Engineering Turbulence Modelling and Experiments 2
W. Rodi and F. Martelli (Editors)

Modelling of Turbulent Dispersion in Two Phase Flow Jets

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Abstract

The paper describes the application of a turbulence model especially developed for two-phase flows to the prediction of dispersion of particles in co-axial confined air jets.

In this model, the transport equations describing dispersed two-phase flow in an Eulerian frame are ensemble averaged using phase-fraction weighted quantities. A number of terms arise from the averaging process in two-phase flow in addition to those which result from a similar averaging process in single-phase flow. The effect of these additional terms on the prediction of particle dispersion is evaluated by comparing calculations with existing data for the case of two co-axial jets, one of which is particle laden.

The results show that two terms in the averaged equations are mainly responsible in determining the computed rate of dispersion. They also show that the assumed particle response to eddy fluctuations has a marked influence on these predictions.

1. INTRODUCTION

There are a number of two-phase flow phenomena in engineering for which reasonable predictions cannot be obtained by application of single-phase turbulence models; such models do not account for the dispersion of one phase into the other by the action of the eddies. Two-phase flow models have been developed in the recent past and the present work is concerned with the development and assessment of one such model.

The base model was proposed by Gosman et al (1989) and developed and implemented by Politis (1989). It is based on the two-fluid concept (Ishii 1975) in which transport equations are formulated for each of the phases. These equations are then ensemble averaged using the phase-fraction as a weighting quantity for the averaging of all other fluctuating quantities; this is akin to Favre averaging in variable density flow. Such an averaging process possesses the distinct advantage of leading to equations with far less terms than what is obtained from straight ensemble averaging (e.g. Elghobashi & Abou-Arab 1983). The model employs the eddy viscosity concept and equations for k and ε are derived also using phase-fraction weighting.

Correlations appear in the averaged equations which involve fluctuations of both the continuous and dispersed phase velocities. Such terms are modelled with the aid of the assumption that the dispersed velocity fluctuation is directly proportional to that of the continuous phase, the proportionality factor (C_t) being obtained from a consideration of the response of a single particle traversing an eddy.

The objective of this paper is to assess and develop the two-phase turbulence model mentioned above. The equations involved are solved by a numerical finite-volume

methodology which is detailed by Oliveira (1992) and need not be described here. The method was applied to the problem of a two-phase particulate jet formed by an inner air jet laden with solid particles, confined by an external low-velocity unladen air stream. The numerical results obtained after the systematic inclusion of each term of the extended turbulence model were compared with experimental measurements of Hishida & Maeda (1991) thereby enabling an assessment of the more important factors in the turbulence model.

This assessment shows that some of the extra terms in the turbulence model are required in order to predict dispersion of the particle phase; however, additional refinement of the model is still needed for predicting this dispersion accurately.

2. EQUATIONS AND TURBULENCE MODELLING

The extension of the single-phase k-ε turbulence model to two-phase flows is now presented. This is done by introducing into the equations of motion, turbulence kinetic energy (k) and dissipation (ε), the additional terms resulting from correlations of volume fraction and velocities. This follows the work of Gosman et al (1989) and Politis (1989).

2.1. The α-weighted, ensemble-average equations of motion

These are based on the Eulerian treatment of both phases, following the two-fluid model (Ishii 1975). The continuity and momentum equation obtained after applying a double averaging procedure (volume-average followed by ensemble-average) to the usual single-phase equations can be written as (Oliveira 1992):

$$\rho_k\left(\frac{\partial}{\partial t}\bar{\alpha}_k + \nabla.\bar{\alpha}_k\,\tilde{u}_k\right) = 0 \tag{1}$$

$$\rho_k\left(\frac{\partial}{\partial t}\bar{\alpha}_k\tilde{u}_k + \nabla.\,\bar{\alpha}_k\,\tilde{u}_k\,\tilde{u}_k\right) = -\,\bar{\alpha}_k\nabla\tilde{p} + \bar{\alpha}_k\nabla.\,\tilde{\tau}_k + \nabla.\bar{\alpha}_k\tilde{\tau}^t_k + \rho_k\bar{\alpha}_k\,\tilde{g} + \overline{F_{D_k}} \ . \tag{2}$$

In these equations the subscript k denotes the phases (c for the continuous and d for the dispersed) and ρ, α, p, u and τ are the density, volume-fraction, pressure, velocity vector and stress tensor. The turbulent stresses are denoted with a superscript t. The interphase momentum exchange is represented by F_D, resulting from the action at the interface of the pressure forces (F_p) and viscous stresses (F_τ). The sum of F_τ with part of F_p can be identified as the usual drag force, whereas the remaining part of F_p contributes to the virtual mass and inviscid lift forces, which will not be considered here. The reason for neglecting these terms is based on an order-of-magnitude analysis for the case of particle laden air jets where $\rho_d/\rho_c \sim 10^3$. In equations (1) and (2) the overbar is used, as usual, to denote ensemble-averaging. The symbol ~ is used to denote α-weighted averaging, which is similar to Favre averaging used in variable density single-phase flows. The definition of α-weighted averaging is:

$$\tilde{\phi} = \overline{\alpha\,\phi}\,/\,\bar{\alpha} \ , \tag{3}$$

where ø represents any phase averaged quantity (i.e. one obtained after the first volume-average operation) and which may be split into a mean plus a fluctuating value, as:

$$\phi = \tilde{\phi} + \phi'' = \bar{\phi} + \phi'$$

The expression for the turbulent stress in the momentum equation (2) is:

$$\tilde{\tau}_k^t = - \frac{\overline{\rho_k \alpha_k (u'' u'')_k}}{\overline{\alpha_k}} . \tag{4}$$

2.2. Main modelling assumptions

To solve the momentum equation for each phase it is necessary to define the correlations appearing in those equations. The turbulent stress (eqn. 4) for each phase is modelled following the Boussinesq approximation:

$$\tilde{\tau}_k^t = \mu_k^t (\nabla \tilde{u}_k + \nabla \tilde{u}_k^T) - \frac{2}{3} (\mu_k^t \nabla . \tilde{u}_k + \rho_k \tilde{k}_k) \delta , \tag{5}$$

where δ is the identity tensor. For the continuous phase, the turbulence kinetic energy $\tilde{k}_c$ will be obtained from its own transport equation and the turbulent viscosity $\mu_c{}^t$ is given by the k-ε model, as explained in section 2.5. On the other hand, the dispersed phase turbulent viscosity and kinetic energy need to be specified as functions of the respective continuous phase values. To do this, and to develop all the correlations, two main model assumptions are required.

The first is the gradient diffusion for the transport of volume fraction by velocity fluctuations:

$$\overline{\alpha_c u_c'} = - \eta_c \nabla \bar{\alpha}_c , \tag{6}$$

$$\overline{\alpha_d u_d'} = - \eta_d \nabla \bar{\alpha}_d . \tag{7}$$

In these equations η is the turbulent diffusivity of α which will be obtained from $\eta_c = \nu^t/\sigma_\alpha$, with the "Schmidt" number here taken as unity, $\sigma_\alpha = 1$.

The second main model assumption (introduced by Gosman et al 1989) links the instantaneous velocity fluctuations of one phase to the velocity fluctuations of the other. This is a key point in the modelling and it is expressed as:

$$\frac{u_d'}{u_c'} = C_t , \tag{8}$$

where the turbulence correlation function C_t is given by:

$$C_t = 1 - \exp (- t_\varepsilon / t_p) . \tag{9}$$

Expression (9) is derived from the integration of the Lagrangian equation of motion of a particle:

$$\frac{du_d'}{dt} = \frac{(u_c' - u_d')}{t_p}$$

subject to the initial condition $t = 0$, $u_d' = 0$, and where the relaxation time and the fluid fluctuating velocity are assumed constant. The two time scales in eqn. (9) are the eddy lifetime (t_ε) and the particle relaxation time (t_p), which take the forms:

$$t_\varepsilon = 0.4\left(\frac{k}{\varepsilon}\right) \tag{10}$$

$$t_p = \Big((1 - \alpha_d) / A_D\Big)\ (1 + C_M \frac{\rho_c}{\rho_d}) \tag{11}$$

where the drag factor A_D is given in the next section and the virtual mass coefficient C_M takes the value 0.5. Note that the virtual mass effect is important in eqn. (11) regardless of whether it is included in the averaged momentum eqn. (2) or not.

Typical values of relaxation time is 28 ms for the present particulate flow ($d_p = 64\ \mu$, $u_{r\infty} = 0.28$ m/s, $Re_p \simeq 1$).

It can also be shown that the two diffusivities in eqns. (6) and (7) are related by:

$$\eta_d = C_t \eta_c . \tag{12}$$

For responsive particles $C_t = 1$, and the two diffusivities are identical.

2.3 Modelling the drag force

Drag is modelled assuming that the dispersed phase is composed of many small spherical particles which do not interact with each other - this interaction is absorbed into the dispersed phase stress tensor. This is true for the low volume-fractions encountered in most particle laden jets ($\alpha \equiv \overline{\alpha}_d \sim 10^{-4}$). The drag force is first linearised and modelled as:

$$\overline{F_{D_c}} = F_D\,(\overline{u}_d - \overline{u}_c) \tag{13}$$

where

$$F_D = A_D \rho_d \overline{\alpha}_d\ , \quad \text{and } A_D = (\frac{3}{4}\rho_c u_r C_D) / (d_p \rho_d). \tag{14}$$

In these expressions, u_r is the relative or slip velocity ($u_r = ||u_d - u_c||$), d_p is the particle diameter, and the drag coefficient C_D is given as a function of the particle Reynolds number ($Re_p = u_r d_p / \nu_c$, $\nu_c = \mu_c / \rho_c$) by an empirical relationship such as:

$$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687}). \tag{15}$$

Unlike the work of Gosman et al (1989) and others such as McTigue (1983) the drag term is here modelled after, and not before, the second (ensemble) averaging operation; the result

however is the same. Now, since ultimately the velocities solved for are the α-weighted ones it becomes necessary to transform $\overline{u}$ into $\tilde{u}$. This can be done by using the usual Favre-average relations (see eqns. (3) (6) and (7)), to obtain:

$$\overline{F_{D_c}} = A_D \rho_d \overline{\alpha}_d (\tilde{u}_d - \tilde{u}_c) + (A_D \rho_d \eta_c / \overline{\alpha}_c) \nabla \overline{\alpha}_d , \tag{16}$$

where it has been assumed that the two diffusivities η_d and η_c are equal. It can be seen that the drag is composed of the usual mean drag plus a contribution proportional to the void-fraction gradient which arises from turbulent fluctuations of α and u. The contribution of the "turbulent drag" can be quite important, mainly in the radial direction where volume-fraction gradients are high and the mean drag is small.

2.4. Modelling the dispersed phase turbulent stress and kinetic energy

The expression for the turbulence kinetic energy of the dispersed phase is:

$$\tilde{k}_k = \frac{1}{2} \frac{\overline{\alpha_k (u'' . u'')_k}}{\overline{\alpha}_k} , \tag{17}$$

which is somewhat similar to the expression for $\tau_d{}^t$ (eqn. 4). The simplified expressions to be used for k_d and $\tau_d{}^t$ turn out to be:

$$\tilde{k}_d = C_k \tilde{k}_c , \tag{18}$$

$$\tilde{\tau}_d^t = C_k \frac{\rho_d}{\rho_c} \tilde{\tau}_c^t \tag{19}$$

where $C_k = C_t^2$. The turbulent kinematic viscosity of the dispersed phase is obtained by comparing eqn. (19) with the Boussinesq stress model (eqn. 5) to obtain:

$$\nu_d^t = C_v \nu_c^t \tag{20}$$

where again $C_v = C_t^2$.

2.5. The k and ε equations and the modelling of the additional terms

The α-weighted equations for the transport of turbulence kinetic energy (k) and its rate of dissipation (ε), for the continuous phase, are written as:

$$\rho_c \left(\frac{\partial}{\partial t} \overline{\alpha}_c \tilde{k}_c + \nabla . \overline{\alpha}_c \tilde{u}_c \tilde{k}_c \right) = \nabla . (\overline{\alpha}_c \frac{\mu_c^t}{\sigma_k} \nabla \tilde{k}_c) + \overline{\alpha}_c (G - \rho_c \tilde{\varepsilon}_c) + S_d^k \tag{21}$$

$$\rho_c \left(\frac{\partial}{\partial t} \overline{\alpha}_c \tilde{\varepsilon}_c + \nabla . \overline{\alpha}_c \tilde{u}_c \tilde{\varepsilon}_c \right) = \nabla . (\overline{\alpha}_c \frac{\mu_c^t}{\sigma_\varepsilon} \nabla \tilde{\varepsilon}_c) + \overline{\alpha}_c \frac{\tilde{\varepsilon}_c}{\tilde{k}_c} (C_1 G - C_2 \rho_c \tilde{\varepsilon}_c) + S_d^\varepsilon . \tag{22}$$

These equations are a standard generalisation of the single-phase k-ε model (Jones and Launder 1972) applied to the continuous phase, except for the additional terms S_d which account for the interaction between dispersed and continuous phase turbulence. The turbulent or eddy viscosity and the generation of $\tilde{k}$ are computed from:

$$\nu_c^t = C_\mu \frac{\tilde{k}_c^2}{\tilde{\varepsilon}_c}, \tag{23}$$

$$G = \mu_c^t \nabla \tilde{u}_c . (\nabla \tilde{u}_c + \nabla \tilde{u}_c^T), \tag{24}$$

and the constants used in the present work are the standard ones ($C_1 = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.22$).

The additional drag-related source terms in the k and ε equations arise from the time average of the inner product between the instantaneous drag force and the fluctuating continuous-phase velocity. This term when expanded and then modelled using the preceding assumptions becomes:

$$S_d^k = - F_D \left(\frac{\eta_c}{\overline{\alpha}_c \overline{\alpha}_d} (\tilde{u}_d - \tilde{u}_c) . \nabla \overline{\alpha}_d + 2 \tilde{k}_c (1 - C_t) \right) \tag{25}$$

The main contribution for S_k is given by the last term in eqn. (25), which constitutes a sink of turbulence energy because $C_t \leq 1$. It will induce a dissipation equal to the term divided by the turbulence time scale (k/ε). Hence the additional source in the ε-equation is modelled as:

$$S_d^\varepsilon = - C_3 \frac{\tilde{\varepsilon}_c}{\tilde{k}_c} F_D 2 \tilde{k}_c (1 - C_t), \tag{26}$$

where the model coefficient C_3 is taken as unity.

2.6. Alternative models for C_t

Initial computations by Issa and Oliveira (1991) with the model of Gosman et al (1989) for the case of particle laden jets treated herein showed that the rate of dispersion of particles was grossly underpredicted by the model. A subsequent study revealed that two terms in the model play the dominant role in determining the dispersion rate; these are:

$$-\frac{2}{3} \nabla (C_k \rho_d \overline{\alpha}_d \tilde{k}_d) \quad \text{and} \quad - (F_D \nu_c^t / \sigma_a \alpha_c \alpha_d) \nabla \overline{\alpha}_d$$

both of which arise in the dispersed phase momentum equations. The first originates from modelling the turbulent stresses (eqn. (5)) and the second results from considering the fluctuation of the drag term (eqn. (16)). The magnitudes of these terms affect the transverse dispersed phase velocities and thereby the rate of dispersion of that phase.

Both of the above terms depend on the value of the particle response coefficient C_t (eqns. (18) and (20)). This suggests that the dispersion rate is closely linked to the value of C_t as indeed was discovered by numerical experimentation with different models for calculating C_t.

Those tried were amongst the models found in the literature that are listed below:

$$C_{t_1} = 1 - \exp(-t_\varepsilon / t_p) \qquad \text{(Gosman et al)}$$

$$C_{t_2} = \left[1 + t_p / t_\varepsilon\right]^{-1} \qquad \text{(Faeth 1987)}$$

$$C_{t_4} = \left[1 + 0.45\, u_r^2 \Big/ \left(\frac{2}{3}k\right)\right]^{-1/2} \qquad \text{(Csanady 1963, Picart et al 1986)}$$

$$C_{t_5} = \left[1 + t_p / (C_{t_4} t_\varepsilon)\right]^{-1} \qquad \text{(Simonin 1991)}$$

$$C_{t_6} = \left[1 + 0.45\, u_r^2 \Big/ \left(\frac{2}{3}k\right) / C_{t_2}\right]^{-1/2} \qquad \text{(Mostafa \& Mongia 1987)}$$

Furthermore, many workers use values for C_k and C_v in eqns. (18) and (20) that are different from $C_{t_1}{}^2$ as proposed by Gosman et al (1989). For example, Melville & Bray (1979) use C_{t_2} for both C_k and C_v, Chen & Wood (1985) take C_{t_2} for C_v whereas Mostafa and Mongia (1987) use C_{t_2} for C_k. These alternatives have also been tried in the present work.

3. RESULTS

The geometry to which the model is applied consists of two vertical co-axial pipes (Fig. 1): the inner pipe carries a mixture of glass sphere particles and air; the outer pipe is used to confine the jet and carries a lower velocity air-stream. The inner pipe diameter is D = 13 mm (R = D/2) and the diameter of the outer pipe is D_2 = 60 mm. For the numerical simulation the length of the domain (along x) was taken as 45 times the inner diameter (D).

The physical properties are: ρ_c = 1.18 Kg/m^3, μ_c = 1.8 10^{-5} Kg/(m.s), ρ_d = 2590 Kg/m^3. The average particle diameter is 64.4 μm.

The inlet profiles of axial and radial velocity, and of turbulence kinetic energy are given by the experimenters (Hishida & Maeda 1991). The centre-line mean values at inlet are: U_{c_o} = 29 m/s, U_{d_o} = 23 m/s, and α_o = 2.5 10^{-4}. The air velocity in the outer pipe at inlet (U_2 in Fig. 1) is almost constant at 15.6 m/s as could be observed from the measured velocity profile.

The numerical mesh overlaying the 2-D (axial-radial) physical domain consisted of 50 x 48 non-uniformly distributed internal cells. The overall dimensions of the solution domain are 600 mm x 30 mm (axial and radial directions) and is bounded by an inlet (x=0), outlet (x=0.6 m), axis of symmetry (y=0) and wall (y=0.03 m). The mesh is more concentrated in the region between the axis and the line y=6.5 mm (y=R), which is the radius of the inner jet at inlet, and then expands in the direction of the outer wall, where it contracts again.

Fig. 2 shows the radial profiles of the particle flux (which is a measure of the phase fraction) normalised by its centre line value at two axial stations. Calculations with the

standard model of Gosman et al (with $C_v = C_t^2$ as defined in eqn. (20)) can be clearly seen to underpredict the dispersion effect exhibited by the data. An attempt to enhance the dispersive mechanism by taking $C_v = 1$ gives some improvement but not quite what is sought. This can be explained by examining the quantities responsible for the particle dispersion: the magnitudes of the fluctuations of the dispersed phase. Fig. 3 shows the profiles of the rms fluctuations of the radial and axial velocities respectively at the second measuring station. The first thing to note is the anisotropy of the turbulence which could not be captured by the present k and ε model. However, this is only part of the reason why the predictions with the standard model (with $C_k = C_{t_1}^2$ as defined in eqn. (18)) give too low a spread rate. From Fig. 3 it is apparent that the fluctuations which are responsible for the dispersive effect are grossly underpredicted. It takes the use of C_{t_2} and C_{t_4} for C_k (see section 2.6) to increase the computed fluctuations up to the measured levels of v_d' and u_d'.

In Fig. 4, the profiles for the normalised particle flux at the two axial stations are displayed for different formulations of C_k. Comparison with the data shows that like C_{t_1} as suggested by Gosman et al, C_{t_2} also gives too low a dispersion rate. On the other hand C_{t_4} (see section 2.6) yields too high a value. The sensitivity of the predictions to the value of C_k can also be gleaned from the predictions when C_k is chosen to be 0.5 C_{t_4}; the dispersion rate is now much lower than what is measured suggesting that further refinement of the model for calculating C_t is essential in order to predict the real behaviour better.

4. CONCLUSIONS

The paper presents developments and application of a turbulence model for two-phase flows. The model is applied to the prediction of a particle-laden jet flow which is a convenient problem for model assessment since the dispersion of the particles is mainly due to turbulence effects. This model leads to additional terms in the equations as compared with the standard k-ε model applied to the continuous phase. Such terms were introduced systematically in the equations and the resulting predictions were analysed and compared with data. The main conclusions from this study are:

1. The standard model of Gosman et al (1989) predicts dispersion of the particle-phase; however the dispersion is under-predicted, as revealed by a comparison with measured particle-flux profiles.
2. The main terms promoting dispersion are the turbulent drag and the $-2/3\nabla C_k \alpha k$ term in the dispersed-phase radial momentum equation; in this last term, C_k should be higher than the function $C_{t_1}^2$ as mentioned earlier and smaller than 1.
3. The dispersed-phase eddy-viscosity obtained by setting $\nu_d^t = C_{t_1}^2 \nu_c^t$ appears to be too small; with such small $\nu_d^t (\approx 0)$ the results become very sensitive to the imposed radial velocity for both phases at inlet. With higher ν_d^t (either $\nu_d^t = \nu_c^t$ or $\nu_d^t = C_{t_4} \nu_c^t$), the results are not sensitive to the given inlet radial-velocities.
4. If the C_t-function used in the term $-2/3\nabla C_k \alpha k$ is too high (e.g. $C_k = C_{t_4}$), an overshoot of the distribution of α along the axis occurs close to inlet ($x/D \leq 5$). This overshoot is

more accentuated if ν_d^t is small. However, even for medium or high ν_d^t the overshoot is present, although less accentuated. Use of $C_k=C_{t_1}$ or $C_k=C_{t_2}$ (related to inertia effects only) under-predict the dispersion; use of $C_k=C_{t_4}$ (related with crossing-trajectories effect) yields over-predictions. This suggests use of a C_t-function for C_k which takes into account both effects (inertia and crossing-trajectories).

5. The predictions of particle-dispersion are much improved with the modifications to the C_t-functions mentioned above; agreement with the particle-flux data (and also with α) is still not perfect but it is similar to other authors (in Sommerfeld & Wennerberg 1991). Further improvement could be obtained by using a Schmidt number σ_α smaller than 1 in the turbulence drag term (as Simonin 1991).

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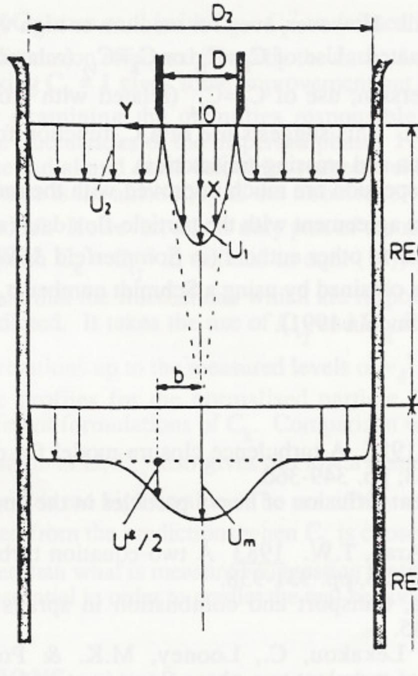

Fig. 1 Experimental Flow Configuration

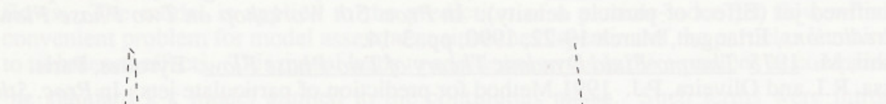

Fig. 2 Radial Profiles of the Normalised Particle Flux at Two Axial Stations with Different C_ν

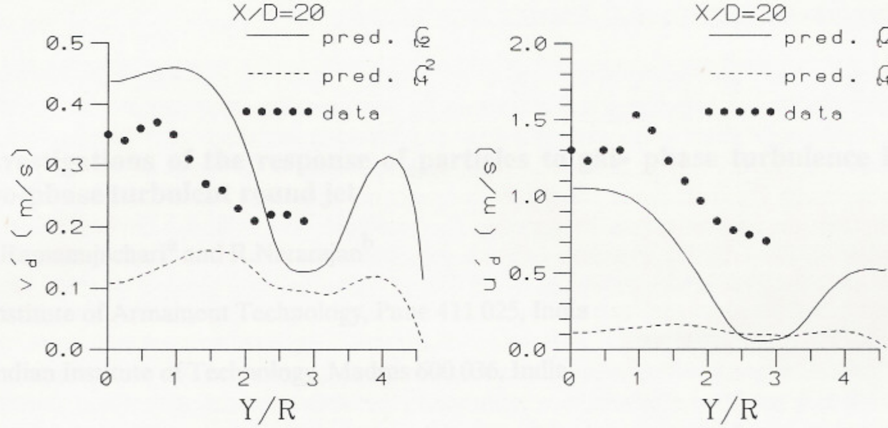

Fig. 3 Radial Profiles of the RMS Fluctuating Dispersed Phase Velocities

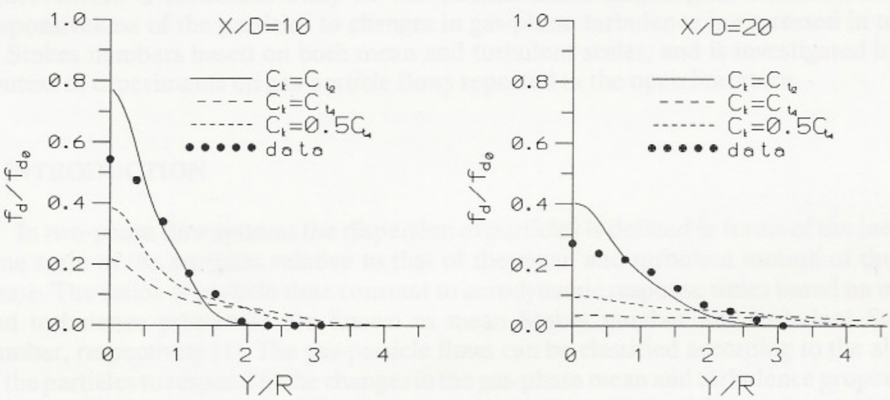

Fig. 4 Radial Profiles of the Normalised Particle Flux at Two Axial Stations with Different C_k