Pergamon

Int. J. Multiphase Flow Vol. 23, No. 2, pp. 403–408, 1997

0301-9322/97 $17.00 + 0.00

PII: S0301-9322(96)00070-5

BRIEF COMMUNICATION

ON THE EFFECT OF PARTICLES ON CARRIER PHASE TURBULENCE IN GAS–PARTICLE FLOWS

V. M. KENNING and C. T. CROWE

School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920, U.S.A.

(Received 15 May 1996; in revised form 25 September 1996)

1. INTRODUCTION

A key issue in the development of models for fluid–particle flows is the turbulence of the carrier phase. Increased turbulence leads to higher Reynolds stresses, increased heat transfer and enhanced particle dispersion and mixing. There is no general consensus on the effect of particles on carrier phase turbulence. Some experimental data suggest an increase in turbulence with the addition of particles (Tsuji and Morikawa 1982; Lee and Durst 1982; Parthasarathy and Faeth 1990; Yokuda 1990) while other data imply that turbulence is decreased (Modarress *et al.* 1984a, b; Schreck and Kleis 1993). Some researchers have seen both increases and decreases in turbulence with the addition of particles (Levy and Lockwood 1981; Tsuji *et al.* 1984). Gore and Crowe (1989) gathered data from a variety of researchers in order to generalize a trend for turbulence attenuation or augmentation and found that the ratio of particle diameter to integral length scale of the fluid (D/L) was important. When this ratio is less than 0.1 the data show that the turbulence level decreases with the addition of particles while an increase is observed for ratios greater than 0.1. No conclusion could be made about the magnitude of the increase or decrease based on the length scale ratio. Hetsroni (1989) performed an order of magnitude analysis and stated that particles with Reynolds numbers greater than 400 would augment the turbulence due to vortex shedding from the particles and those with Reynolds numbers less than 400 would attenuate it. Yuan and Michaelides (1992) proposed a mechanistic model based on wake shedding for turbulence generation. Squires and Eaton (1990), and Elghobashi and Truesdell (1993) have applied direct numerical simulation with 'point' particles and predicted turbulence modulation for certain situations but the results have not been conclusive. Yarin and Hetsroni (1994) developed a theory which accounted for both production due to velocity gradients in the carrier fluid and turbulent wakes behind the particles. There have been numerous other numerical models (Al Taweel and Landau 1977; Elghobashi and Abou-Arab 1983; Kataoka and Serizawa 1989; Hwang and Shen 1993; Liljegren and Fosslein 1994) developed for multiphase flows. Various numerical models for multiphase turbulent flows are summarized in Crowe *et al.* (1996).

The purpose of this note is to present a new idea on modulation of carrier phase turbulence based on a simple physical model for turbulence generation and dissipation by the particles. In the present work, an effort is made to predict the turbulence level in a gas–solid flow and to determine a parameter which will capture the general trend of the experimental data.

2. PHYSICAL MODEL

An energy balance is formulated to calculate the level of turbulence resulting from the introduction of the particles, as shown in figure 1. The turbulence of the fluid in the absence of particles, P_i, is referred to as the 'inherent' turbulence. A source term must appear in the model to account for production of this inherent turbulence. Production of turbulence due to the presence of the dispersed phase, P_d, is an additional source of turbulence energy. The possible losses of turbulence energy are viscous dissipation, ϵ, and retransmission of energy to the motion of the solid particles, ϵ_d.

The inherent production represents the rate of turbulence production that is necessary to offset the viscous dissipation and maintain a stationary level of turbulence in the absence of particles. Thus, P_i is given by:

$$P_i = \epsilon_i = \frac{k_i^{3/2}}{L_i} \qquad [1]$$

where k_i is the inherent turbulence kinetic energy and L_i is the dissipation length scale of the flow without particles.

Considering the components of velocity along the main flow direction, the average energy produced by the fluid per unit mass of particles per unit time due to the velocity difference between the particles and the fluid is given by

$$\bar{P}_d = \frac{f}{\tau_d}[(\bar{u} - \bar{v})^2 + \overline{(u' - v')^2}] \qquad [2]$$

where $\bar{u}$ and $\bar{v}$ represent the mean velocities of the fluid and particles, respectively, u' and v' are the fluctuating fluid and particle velocities, τ_d is the particle aerodynamic response time and the factor f is the ratio of particle drag to Stokes drag. Turbulence production terms involving the velocity difference between the particle and the carrier fluid have been derived by Kataoka and Serizawa (1989), Hwang and Shen (1993), Liljegren and Fosslein (1994) and Kenning (1996). However, for the application considered here, $(\bar{u} - \bar{v})^2 \gg (u' - v')^2$, so the production term reduces to

$$\bar{P}_d = \frac{f}{\tau_d}[(\bar{u} - \bar{v})^2]. \qquad [3]$$

A source of energy loss in the carrier phase is the rate of work done by the carrier phase to oscillate the dispersed phase. The energy lost by the carrier phase per unit mass per unit time is given by

$$\epsilon_d = f\left(\frac{u' - v'}{\tau_d}\right)v'. \qquad [4]$$

The dissipation due to the particles, ϵ_d, is small relative to the production term derived above and is negligible for gas–particle flows addressed here. This result makes sense intuitively since the particles are too heavy to be oscillated significantly by the fluid, so they absorb little energy from the flow. The general derivation of the dissipation term may be found in Kenning (1996).

The rate of dissipation of turbulent kinetic energy is represented by

$$\epsilon = \frac{k^{3/2}}{L} \qquad [5]$$

where L is the dissipation length scale. The choice of a length scale to be used in the current situation requires some consideration.

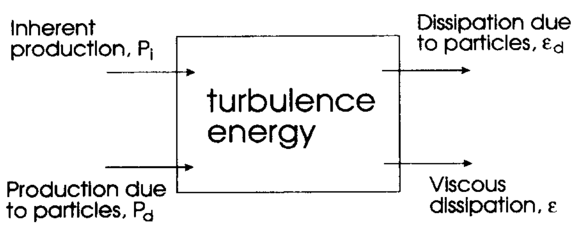

Figure 1. Schematic of turbulence model.

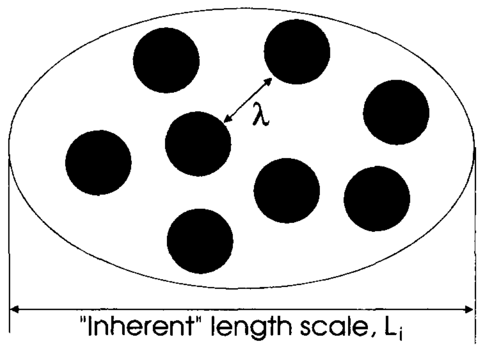

Figure 2. Illustration of interparticle spacing superseding dissipation length scale.

In single phase flows, various length scales are used to characterize a turbulent flow. These include the integral (dissipation) length scale which is a measure of the largest scales of the flow and would be taken in general to be proportional to the pipe diameter or the jet diameter depending on the flow configuration. The smallest scale is the Kolmogorov length scale which is independent of the large scales and is defined using the energy dissipation rate and the fluid viscosity. Between these two extremes, other length scales such as the Taylor microscale can also be defined. When particles are introduced into a flow, further complexities are introduced in that additional length scales may need to be considered. Some obvious examples are the diameter of the particles (or perhaps more than one particle length scale for oddly shaped particles) and the average interparticle spacing. The wakes produced by particles yield a length scale on the order of the particle size. If the particle size is smaller than the Kolmogorov scale, the particle diameter is probably not a significant length scale affecting dissipation. If the concentration of particles introduced into a flow yields an average interparticle spacing smaller than the inherent dissipation length scale, the particles may interfere with the existing eddies breaking them up so that the new dissipation length scale is proportional to the average interparticle spacing rather than the geometry of the pipe or jet. This is illustrated schematically in figure 2. Experimental studies by Kenning (1966) on turbulence generation by particles falling in an initially quiescent fluid show that the turbulence intensity based on the particle terminal velocity correlated with the particle volume fraction and the interparticle spacing.

For the current analysis, a hybrid length scale dependent on both the inherent dissipation length scale, L_i, and the average interparticle spacing, $\lambda/D \approx (\pi/6\epsilon_d)^{1/3} - 1$, is used where D is the sphere equivalent diameter of a particle and ϵ_d is the volume fraction of particle phase. This hybrid scale is defined as

$$L_h = \frac{2L_i\lambda}{L_i + \lambda}. \tag{6}$$

In the limit of the two scales, L_i and λ, being equal, there is no change in length scale. If the length scales are not equal, the hybrid scale will fall between them, but closer to the smaller of the two scales. Obviously this is a very simplistic assumption but it does capture the anticipated trends in length scale. The viscous dissipation then takes the form

$$\epsilon = \frac{k^{3/2}}{L_h}. \tag{7}$$

If a steady state has been reached after the addition of the particles, the energy balance takes the form

$$(\bar{u} - \bar{v})^2 \frac{f}{\tau_d}\frac{\tilde{\rho}_d}{\tilde{\rho}_G} - \frac{k^{3/2}}{L_h} + \frac{k_i^{3/2}}{L_i} = 0 \tag{8}$$

where $\tilde{\rho}_d$ and $\tilde{\rho}_G$ are the bulk densities of the particle and gas phases, respectively. This equation can be rearranged to yield the ratio of the turbulence energy to the inherent turbulence energy in the form

$$\frac{k^{3/2}}{k_i^{3/2}}\frac{k_i^{1/2}}{L_h} = \frac{k_i^{1/2}}{L_i} + \frac{(\bar{u}-\bar{v})^2}{\tau_d k_i}\frac{\tilde{\rho}_d}{\tilde{\rho}_G}. \qquad [9]$$

Recognizing that the ratio of turbulence energies can be expressed as the turbulence intensity ratio

$$\frac{k}{k_i} = \frac{\sigma^2}{\sigma_i^2} \qquad [10]$$

the expression for the turbulence intensity ratio becomes

$$\frac{\sigma}{\sigma_i} = \left[\frac{\dfrac{k_i^{1/2}}{L_i} + \dfrac{f(\bar{u}-\bar{v})^2}{\tau_d k_i}\dfrac{\tilde{\rho}_d}{\tilde{\rho}_G}}{\dfrac{k_i^{1/2}}{L_h}}\right]^{1/3}. \qquad [11]$$

Solving the fractional change in turbulence intensity, one has

$$\frac{\sigma-\sigma_i}{\sigma_i} = \left[\frac{L_h}{L_i} + \frac{L_h}{k_i^{3/2}}\frac{f(\bar{u}-\bar{v})^2}{\tau_d}\frac{\tilde{\rho}_d}{\tilde{\rho}_G}\right]^{1/3} - 1 = M. \qquad [12]$$

This model predicts that the turbulence can be attenuated if the hybrid length scale becomes smaller than the intrinsic length scale. In other words, the surfaces associated with the particulate phase become more prominent in damping the carrier phase turbulence.

3. COMPARISON WITH EXPERIMENTAL DATA

The amount of experimental data for comparison is limited. Lee and Durst (1982) and Tsuji *et al.* (1984) report measurements on the turbulence intensity change of the carrier fluid (air) with particles flowing upward is vertical ducts. Levy and Lockwood (1981) report similar measurement

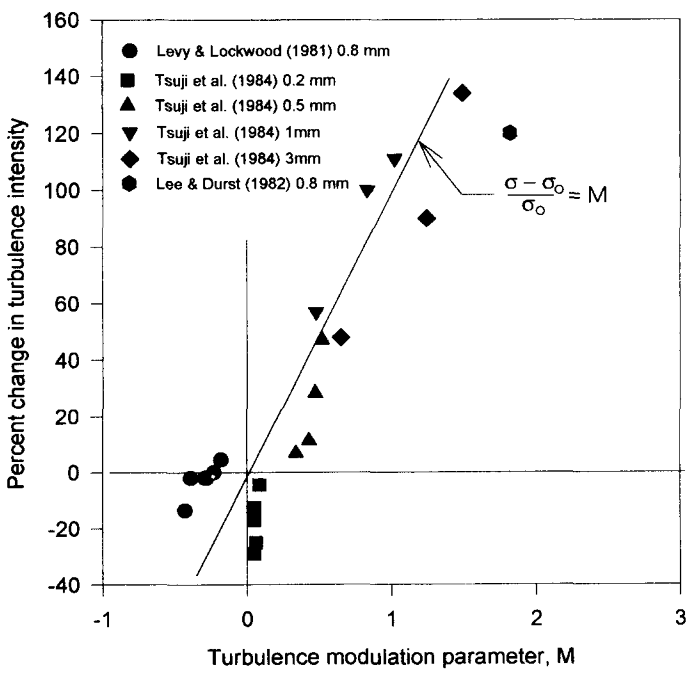

Figure 3. Experimental results vs turbulence modulation parameter.

in particle-laden jets. These data were used for comparison with the model and the results are shown in figure 3. The measured percent change in turbulence intensity ($\sigma - \sigma_i/\sigma_i \cdot 100\%$) is plotted versus the parameter M defined in [12] and reduced from the experimental data. Shown on the same figure is the model prediction represented by [12]. One notes that the model compares reasonably well with the available data. Obviously, the model is based simple idea which requires further substantiation but the comparison suggests the importance of interparticle spacing as a turbulent length scale in particle-laden flows. This finding implies that using 'point' particles to simulate turbulence in fluid particle systems will not capture the contribution due to interparticle spacing.

4. CONCLUSION

A simple model has been developed for carrier phase turbulence in gas-particle flows. The model suggests the importance or interparticle spacing in establishing a turbulence length scale in particle–gas suspensions. The model shows reasonable agreement with the available data though the data are limited.

REFERENCES

Al Taweel, A. M. and Landau, J. (1977) Turbulence modulation in two-phase jets. *Int. J. Multiphase Flow* **3,** 341–351.

Crowe, C. T., Troutt, T. R. and Chung, J. N. (1996) Numerical models for two-phase turbulent flows. *Annual Rev. Fluid Mech.* **28,** 11–43.

Elghobashi, S. E. and Abou-Arab, T. W. (1983) A two-equation turbulence model for two-phase flows. *Phys. Fluids A* **26,** 931–938.

Elghobashi, S. E. and Truesdell, G. C. (1993) On the two-way interaction between homogeneous turbulence and dispersed solid particles. I: Turbulence modification. *Physics of Fluids* **5,** 1790–1796.

Gore, R. A. and Crowe, C. T. (1989) Effect of particle size on modulating turbulent intensity. *Int. J. Multiphase Flow* **15,** 279–285.

Hetsroni, G. (1989) Particles–turbulence interaction. *Int. J. Multiphase Flow* **15,** 735–746.

Hwang, G. J. and Shen, H. H. (1993) Fluctuating energy equations for turbulent fluid–solid flows. *Int. J. Multiphase Flow* **19,** 887–895.

Kataoka, I. (1986) Local instant formulation of two-phase flow. *Int. J. Multiphase Flow* **12,** 745–758.

Kataoka, I. and Serizawa, A. (1989) Basic equations of turbulence in gas–liquid two-phase flow. *Int. J. Multiphase Flow* **15,** 843–855.

Kenning, V. M. (1996) Self-induced turbulence in solid–liquid flow. Ph.D. thesis, Washington State University.

Lee, S. L. and Durst, F. (1982) On the motion of particles in turbulent duct flows. *Int. J. Multiphase Flow* **8,** 125–146.

Levy, Y. and Lockwood, F. C. (1981) Velocity measurements in a particle laden turbulent free jet. *Combustion and Flame* **40,** 333–339.

Liljegren, L. M. and Fosslein, W. (1994) The fluctuating kinetic energy budget in a fluid solid mixture. Battelle PNL Rep. No. SA24560.

Mizukami, M., Parthasarathy, R. N. and Faeth, G. M. (1992) Particle-generated turbulence in homogeneous dilute dispersed flow. *Int. J. Multiphase Flow* **18,** 397–412.

Modarress, D., Tan, H. and Elghobashi, S. E. (1984a) Two-component LDA measurement in a two-phase turbulent jet. *AIAA Journal* **22,** 624–630.

Modarress, D., Wuerer, J. and Elghobashi, S. E. (1984b) An experimental study of a turbulent round two-phase jet. *Chem. Engng Commun.* **28,** 341–354.

Parthasarathy, R. N. and Faeth, G. M. (1990) Turbulence modulation in homogeneous dilute particle-laden flows. *J. Fluid Mech.* **220,** 485–537.

Schreck, S. and Kleis, S. J. (1993) Modification of grid-generated turbulence by solid particles. *J. Fluid Mech.* **249,** 665–688.

Shuen, J. S., Solomon, A. S. P., Shang, Q. F. and Faeth, G. M. (1985) Structure of particle-laden jets: measurements and predictions. *AIAA Journal* **23,** 396–404.

Squires, K. D. and Eaton, J. K. (1990) Particle response and turbulence modification in isotropic turbulence. *Phys. Fluids A* **2,** 1191–1203.

Tsuji, Y., Morikawa, Y. and Shiomi, H. (1984) LDV measurements of an air–solid two-phase flow in a vertical pipe. *J. Fluid Mech.* **139,** 417–434.

Yarin, L. P. and Hetsroni, G. (1994) Turbulence intensity in dilute two-phase flows—3. *Int. J. Multiphase Flow* **20,** 27–44.

Yokuda, E. (1990) Particle dispersion in particle generated turbulence. M.S. thesis, Washington State University.

Yuan, Z. and Michaelides, E. E. (1992) Turbulence modulation in particulate flows—a theoretical approach. *Int. J. Multiphase Flow* **18,** 779–785.