sphere has a density about 2.5 times that of polystyrene. Fig (4) shows this comparison, for a suspension having X= 0.5. All other conditions are the same as in Fig (2).

From this figure , it can be seen that the pressure and temperature curves have a higher value with increasing solid material density (glass spheres). While the solids and gas velocities have a lower values than those for polystyrene powder, i.e. the velocity profiles are influenced by changing the particle properties, but thereis no change in their characteristic shape. All these effects, due to change of powder material, can be explained as being due to an increase in the solid material density, for a given solids loading ratio, reducing the number of particles present, This has the effect of reducing the heat transfer rate and the total particle drag force which is reflected in the variation of flow properties.

3.4. Effect of varying the particle diameter.

Fig (5) shows the effect of varying the particle diameter on the flow behaviour through the 20° diffuser. The solids loading ratio is $X = 3.0$ and the other conditions are the same as in Fig (2). From this figure it can be seen that the particle diameter has a significant effect on the flow properties, where the pressure, gas temperature and solid velocity are increase with a decrease in the particle diameter. While the gas velocity and solid temperature are decrease with a decrease in the particle diameter. These results can be explained as follows; for a given solids loading and solids density an increase in particle diameter results in a reduction in the number of particles present with consequences similar to those due to increasing the solids density. An additional factor in this case is the increase in particle Reynolds number due to an increase in diameter. This means a decrease in drag coefficient and an increase in Nusselt number. The drag per particle is therefore reduced and the heat transfer per particle increased for the same relative velocity. The results, however, indicate that the reduction in the number of particles is the more important factor.

4. CONCLUSIONS

A theory for a compressible non-equilibrium gas - solids flows through a subsonic diffuser has been developed, assuming that the flow is one-dimensional. The powders were found to have a significant effect on the diffuser performance, i.e. the flow properties through the diffuser such as; pressure, gas velocity, solid velocity, gas temperature and solids temperature were found to depend on the amount of solids in the mixture, particle material density, particle diameter and the diffuser angle. The results indicate also that the reduction in the number of particles in the mixture is the more important factor. The thermal stresses were found to increase with an increase in the diffuser angle. Finally, the success or otherwise of the theoretical model used here will be proved by comparing the results of the numerical computation with the experimental results, which will be discussed in the next part of this paper, part II.

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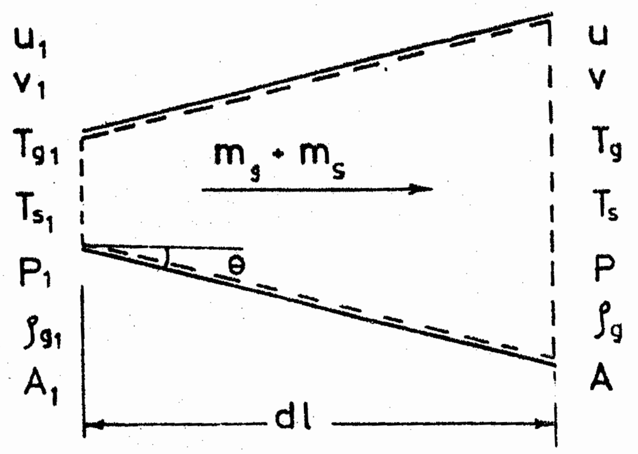
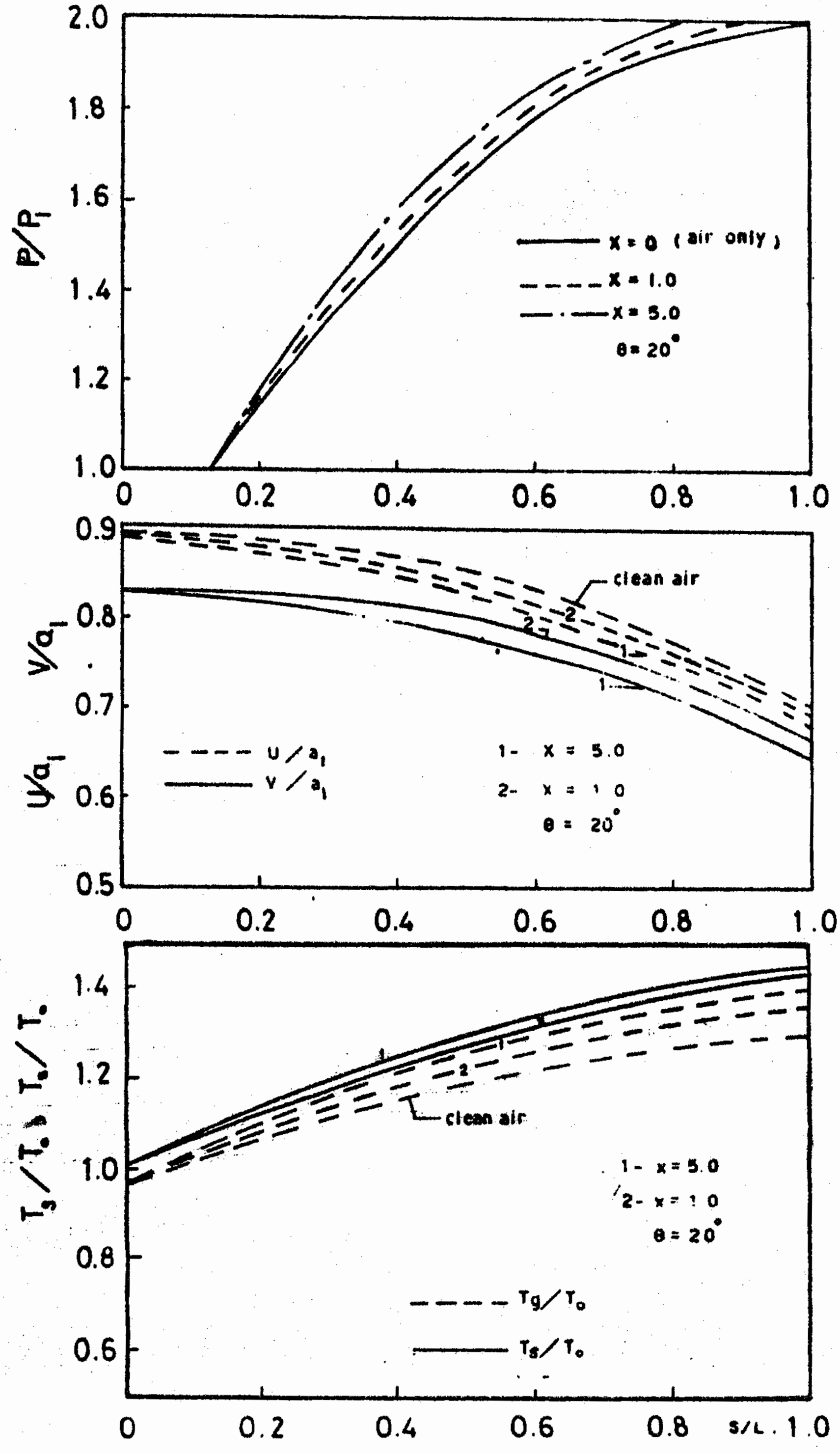
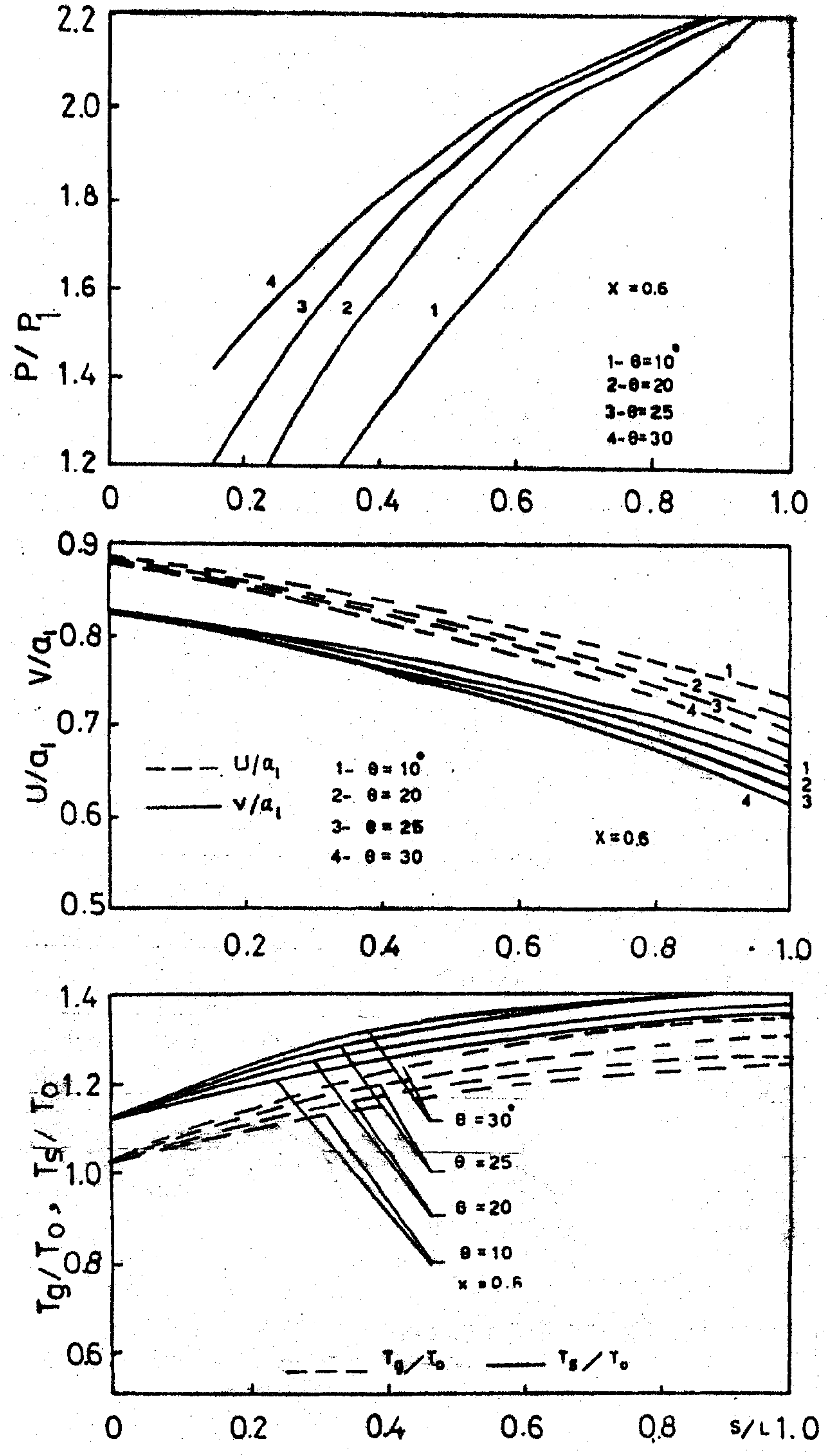


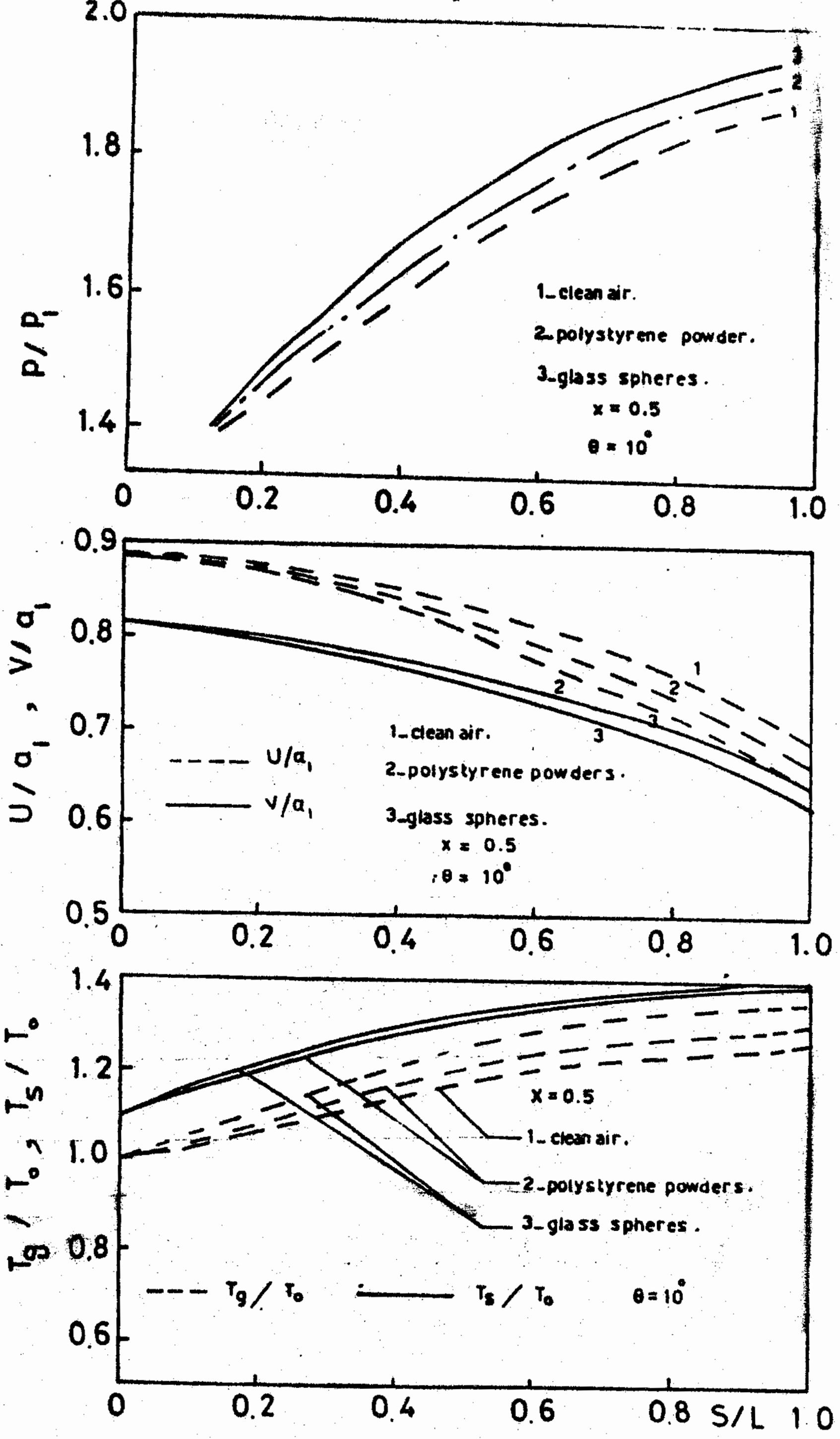
FIG(1) AN ELEMENTAL LENGTH OF THE FLOW



FIG(2) EFFECT OF VARYING THE SOLIDS LOADING RATIO



FIG(3)EFFET OF VARYING THE DIFFUSER TOTAL ANGLE



FIG(4) EFFECT OF VARYING THE SOLIDS MATERIAL DENSITY

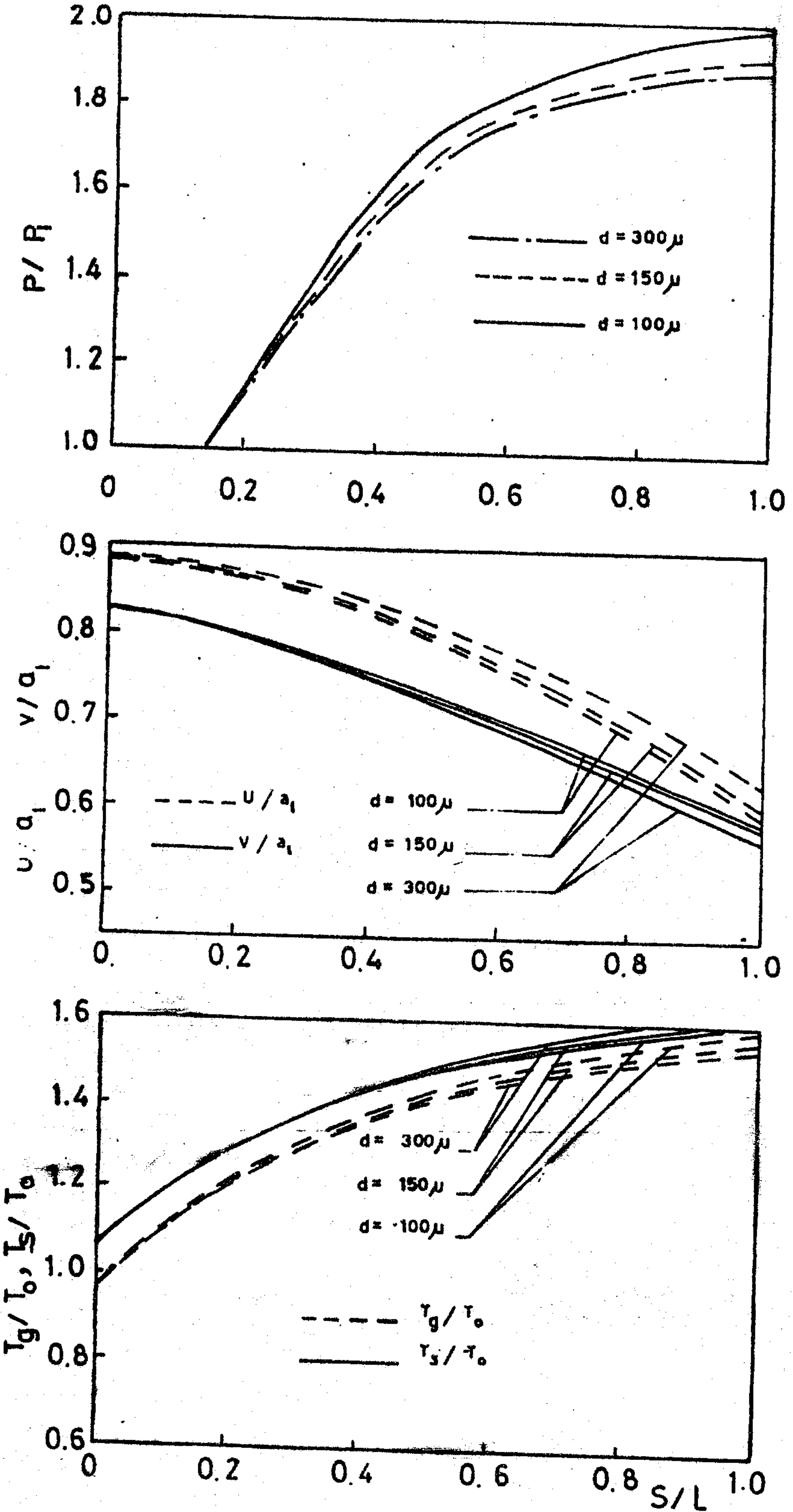


FIG (5) EFFECT OF VARYING THE PARTICLE DIAMETER