*Proceedings of the 11[th] Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2006*
Braz. Soc. of Mechanical Sciences and Engineering – ABCM, Curitiba, Brazil, Dec. 5-8, 2006

**Paper CIT06-0477**

# TURBULENCE MODELLING OF THE GAS-PARTICLE FLOW IN A SUSPENSION BED

**Marcos Sebastião de Paula Gomes**
Mechanical Engineering Department of PUC-RIO.
mspgomes@mec.puc-rio.br

**Reginaldo Rosa Cotto de Paula**
CEFET-E.S. and Mechanical Engineering Department of PUC-RIO.
rcotto@bol.com.br

***Abstract.*** *The Turbulence modelling is a crucial question in the application of computational fluid dynamics (CFD) to gas-solid flow systems. This paper presents a two-dimensional numerical simulation of gas-particle two-phase flow using commercial software, Fluent 6.2.16. The velocity distribution of gas and solid particles were obtained from a mixture model incorporating the standard $k-\varepsilon$ turbulence model. The models results were compared to numerical simulation from diffusion flux model and experimental study of gas-particle flow in a suspension bed performed out by Shang et al. (2004). The results of the velocity distributions showed good quantitative agreement between CFD predicted and the experimental investigation.*

***keywords:*** *mixture model, gas-particle flow, turbulence*

## 1. Introduction

Two-phase turbulent flow are of considerable engineering importance in a wide range of the practical applications, such as power systems and environmental control.

The two-phase flow can give rise to very complex combination of phases as well from the flow structures. The two main approaches for modelling the two-phase flow are the Lagrangian-Eulerian and Eulerian-Eulerian (or continuum-continuum) approaches. In the Lagrangian-Eulerian approach the fluid phase is treated as continuum by solving of the Navier-Stokes equation, while the dispersed phase is considered to represent a group of particles interacting with the fluid and possessing the same characteristics such as size, composition, etc. (Patankar and Joseph, 2001). Particles trajectories are calculated from the Newton's equations of motion. In turbulent flow the problem with Lagrangian particle-tracking methods is that the number of particles needed for description of particle dispersion is often too large for practical calculations.

Eulerian-Eulerian approach considers the particulate phase to be a continuous fluid interpenetrating and interacting with the fluid phase (Gidaspow, 1994). The concept of the volume concentration or volume fraction is introduced due to the volume of a phase cannot be occupied by the other phases. The Eulerian-Eulerian approach introduces more unknowns quantities than equations. Hence, it is necessary to use closure equations. This formulation consists of three essential parts: (a) the derivation of the field equations of the conservation principles, such as mass and momentum; (b) constitutive equations from empirical formulation for the closure of the equation system by taking into account the structure of the flow field and material properties and, (c) interfacial conditions.

In the context of the Eulerian-Eulerian approach an alternative method is the mixture theory, also called the theory of this sort (Bowen, 1976; Xu et al., 2004). The mixture model method is considered a simplification of the full multiphase equations, due to their simple theory and implementation. In this approach the phases are treated as interpenetrating continua and at any instant of time, all phases are present at every material point. Instead of applied the continuity and momentum equations of each phase separately, this method solves to the continuity and momentum equations for the mixture. In addition, the local equilibrium condition is expressed by means of the momentum equation for the dispersed phase and the phases may be move at different velocities.

In the present work, a numerical investigation was conducted in order to simulate the velocities of the air flow and particles in two-phase flow using mixture model. The aim of this paper is to examine the application of the mixture turbulence model for simulation of the two-phase flows of the gas-particle in a cold model suspension bed.

## 2. Mathematical Formulation of the Mixture Model

The mixture model is employed in the simulation by assuming that the coupling between phases is strong, and particles closely follow the flow when the Stokes number, $S_t$, is less than or close to one. The Stokes number is defined as the ratio of the particle time response, $t_p$, to the system response time (Crowe *et al.*, 1998):

$$S_t = \frac{t_p}{t_s} = \frac{\rho_p d_p^2/18\mu_c}{L_s/V_s} \tag{1}$$

where $\rho_p$ and $d_p$ are the density and diameter of the particle, respectively; $\mu_c$ is continuity viscosity. $L_s$ and $V_s$ represent the length and velocity characteristics of a system, respectively.

For the case of only one dispersed phase, as in the present study, the mixture continuity and mixture momentum equation are given as

$$\frac{\partial}{\partial t}(\rho_m) + \nabla.(\rho_m \vec{u}_m) = 0 \tag{2}$$

and

$$\begin{aligned}\frac{\partial}{\partial t}(\rho_m \vec{u}_m) + \nabla.(\rho_m \vec{u}_m \vec{u}_m) &= -\nabla p_m + \nabla.[\mu_m(\nabla \vec{u}_m + \nabla \vec{u}_m^T)] + \rho_m \vec{g} + \\ &\quad + \vec{F} + \nabla.\left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{u}_{dr,k} \vec{u}_{dr,k}\right)\end{aligned} \tag{3}$$

above $\rho_m$ is the mixture density, $\vec{u}_m$ is the mass-average velocity given, $\alpha_k$ is the volume fraction of phase $k$, $p_m$ is the pressure of mixture, $\vec{F}$ is a body force and $\mu_m$ is the viscosity of the mixture. The mass-average velocity, mixture density and viscosity of the mixture can be expressed, respectively, by

$$\vec{u}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{u}_k}{\rho_m} \tag{4}$$

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{5}$$

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \tag{6}$$

### 2.1. Volume Fraction of the Secondary Phase

From the continuity equation for secondary phase $p$, the volume fraction is governed by

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla.(\alpha_p \rho_p \vec{u}_m) = -\nabla.(\alpha_p \rho_p \vec{u}_{dr,p}) \tag{7}$$

## 3. The Mixture Turbulence Model

The mixture turbulence model is an extension of a single-phase $k-\varepsilon$ model. The transport equations of the $k-\varepsilon$ model, which is based on the solution of the conservation equations of the kinetic energy of turbulence, $k$, and its dissipation rate, $\varepsilon$, are given by

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla.(\rho_m \vec{u}_m k) = \nabla.\left(\frac{\mu_{t,m}}{\sigma_k} \nabla k\right) + G_{k,m} - \rho_m \varepsilon \tag{8}$$

and

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla.(\rho_m \vec{u}_m \varepsilon) = \nabla.\left(\frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon\right) + \frac{\varepsilon}{k}\left(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon\right) \tag{9}$$

where the turbulent viscosity of the mixture, $\mu_{t,m}$, is computed from

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon} \tag{10}$$

where $C_\mu = 0.09$. The production of turbulent kinetic energy, $G_{k,m}$, is computed by

$$G_{k,m} = \mu_{t,m}(\nabla \vec{u}_m + (\nabla \vec{u}_m^T)) : \nabla \vec{u}_m \tag{11}$$

The closure constants in Eqs. (10) and (11) are: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$.

## 4. Experimental Procedure

Figure (1) shows a schematic representation of the experimental facility (Shang *et al.*, 2004). Air supply was supplied by a blower and a suction fan. A pitometer was used for the measurement of the air flow. The gas-particle flow enters a single central circular pipe nozzle of 250 mm in diameter. Round glass granules with mean diameter of 45 $\mu$m and density of about 2300 kg m$^{-3}$, were chosen as particles for the experiments. The particles of diameter less than 5 $\mu$m were chosen as air flow tracing particles. The established dimensions of the measurement segment were 500 mm $\times$ 500 mm in cross-section and height of 1400 mn. The front-wall of the measurement section (250 mm $\times$ 1400 mm) was made of glass, so that particle motion in the bed could be measured by a particle dynamic analyzer (PDA). Three two-dimensional laser beams were emitted by the PDA into the bed and focused on the measuring point.

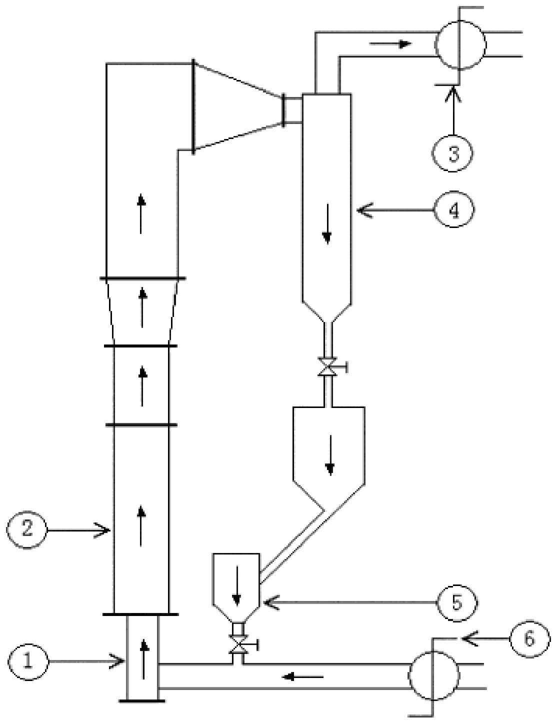


Figure 1: Schematic representation of the test facility: (1) entrance section; (2) measurement section; (3) suction fan; (4) cyclone separator; (5) particle hopper and (6) blower. Source: Shang et al. (2004).

One rectangle area was chosen as the measurement section, which was parallel to the front wall of the bed and contained the nozzle center line, as shown in Fig. (2). The flow upstream of the measurement section was from the bottom to top. The experiments were carried out at atmospheric pressure and the temperatures of the working mediums were about $20^{OC}$, (Shang *et al.*, 2004).

## 5. Model Parameters

In this work, in order to modelled the gas-particle flow was used the commercial code FLUENT 6.2.16. In this study were considering the following conditions: (a) two-phase flow for immiscible phases; (b) the gas phase was the continuous phase and particles were the dispersed phase; (c) there is no mass transfer between the gas phase and particle phase and; (d) the gas-particle two-phase flow was steady turbulent flow. In context of mixture models the particulate phase also was considered a continuous fluid interpenetrating. The resulting system of the equations was solved via finite volume method using the SIMPLE algorithm. The QUICK scheme was used to discretize the equation of the volume fraction.

Based on the geometry of the measurement section, it was decided to model the central plane of the flow using a two-dimensional, Cartesian coordinates, with 250 mm $\times$ 1400 mm. According the to the proposed design, the flow was forced to enter in the entrance section of the domain of 125mm in radius. In the numerical simulation the particle concentration was 50 g m$^{-3}$.

The boundary conditions for the inlet flow at the entrance section were evaluated according to the experimental condition. The the average velocity of the mixture at the exit of the entrance section was 8.66 m s$^{-1}$.

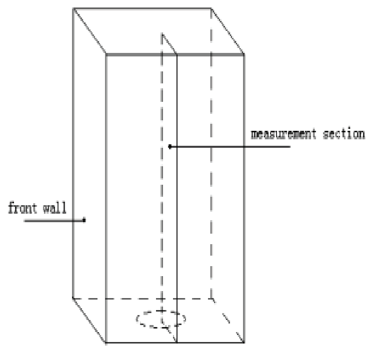


Figure 2: Position of the measurements.Source: Shang et al. (2004).

The turbulent kinetic energy and its dissipation rate at the inlet boundary were calculated as (Zhou, 1993)

$$k_{in} = 0.005 V_{m,in}^2 \tag{12}$$

and

$$\varepsilon_{in} = \frac{k_{in}^{3/2}}{0.025R} \tag{13}$$

where $V_{in,m}$ represent the average velocity of the mixture at the inlet of the suspension bed and $R$ is the radius of the entrance section.

The coefficient of drag force was calculated by following approach,

$$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687}) \text{ for } Re_p \ \leq 1000 \tag{14}$$

where $Re_p$ is the Reynolds number of particle given by,

$$Re_p = \frac{\rho_c d_p |\vec{u}_p - \vec{u}_c}{\mu_c} \tag{15}$$

## 6. Results

Numerical simulations were conducted to characterize the gas-particles two phase flow in a suspension bed using the mixture turbulence model with an extension of a single-phase $k - \varepsilon$ model for two-phase flow. The average velocity of the mixture at the exit of the entrance of test section was 8.66 m $s^{-1}$, the concentration and volume fraction of the particle were 50 g $m^{-3}$ and $2.17 \times 10^{-5}$, respectively. The numerical mean axial gas and particle velocity vectors were presented in Fig. (3). The numerical results demonstrate the existence of three different regions of the flow in both the gas and particle phases: (a) a core region; (b) a main flow region and; (c) a back-flow region. It is suggested that the the geometry of the suspension bed has a significantly influence on the gas-particle flow structure. At the corner of the suspension bed, the gas and particle vector field shown that gas and particle entered in the vortex region and occurs a back-flow region. Besides the core region and the back-flow region, the flow region in the suspension bed belongs to the main flow direction. In the main flow region, both the gas and particles flow upward, but their velocities were lower than that at the exit of the entrance section. In Fig. (3) the results indicate that the distribution of the gas and particle velocities exhibits the similar flow patterns.

Figures (4) and (5) presented a comparison of the gas and particles velocities, respectively, at different width for different bed height obtained in the present work with mixture turbulence model and diffusion flux turbulence model from the work performed out by Shang et al. (2004) against the measurements. There was no significant difference between the predictions with the mixture turbulence model and the diffusion flux model. The results show that both the axial gas velocities and particle velocities decrease with increasing radial distance from the central axis and decrease with increasing axial height from the bottom of the bed.

Figure (6) shows the comparison of the computed gas and particles velocities at different bed heights obtained from mixture turbulence model and experimental data. The comparison of the distribution of the gas and particles velocities from Fig. (6) showed that the flow patterns were quite similar. Figures 4, 5, and 6 show that numerical results were in agreement with the experimental results for gas-particles flows in suspension bed obtained by Shang et al. (2004).

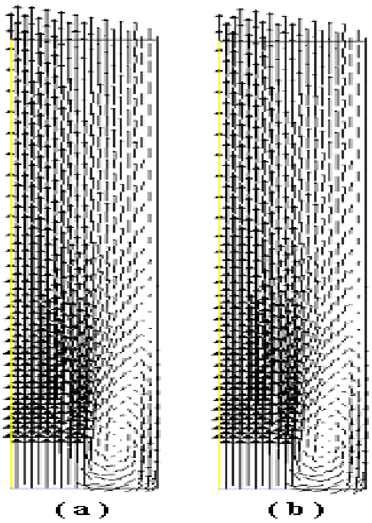


Figure 3: Results of the numerical simulations from mixture turbulence model: (a) velocity distribution of gas and (b) velocity distribution of particle.

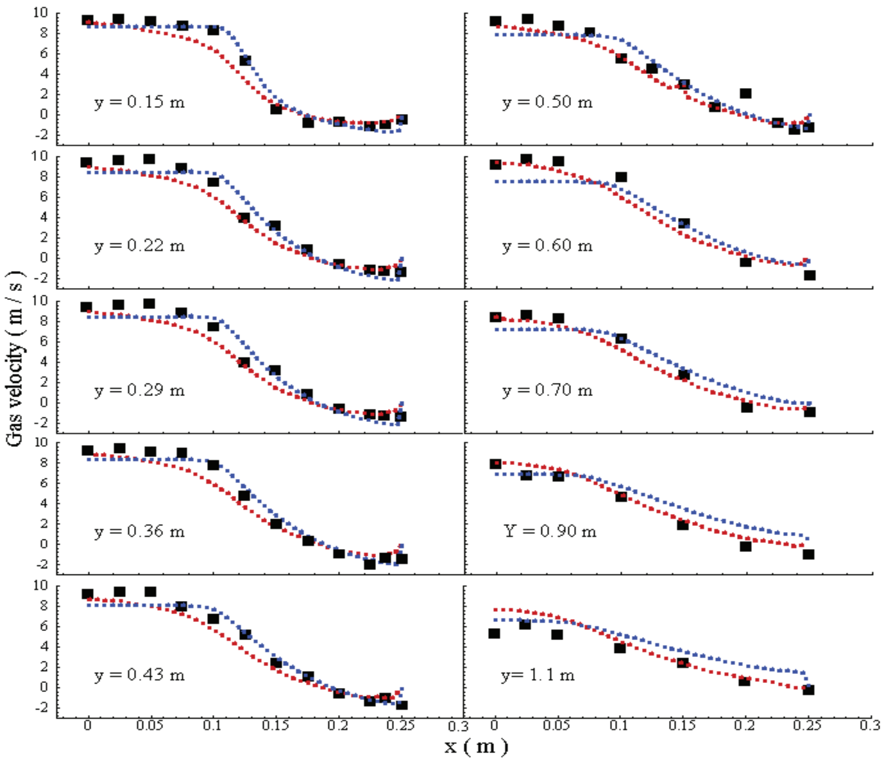


Figure 4: Comparisons of computed and measured axial velocities of the gas for different bed height: square - measurement, blue dashed - predictions with the mixture turbulence model and red dashed - predictions with the diffusion flux model.

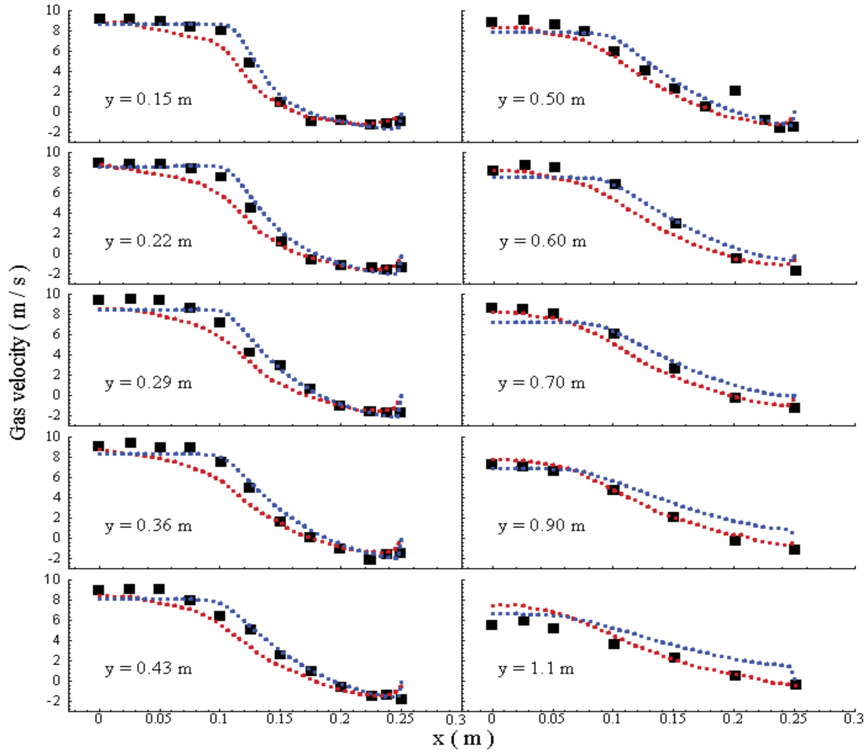


Figure 5: Comparisons of computed and measured axial velocities of the particles for different bed height: square - measurement, blue dashed - predictions with the mixture turbulence model and red dashed - predictions with the diffusion flux model.

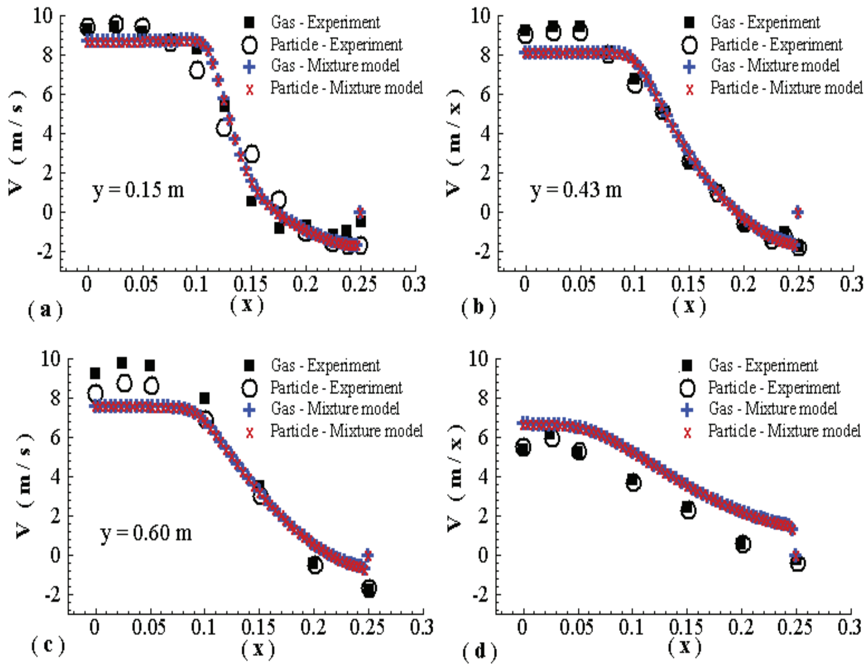


Figure 6: Comparisons of computed and measured axial gas and particle velocities at different bed height:(a)bed level $y = 0.15$ m; b) bed level $y = 0.43$ m, (c) bed level $y = 0.60$ m and (d) bed level$y = 1.1$m

## 7. Conclusion

In the present work, a numerical investigation was conducted to simulate the velocities of the air flow and particles in two-phase flow using mixture turbulence model. Although the mixture model is considered a simples model in the context of the multiphase flow, this model was a good tool to provide some understanding of the complex physical phenomena of the gas-particle two phase flow in suspension bed. As mentioned, the gas-particle two phase flow showed the existence of three different regions: a core region; a main flow region and a back-flow region. It is suggested that there was a connection between the geometry of the suspension bed and the gas-particle flow structure.

There was no significant difference between the predictions with the mixture turbulence model (present work) and the diffusion flux model (Shang et al., 2004). The numerical predictions with both the models showed good agreed with the measurements performed out in a suspension bed.

## 8. Acknowledgements

The authors acknowledge support from CNPq. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of this institution.

## 9. References

Bowen, R. M., 1976, "Theory of Mixtures, Continuum Physics III", Ed. by Eringen, A.C., Academic Press, New York, pp. 1–127.

Crowe, C., Sommerfeld, M. and Tsuji, Y., 1998, "Multiphase Flow with Droplets and Particles", CRC Press, Boca Raton, Florida.

Gidaspow, D., 1994, "Multiphase flow and fluidization. Continuum and kinetic theory descriptions", Academic Press, San Diego.

Patankar, N. A. and Joseph, D. D., 2001, Modeling and numerical simulation of particulate flows by the EulerianLagrangian approach, "International Journal of Multiphase Flow", vol. 27, pp. 1659–1684.

Shang, Z., Yang, R., Fukuda, K., Li D. And He, X., 2004, Experiment and simulation using diffusion flux model for gas-particle two-phase flow in a suspension bed, "Chemical Engineering Science", vol. 59, pp. 1505-1514.

Zhou, L.X. , 1993, "Theory and Numerical Modeling of Turbulent Gas-Particle Flows and Combustion", Science Press & CRC Press, New York.

Xu, J., Rouelle, A., Smith, K. M., Celik, D., Hussaini, M.Y., Van Sciver, S.W., 2004, Two-phase flow of solid hydrogen particles and liquid helium, "Cryogenics", vol. 44, pp. 459–466.

## 10. Author rights