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A NEW MODEL FOR GAS/SOLID PIPE FLOW

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ABSTRACT

A new model of particle turbulent dispersion in vertical gas/solid pipe flow is presented in this paper. The essence of the model is to pay more attention to the active and discrete behavior of particles in the dispersion process in non-homogeneous turbulent vertical pipe flows using two-fluid approaches. In the new model, a non-gradient type of diffusion term is included in the expression of radial particle dispersion flux; the transport equation for particle turbulent kinetic energy (PTKE) is developed and solved for its distribution; the effect of intra-particle collision is considered for the generation and dissipation of PTKE; turbulence modulation due to particle presence is taken into account. Preliminary numerical results based on this new model are also presented in this paper.

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INTRODUCTION

It is well known that particulate flow in a large scale vertical riser manifests itself in a highly nonuniform distribution with a dense curtain of solids falling near the wall under a wide range of operating conditions. In fast fluidized beds particles in the upper space display a nonuniform distribution both vertically and radially. This phenomenon has been experimentally observed and widely investigated over the last decade. The segregated nature of the gas/solid flow in a vertical pipe has a strong impact on the processes (such as chemical reaction, mass and heat transfer) occurring inside. Obviously, understanding of the segregation mechanism in gas/solid flows is very important in the prediction and analysis of the various processes occurring in the flow. Traditional two-fluid two-phase flow models (widely used now in available commercial codes) fail to model and predict the observed heterogeneous distribution of particle flow in vertical pipes. This deficiency can be attributed to the fact that most of these models are basically a direct extension of single phase flow models. Particles are usually considered as a pseudo-fluid with its properties (such as diffusivity) similar to their counterpart in gas. Particle dispersion evaluated by this approach is mainly based on its passive, continuum behavior. On the other hand, particles may possess intrinsic characteristics of both an active and discrete nature in the transport of mass, momentum, energy and other quantities, which is due to both the particle's inertia and especially to the fluctuation energy of particles themselves, which are often neglected or underestimated in continuum modeling. These kinds of effects on particle dispersion have been reported by some researchers (such as Tsuji, 1991).

Much effort has been expended in recent years to explain and predict the distribution of the particle concentration in long slender vertical reactors and fast fluidized beds. Among others, Pita and Sundaresan (1993) and Bolio, Yasuna, and Sinclair (1994) used and extended a model which was developed by Sinclair and Jackson (1989) for fully- developed laminar pipe flow to investigate turbulent, developing pipe flows. In the model, a quasi-thermal energy equation as well as momentum equations containing particle stress terms obtained from kinetic theory are solved and a new concept of 'particle granular temperature' was introduced. They computed different flow patterns and particle distributions with some success. Berker and Tulik (1986) included an extra anti-gradient diffusion term in the particle continuity of the two-phase turbulent flow model to account for 'imperfect particle response' and qualitatively obtained particle distribution patterns similar to the experimental data in a fluid catalytic cracking riser. In the investigation of phase distribution phenomena in fast fluidized beds, Wu and Liu (1991), and Wu (1993) developed a correlation between particle volume fraction and the local particle turbulence intensity. Shraiber (1993) developed a set of two-phase flow equations for fast fluidized beds, in which particle collision is taken into account as a source term in the equations of particle momentum and particle turbulent kinetic energy (PTKE). Much the above work attempts to correlate particle dispersion with particle turbulent kinetic energy (or fluctuation velocity) one way or another. This paper presents a new approach to modeling the condensed phase flow in pipes by including more comprehensive effects of PTKE in the relevant particle transport equations.

Starting from a set of instantaneous particle motion equations, using the Reynolds averaging procedure similar to that done in single phase gas flow, the averaged particle transport equations including continuity, momentum (axial and radial) and turbulent kinetic energy are obtained. In the derivation for the pipe (or bed) flow, a couple of basic assumptions: $v_p << u_p$, $\partial/\partial z << \partial/\partial r$ were adopted. In the particle momentum equation and the particle turbulent kinetic energy equation, the effect of particle collisions are considered by using binary collision theory.

MAIN FEATURES OF NEW MODEL

1. As usually accepted, particle dispersion occurs due to gas turbulent eddy motion and can be evaluated by Fick's Law, similar to gas diffusion, which is basically dependent on the gradient of the particle concentration. In inhomogeneous turbulent pipe/bed flows, an expression for radial particle dispersion flux is derived from an approximate radial particle momentum equation (Wu and Liu, 1991). It has the following form:

$$J = \overline{\alpha' v'_p} = -\tau_t \overline{v'^2_p} \frac{\partial \bar{\alpha}}{\partial r} - \tau_t \bar{\alpha} \frac{\partial \overline{v'^2_p}}{\partial r} \qquad (1)$$

where α is the particle volume fraction, τ_t is the characteristic time of gas turbulence and v is radial velocity. Subscript p refers to particles and superscript $'$ refers to a fluctuation quantity.

The expression implies that particle dispersion in vertical inhomogeneous turbulent pipe flows depends not only on the gradient of the particle concentration (gradient transport), but also on the gradient of the particle turbulent kinetic energy (PTKE) or as Lumley (1975) suggested, on the convective transport with the coefficient proportional to the gradient of the gradient transport coefficient. This expression, therefore, will be used as the expression for the turbulent correlation terms in vertical inhomogeneous turbulent pipe flows.

The particle continuity equation based on expression (1) can be written as,

$$
\begin{aligned}
\rho_p \frac{\partial}{\partial z}(\overline{\alpha u_p}) + \frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\overline{\alpha v_p})] &= -\frac{\rho_p}{r}\frac{\partial}{\partial r}(r\overline{\alpha' v'_p}) \\
&= \frac{\rho_p}{r}\frac{\partial}{\partial r}\left[r\left(\tau_t \overline{v'^2_p}\frac{\partial \bar{\alpha}}{\partial r} + \tau_t \bar{\alpha}\frac{\partial \overline{v'^2_p}}{\partial r}\right)\right]
\end{aligned}
\tag{2}
$$

Equation (2) represents a mass balance among the convection (with mean velocity v_p), the gradient transport (with particle diffusivity) and the convective transport due to the inhomogeneous nature of the turbulent flow.

The radial particle momentum equation is expressed as,

$$
\begin{aligned}
&\rho_p \frac{\partial}{\partial z}(\overline{\alpha u_p v_p}) + \frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\bar{\alpha}\overline{v_p}^2 + \overline{\alpha' v'_p v_p})] \\
&= -\frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\overline{v_p \alpha' v'_p} + \bar{\alpha}\overline{v'^2_p})] + f_{dr}
\end{aligned}
\tag{3}
$$

where f_{dr} is the drag term. In equation (3) the first term on the right side is the particle Reynolds stress and is related to particle collisions. The second term in the bracket on the right side presumably has the function of pushing particles toward the region with lower fluctuation energy (near the wall) via developing radial particle velocity, v_p. The fully-developed form of the equation would be in the form,

$$\frac{\partial}{r\partial r}[r(\overline{\alpha}\overline{v'_p{}^2})] = 0 \tag{4}$$

Evidently, large scale fluctuations in suspension velocity can be responsible for the segregation effect in vertical turbulent gas/particle pipe flow.

The axial particle momentum is written as,

$$\begin{aligned}\rho_p\frac{\partial}{\partial z}(\overline{\alpha}\overline{u_p}^2) + \frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\overline{\alpha u_p v_p} + \overline{\alpha' v'_p u_p})] \\ = -\frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\overline{\alpha u'_p v'_p})] + f_{dz} - \rho_p \alpha g\end{aligned} \tag{5}$$

2. According to C. M. Tchen (1947), particles respond completely to local gas turbulence. PTKE evaluated based on this assumption is usually less than TKE of the gas, and particle diffusivity would also be less than that of the gas. Recent observations had indicated this condition is not always true. In fact, particles can carry their fluctuation energy upstream, they also collide with the wall and with each other, all of which implies that particles are very often in a non-equilibrium state with the surrounding gas. Therefore, it is better to calculate the PTKE distribution using its own transport equation. Using an averaging procedure similar to that used for single-phase gas flow applied to the instantaneous momentum balance for particles and with some mathematical manipulation, the K_p equation can be obtained as follows:

$$\rho_p \frac{\partial}{\partial z}(\overline{\alpha u_p} K_p) + \frac{\rho_p}{r}\frac{\partial}{\partial r}[r(\overline{\alpha v_p} + \overline{\alpha' v_{p'}}) K_p]$$

$$= \frac{\rho_p}{r}\frac{\partial}{\partial r}[r\overline{\alpha}\frac{\nu_p}{\sigma_k}\frac{\partial K_p}{\partial r}] - \rho_p \overline{\alpha u'_p v'_p}\frac{\partial \overline{u_p}}{\partial r} + \overline{f' v'_p} + G_c - \varepsilon_c \tag{6}$$

where the convective terms in the equation provide a mechanism for PTKE to be carried with particles. Local PTKE could be higher than that of gas if PTKE upstream is higher.

The interaction of particles with gas is expressed by drag work $\overline{f'v'_p}$, which is associated with gas eddy motion and can be approximately modeled via its effect on particles and expressed as,

$$\overline{f'v'_p} = c\overline{\alpha}\frac{\rho_p}{\tau_p}(qK - K_p) \tag{7}$$

where the value of q can be taken from an empirical correlation, e.g. $q = \tau_t /(\tau_t+\tau_p)$, (Humphrey 1982). By normalizing Equation (5), the relative magnitude of this term can be evaluated using a nondimensional time scale $L/(u_p\tau_p)$. If $L/(u_p\tau_p) >> O(1)$ (very fine particles), after comparing terms in the equation, the equation reduces to the form,

$$\frac{K_p}{K} = q = \frac{\tau_t}{\tau_t + \tau_p} \tag{8}$$

where τ_p is the particle aerodynamic response time. This relation implies that local complete response of particles to the gas turbulence occurs at the extreme of very small particles. If $L/(u_p\tau_p) << O(1)$ (big particles), the magnitude of this term becomes trivial and can be neglected.

This condition means the interaction between particles and gas turbulence would not contribute to PTKE for the case of large particles.

3. In a moderately dense particle/gas flow, inter-particle collisions make an important contribution to the PTKE as well as the stress in the particle phase. The terms G_c and ε_c in (5) represent the generation of PTKE due to inter-particle collisions and dissipation of PTKE due to inelastic collisions, respectively. G_c constitutes the major contribution to the particle fluctuation energy in the case of dense flows. Based on the dynamics of binary collisions and kinetic theory methodology, an approximate model for G_c and ε_c in vertical pipe flows can be developed and incorporated into the K_p equation as a source and a sink term. The effect of particle collisions with the wall can be taken into account in the boundary condition for K_p.

An approximate model for G_c and ε_c for a mono-dispersed particulate flow system in vertical pipes are written as:

$$G_c = c_G \bar{\alpha} \rho_p N_c \left(\frac{\partial u_p}{\partial r}\right)^2 \left(\frac{d_p}{\alpha}\right)^2 \tag{9}$$

$$\varepsilon_c = c_\varepsilon \bar{\alpha} \rho_p N_c K_p \tag{10}$$

where c_G and c_ε are mainly functions of collision restitution ratio, the collision frequency N_c is expressed as:

$$N_c = c_N \frac{\bar{\alpha}}{d_p}\sqrt{K_p} \tag{11}$$

For poly-dispersed particulate flow systems, the collisions caused by the velocity difference between different particle groups would have a more significant effect on the particle collision effects. In this case, the collision frequency, the generation rate of TKE and its dissipation rate during each inelastic collision would have more complicated forms of expression.

4. For the investigation of particle dispersion in a moderately dense gas/solid pipe flow, the effect of gas turbulence modulation due to particle presence is important and should be taken into account. In some two-phase flow models this is done by including the turbulent correlation of particle and gas velocities in the turbulent kinetic energy equation of the gas which results from the time- averaging procedure and yields the form of (Humphery,1982),

$$-\frac{\alpha}{\tau_A}(\overline{u'u'} - \overline{u'u_p'}) \tag{12}$$

where τ_A is the aerodynamic response time of particles. This term always has a negative value, which implies that a kind of turbulent dissipation effect dominates. In fact, distinguished from fluid particles, the interaction of solid particles with gas takes the form of wakes of particles or vortices shed, which are associated with the characteristics of high inertia and the finite size of particles and could not be directly derived by the Reynolds averaging approach applied upon a continuum equation or covered by a correlation with its fluctuation velocities u_p' or v_p'. In other words, some important information might be lost in normal averaging procedures. To complement this effect, which would contribute to the turbulence generation, an approach is adopted, which is based on the analysis for single particle behavior in the gas flow and the summation of the single effect (Wu and Liu, 1992, Yuan and Michaelides, 1992). The actual version of turbulence modification constructed in this model has the form,

$$\Delta K = \frac{\alpha\rho}{\tau}\frac{l_w}{d_p}(\bar{u}+\bar{u}_p)(\bar{u}-\bar{u}_p) \tag{13}$$

for the turbulence generation due to particle presence and

$$\Delta\varepsilon = -\frac{\alpha\rho_p}{\tau}(\bar{u}-\bar{u}_p)^2\left(1-\exp\left(\frac{-2c_1\tau}{\tau_p}\right)\right) \tag{14}$$

for the change of dissipation rate of K_p due to particle presence, where l_w is the effective wake length and τ is the time for particles to cross the eddies.

The turbulent kinetic energy equation for gas containing these new terms is written as:

$$\begin{aligned} &\rho\frac{\partial}{\partial z}((1-\bar{\alpha})\bar{u}K)+\frac{\rho}{r}\frac{\partial}{\partial r}[r((1-\bar{\alpha})\bar{v}-\overline{\alpha' v'})K] \\ &=\frac{\rho}{r}\frac{\partial}{\partial r}[r(1-\bar{\alpha})\frac{\nu}{\sigma_k}\frac{\partial K}{\partial r}]-\rho(1-\bar{\alpha})\overline{u'v'}\frac{\partial\bar{u}}{\partial r}-\rho(1-\alpha)\varepsilon+\Delta K+\Delta\varepsilon \end{aligned} \tag{15}$$

In summary, the effect of particle fluctuation energy, which can arise either from turbulent motion of particles (eddy motion), or due to inter-particle collisions (random), or both, and its interaction with the distribution of particles are included in the model. These additions constitute the distinctive features of the new model.

NUMERICAL SIMULATION

The new model has been partially incorporated in the multiphase flow code, ICOMFLO, which was developed at Argonne National Laboratory and used to calculate multiphase flow fields (including solid, gas, and droplet phases for applications including the processes of chemical reaction, combustion, evaporation, condensation, and heat and mass transfer) of combustors, reactors, etc., (Chang and Lottes, 1993 and Chang, Lottes, and Berry, 1991). The ICOMFLO computer code uses "x" for the streamwise coordinate and "y" for the cross stream coordinate, which correspond to the variables "z" and "r" respectively in the model development above. From this point on in the presentation of the numerical implementation and numerical results, the "x" and "y" notation will be used for the streamwise and cross stream directions respectively.

The gas-phase state of the multi-phase flow is governed by the elliptic partial differential equations of fluid mechanics, including conservation of momentum, energy, and mass, and transport of turbulent parameters, with separate equations for the state of an ideal gas and for those applications requiring it, gaseous species conservation.

Assuming the gas is ideal, the equation of state becomes

$$P = \rho R T \sum_i f_i / M_i \tag{16}$$

where the "i" subscript refers to different gas species if present. In this application, only one gas species, nitrogen, was used in the computations.

For convenience of numerical formulation the governing transport equations for gas phase are put in a common form:

$$\frac{\partial}{\partial x}(\theta \rho u \xi - \Gamma_\xi \frac{\partial \xi}{\partial x}) + \frac{\partial}{\partial y}(\theta \rho v \xi - \Gamma_\xi \frac{\partial \xi}{\partial y}) = S_\xi \tag{17}$$

in which ξ is a general flow property, x and y are coordinates, θ is gas volume fraction, u,v are velocity components, Γ is effective diffusivity (calculated from both laminar and turbulent viscosities and an appropriate nondimensional scaling factor), and S_ξ is a source term.

Table I lists transport equations of gas properties relevant to this study and source terms of the equations. The general flow property is replaced by the scalar 1 in the continuity equation, a velocity component in a momentum equation, an enthalpy, h, in the energy equation, or a turbulent kinetic energy, k, or dissipation rate, ε, in a turbulence equation. The governing equations contain source terms for interphase and intraphase property exchange rates. The computation of these rates may, in some cases, be based on rather elaborate submodels, which resolve or avoid the numerical instabilities arising out of widely disparate time scales in the macro and micro physical scales of some of the phenomena when they are represented only with simple differential terms. The momentum source terms include pressure gradient, and momentum gain or loss through interfacial drag effects. The energy source terms include the heat transfer between phases, and the heat generation due to turbulent dissipation.

Table I Gas Flow Properties, Transport Equations, and Source terms.

ξ	Transport Equation	Source Term
1	continuity	
u	x-momentum	interfacial drag
v	y-momentum	interfacial drag
h	energy	interfacial heat transfer, and dissipation
k	turbulent kinetic energy	production, dissipation, and interfacial transfer
ε	turbulent dissipation rate	production and dissipation

The turbulence equations are used to determined turbulent viscosity and response of the particles to turbulence. The other transport equations, and the state equations (ideal gas law and caloric equations of state), and the species conservation equations are used to solve for unknown gas properties: pressure, density, temperature, and X- and Y-velocity components.

The particle phase formulation is based on an Eulerian model. In this formulation, the particle phase state of the flow is governed by the elliptic partial differential equations of fluid mechanics, including conservation of particle number density, momentum, and energy. The particles may have a spectrum of particle sizes. To compute particle properties in a particle size distribution, particles need to be divided into size groups, which is simply just a discretization of the particle size spectrum, and for each size group, particle properties are solved from the governing equations. To conserve computational time in this initial phase of developing an enhanced particle turbulence model, only single sized particles are assumed. Similar to the gas phase formulation, the governing transport equations for the particle phase are put in a common form,

$$\frac{\partial}{\partial x}\left(n_k u_{s,k}\xi - \Gamma_\xi \frac{\partial n_k \xi}{\partial x}\right) + \frac{\partial}{\partial y}\left(n_k v_{s,k}\xi - \Gamma_\xi \frac{\partial n_k \xi}{\partial y}\right) = S_\xi \tag{18}$$

in which n_k is particle number density of kth size group, $u_{s,k}$ and $v_{s,k}$ are particle velocity components of kth size group in x and y direction respectively, Γ is diffusivity arising out of general interaction with turbulence in the gas phase, and S_ξ is the source term.

Table II lists the particle properties, transport equations, and source terms. The general flow variable is replaced by a scalar 1 in the particle number density equation, a velocity component u or v in a momentum equation, and a temperature T in the energy conservation equation. The governing equations contain source terms for interphase and intraphase property exchange rates. The momentum source terms include momentum gain or loss through interfacial drag effects. The energy source terms include the heat transfer between solid and gas phases. The initial phase of implementing the new turbulence interaction modeling includes adding a new particle phase transport equation for particle turbulent kinetic energy, k_p, and new source terms in the particle number density equation and the cross stream particle momentum equation.

Table II Particle Flow Properties, Transport Equations, and Source Terms

ξ	Transport Equation	Source Term
1	number density	k_p induced diffusion
u	x-momentum	interfacial drag
v	y-momentum	interfacial drag and dispersion of particle kinetic energy
T	energy	heat transfer between phases
k_p	particle turbulent kinetic energy	production, dissipation, and interfacial transfer

Five transport equations are used to solved for 5 unknown solid properties: number density, X- and Y-velocity components, temperature and particle turbulent kinetic energy. The boundary conditions for the new model assume an impermeable wall and therefore the radial velocity is set to zero on the wall and gradients of particle volume fraction and particle turbulent kinetic energy are set to zero at the wall.

RESULTS AND DISCUSSION

At the beginning stage of the model development, preliminary calculations were performed. The calculations are carried out for a gas/particle pipe flow in a long pipe with a diameter of 0.09 m and a height of 4.0 m. The inlet flow conditions are summarized in Table III.

Table III Inlet Flow Properties

gas superficial velocity at inlet, U_{g0}	8.0 m/s
particle mass flow rate	0.62 kg/s
particle size, R_{m0}	50 μm

Figures 1-5 compare computational results from the ICOMFLO computer code using three different turbulent models. Model 1 is the original gas-solid turbulent model of the ICOMFLO code which is commonly used in many computational fluid dynamic codes. Model 2 is a new turbulent model with partial revisions including the addition of the K_p equation (Equation 6) and the new diffusive source terms in the particle continuity equation (Equation 2). Model 3 is further upgraded with not only a new K_p equation and a new source term in the particle continuity but also an additional source term in the particle radial momentum equation (Equation 3). Figures 1 and 2 show the cross-sectional distributions of particle and gas turbulent kinetic energy at the pipe exit, respectively. Figure 3 shows the radial distributions of the axial gas velocity. Figure 4 shows the radial distribution of the particle number density at the pipe exit. Figure 5 shows the axial development of the particle number density near the pipe wall.

In Figure 1 the distribution of PTKE across the pipe clearly demonstrates a great increase in K_p calculated by the transport equation of K_p. In Figure 2 the gas kinetic energy K_g also shows a big increase due to the effect of two-phase interaction.

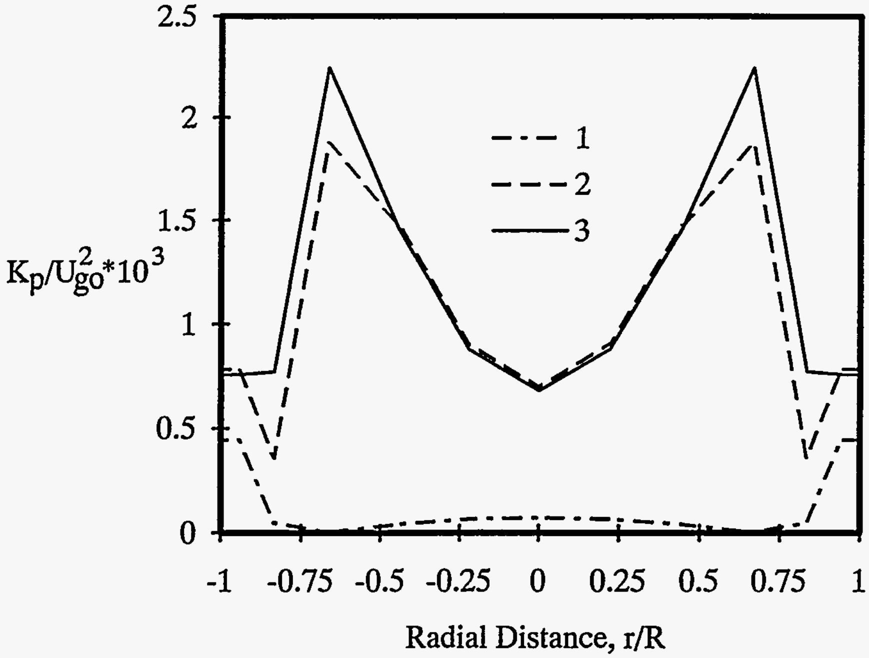

Figure 1 Distribution of PTKE across the Pipe

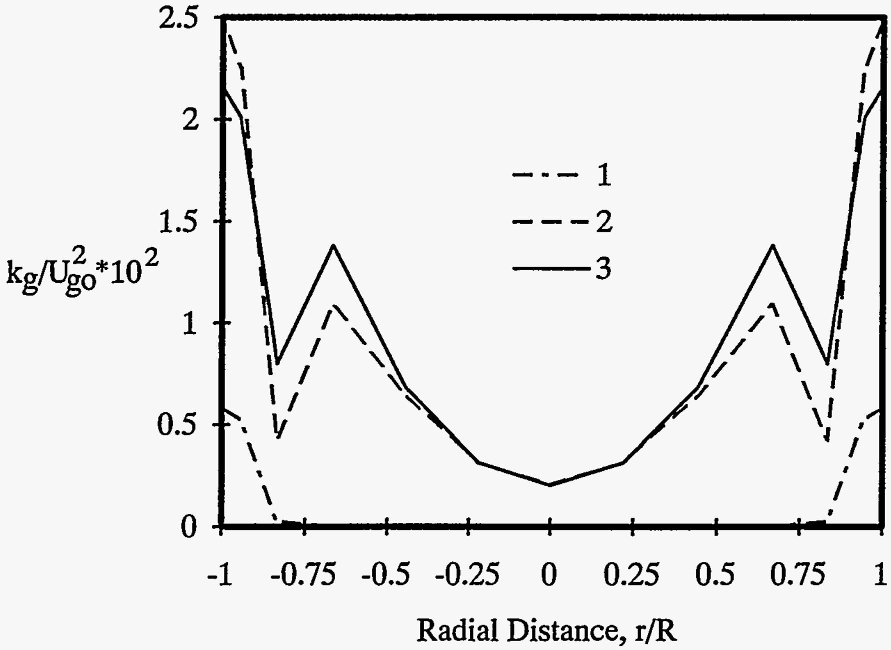

Figure 2 Distribution of gaseous TKE across the Pipe

This increase of turbulence kinetic energy due to particle-gas interactions has an impact on the gas (and particle) velocity especially near the pipe wall as shown in Figure 3. The velocity profiles computed from the new turbulent models appear more closer to a fully-developed flow.

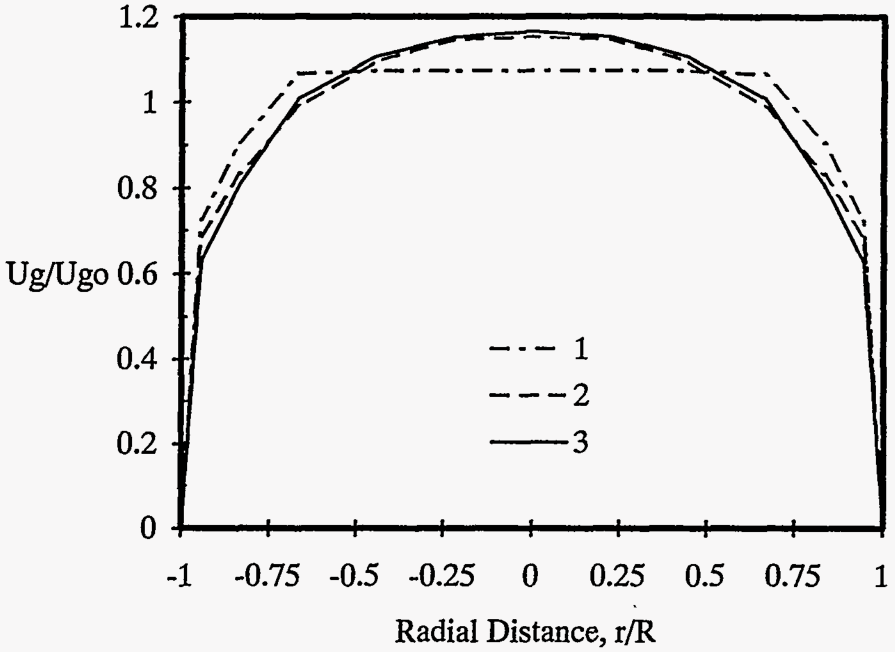

Figure 3 Distribution of Gas Velocity across the Pipe

Both Figure 4 and Figure 5 show the distribution of particle number density N_p. Because of the effect of particle fluctuating energy, particles are more easily motivated to disperse toward the wall, (Figure 4) compared to the result without this kind of effect included. More obvious migration of particles toward the wall occurs in Case 3 than in Case 2 due to the radial particle velocity developed. The change of particle number density near the pipe wall along the pipe shown in Figure 5 vividly demonstrates the process of particle dispersion inside the pipe due to the effect of PTKE. The particle radial velocity developed due to PTKE (Case 3) obviously has a more profound effect on the particle dispersion than the effect included in the particle continuity via mass balance.

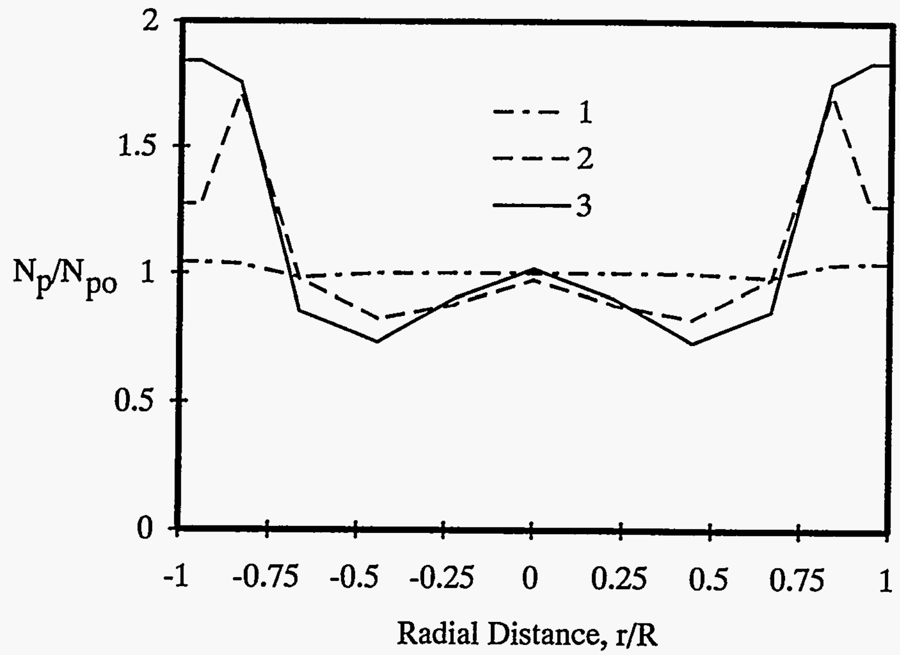

Figure 4 Cross-sectional Profile of Particle Number Density

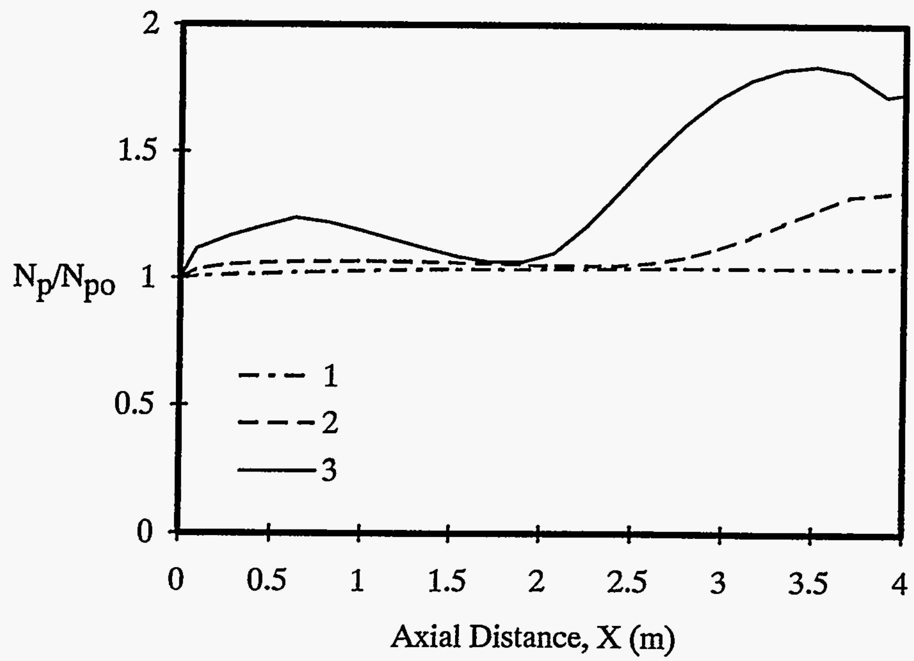

Figure 5 Changes of Particle Number Density Near the Pipe Wall in the Axial Direction

The particle radial velocity thus developed results from the turbulent correlation between fluctuations of particle concentration and PTKE and can be viewed as particle dispersion velocity, Wu and Liu (1991). For the complete model verification, work is continuing and more data can be expected in the near future. The model itself, of course, also needs to be refined during the testing of the phase of the project. However, the basic features of the model have been clearly demonstrated by the preliminary numerical results.

CONCLUDING REMARKS

The two-fluid approach has been widely accepted as a powerful tool for computing multiphase flows in varieties of application due to its convenience. It does give very good results in many cases, even some coefficients or properties involved may be copied from single phase flow data. However, the two fluid approach encounters problems in some complicated applications, such as the *Phase Distribution Phenomena* occurring in fast fluidized beds and vertical pipes. The new model presented in this paper offers a remedy to overcome the intrinsic weakness related to the discrete and active behavior of particles in dispersion phenomena, which is normally not fully considered in the two-fluid approach but very important in some cases.

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REFERENCES

Berker, A. and T.J. Tulig, 1986 , Chemical Engineering Science, 41, 4, 821-827

Bolio, E.J., J.A. Yasuna, and J.L. Sinclair, 1994, AIChE J.

Chang, S.L. and S.A. Lottes, 1993, Numerical Heat Transfer Part A, 24(1):25-43

Chang, S.L., S.A. Lottes, and G.F. Berry, 1991, Numerical Heat Transfer, Part A, 20(2):223-236

Humphrey J.A.C. and F. Pourahmadi, 1982, Proc. of 7th Annual Conf. on Materials for Coal Conversion and Utilization, Gaithersburg, 621-666

Lumley, J.L., 1975, Physics of Fluids, 18, 6, 619-621

Pita, J.A. and S. Sundaresan, 1993, AIChE J., 39, 541

Shraiber, A. A. 1993, Private communication

Sinclair, J.L. and R. Jackson, 1989, AIChE J. 35, 9, 1473-1486

Tchen, C.M., 1947, Ph.D. Dissertation, University of Delft, Martinus Nijhoff, the Hague

Tsuji, Y., 1991, Gas Solid Flows, ASME FED- vol.121

Wu, B. and D. Liu, 1991, Cavitation and Multiphase Flows Forum, ASME FED-vol. 109

Wu, B. and D. Liu, 1992, Cavitation and Multiphase Flow Forum, ASME FED-vol. 135

Wu, B. 1993, Proc. of 4th Int. Conf. on Circulatinf Fluidized Bed, Pennsylvania

Yuan, Z. and E. Michaelides, 1992 Int. J. Multiphase Flow, 18, 779-785