Fluid–Solid Interaction in Particle-Laden Flows

Q. Q. Liu[1] and V. P. Singh, F.ASCE[2]

Abstract: Using a laser-Doppler split-phase measuring technique, the rates of fluctuation in horizontal and vertical directions of pipe flow containing solid particles were observed. Employing these observations the effect of particles on flow turbulence was analyzed and a formula for determining the initial condition of particles restraining the flow turbulence in the mainstream region was developed. The mechanisms affecting the energy loss of flow were then analyzed.

DOI: 10.1061/(ASCE)0733-9399(2004)130:12(1476)

CE Database subject headings: Turbulence; Energy loss; Two phase flow; Particle interactions; Velocity; Pipe flow.

Introduction

Sediment-laden water flow is a special case of two-phase flow. One of the basic problems in two-phase flow is the interaction between particles and water, which has been a subject of much interest during the past half century (Bagnold 1962; Monte and Arthur 1973; Lee and Durst 1982; Hetsroni 1989; Lyn 1992; Lu et al. 1996; Nguyen and Fletcher 1999; Ooms and Jansen 2000; Ljus et al. 2002; Cao et al. 2003). The motion of particles is induced by the flow of water and inversely influences the structure of flow. The flow turbulence, fluctuations of water and particles, and the loss of flow energy caused by particles are related to the interaction between water and particles. Qian and Wan (1986) summarized investigations before the 1980s.

The last two decades have witnessed remarkable advances in the two-phase flow theory, partly due to the considerable progress achieved in measurement techniques, especially in the use of lasers to evaluate the component velocities of the two phases. Laser technology has facilitated acquisition of experimental data which, in turn, have helped develop a better understanding of flow mechanisms (Ohba and Yuhara 1979; Lee and Durst 1982; Tsuji and Morikawa 1982; Lu et al. 1988; Nino and Garcia 1996; Liu 1998; Sommerfeld and Huber 1999; Aísa et al. 2002). Nevertheless, the results of various investigations were significantly different owing to the limitations of measurement technology. As a result, there has been much controversy over the effects of particles on turbulent flows. Among them, two major controversies are turbulence modulation (enhancement or attenuation) and flow energy loss (increase or decrease).

Different experimental observations have, sometimes, obtained different results. For example, Elata and Ippen's (1961) measurements for nearly neutrally buoyant particle-laden flows with high particle concentrations showed an increase in the flow turbulence intensity. Muller (1973) also suggested increased flow turbulence intensity based on the LDV (laser Doppler velocimeter) measurements for coarse sand-laden flows. Van Ingen (1981) and Lyn (1992) reported that no appreciable change occurred in turbulence intensity for fine sand-laden flow, whereas Xingkui and Ning's (1989) experiments for both natural sands and neutrally buoyant plastic particles indicated an appreciable decrease in turbulence intensity. These results have shown that under different conditions the influence of particles on turbulence is different.

Based on experimental data, Gore and Crower (1989) concluded that the influence of particles on turbulence was dependent on the particle diameter. They used $d_p/le=0.1$ (d_p=diameter of particle and le=characteristic length of flow) as a critical characteristic value to evaluate the increase or decrease of the intensity of flow turbulence due to solid particles. It has been found that turbulence may be enhanced when suspended particles are larger than the turbulence length scale, or suppressed as they are so fine as to be enclosed within turbulent eddies. Hetsroni (1989, 1993) further concluded that the grain Reynolds number determined the weakening or strengthening of the flow turbulence intensity. When the grain Reynolds number exceeded a certain value (>400), trailing vortices would divorce from particles, resulting in increased turbulence intensity. On the contrary, when the grain Reynolds number was small (<100), the trailing vortices would not divorce from particles and the turbulence intensity would not increase.

Using a hydrogen bubble as an indicator to observe the sublayer bursts of flow, Rashidi et al. (1990) found that smaller particles reduced the number of bursts of the sublayer in the flow, and consequently the turbulence intensity and Reynolds shear stress were weakened. Likewise, coarser particles increased the number of bursts to increase the turbulence intensity and the Reynolds shear stress. The experiments of Best et al. (1997), using phase Doppler anemometry, showed that both enhancement and attenuation of turbulence intensity depended on the distance from the bed with differing values of the particle Stokes number, the ratio of particle size to turbulence length scale, and sediment concentration. All these investigations emphasize the importance of the interaction between solid and fluid phases on turbulence and the energy interchange between the two phases.

As to the loss of flow energy caused by the existence of par-

[1]Professor, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China; presently, Visiting Professor, Dept. of Civil and Environmental Engineering, Louisiana State Univ., Baton Rouge, LA 70803. E-mail: qqliu@imech.ac.cn, qliul@lsu.edu

[2]A.K. Barton Professor, Dept. of Civil and Environmental Engineering, Louisiana State Univ., Baton Rouge, LA 70803-6405. E-mail: cesing@lsu.edu

Note. Associate Editor: Michelle H. Teng. Discussion open until May 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 5, 2003; approved on May 18, 2004. This paper is part of the ***Journal of Engineering Mechanics***, Vol. 130, No. 12, December 1, 2004. ©ASCE, ISSN 0733-9399/2004/12-1476–1485/$18.00.

ticles, there seem to be three viewpoints (Liu et al. 1996): (1) the existence of particles increases the loss of flow energy; (2) the existence of particles decreases the loss of flow energy; and (3) the loss of flow energy may both be increased or decreased by the particles. Thus the mechanism affecting the loss of flow energy due to particles is not yet completely clear.

The difference between the motion of particles and that of water is rather small but the particle–water interaction is quite complex. As a result, our understanding of the interaction in fluid–solid flow is still limited and far from complete, as compared with gas–solid flow. Thus the objective of this study is to further investigate the particle–water interaction in fluid–solid flow, which includes the following four aspects: (1) evaluate the difference between flow turbulence and particle fluctuation based on experimental observations, especially in the region close to a wall where there are significant effects on the motions of two phases; (2) analyze the influence of particles on flow turbulence from the point of view of changing the source of disturbance and the stability of flow; (3) derive a condition for particles restraining the flow turbulence in the main region of the stream; and (4) determine the mechanism and two aspects of particles affecting the loss of flow energy from two basic points: the mechanism of particles suspension in horizontal water flow and the processes of transmission and loss of flow energy.

Experiment Setup and Measurement Method

Experiment Setup

Experiments were conducted in both horizontal and vertical transparent pipes as shown in Fig. 1. Pipes were 100 cm long, with a rectangular section 1.5 cm $\times$ 3.0 cm. A small water tank was fitted with a small pump. The speed and the rate of flow were adjusted through a variable voltage. During the liquid–solid flow experiments, particles were directly placed in the water tank and mixed with water, forming a self-circulatory flow. In the experiments on both vertical and horizontal pipe flows, the measurement section was 67.5 cm away from the inlet where the flow was relatively stable. The coordinate system of the measurement section is shown in Fig. 2.

Measurement Method

The laser-Doppler split-phase velocity measurement system was used in the experiments. It was comprised of a 1D laser and a set of two-phase data split-phase collecting and processing system (including a two-phase signal phase splitter, time-sharer, data signal processor, and computer) (Lu et al. 1988; Liu 1998). The laser was a one-dimensional fringe type system, working in a forward diffusive model and straightforward acceptance. The power of the He–Ne laser was 12 MW. After expanding 2.2 times, the launching angle of the laser beam in the air was 8.36°. The relative receiving aperture F/No=16, the spin hole diameter was 0.15 mm, and the speed-frequency conversion factor K =230.2 kHz/(m/s).

The time-averaged velocity, turbulent (fluctuation) intensity on any point in the selected section can be measured. The number of particles passing through this point during a certain time can be also obtained and can be regarded as a relative concentration. The concentration in this section was measured by the sampling method, which was used for reference and contrast.

Owing to the limitations of the light permeability of the laser-Doppler velocimeter, the maximum volume concentration of particles in the flow must be less than 0.005. According to the principal of phases splitting, only the particle phase and the fluid phase can be differentiated, and the accurate size of particles cannot be determined. In general, particles larger than 50 μm in diameter are regarded as constituting the particle phase, and particles smaller than 6 μm in diameter are regarded as constituting the fluid phase. The particles with a diameter between 6 and 50 μm will not be differentiated to maintain the reliability of the separation of the two phases.

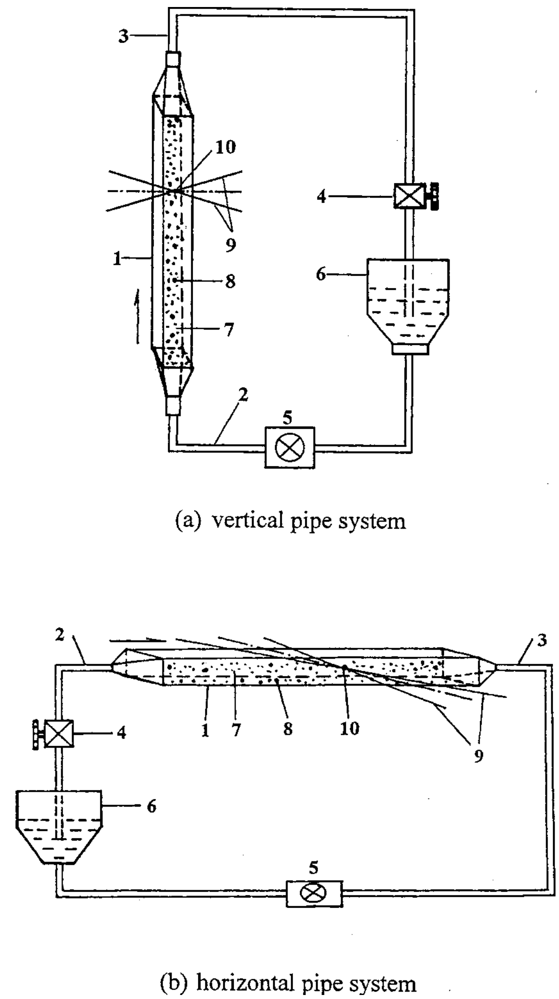


Fig. 1. Schematic view of experimental setup: 1. Experimental pipe; 2. up pipe; 3. down pipe; 4. control valve; 5.pump; 6. fluid vessel; 7. water flow; 8. particle; 9. laser beam; and 10. measurement point

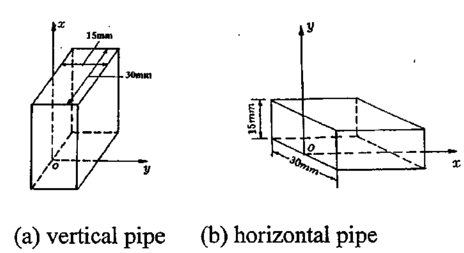


Fig. 2. Schematic diagram of the coordinate system of the measurement sections

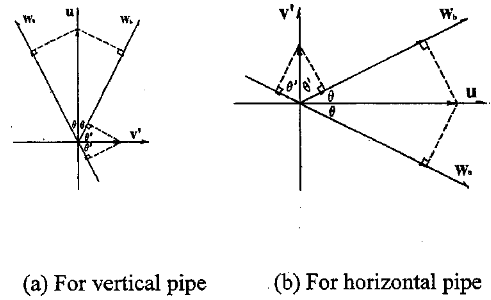


Fig. 3. Coordinate system for deriving the transverse turbulent velocity

In the experiments, a moderate amount of silica gel particles with 3 μm diameter were added to the filtered water which was used to represent the fluid phase, and the Reynolds number of the flow was controlled between 5×10^3–2×10^4. In order to eliminate the influence caused by the particle tail separation, the particle Reynolds number was generally less than 110. In practical applications the particle Reynolds number can be chosen to be less than 400.

The longitudinal velocity fluctuation (along the flow direction) was directly measured. However, the transverse velocity fluctuation (perpendicular to the flow direction) was not directly measured but was obtained by combining velocity fluctuations in the directions with an angle of θ and −θ to the main flow with the results in the mainstream (Liu and Lu 1993).

As shown in Fig. 3, ignoring the transverse time-averaged velocity, one has

$$\overline{v'^2}=\frac{1}{2\sin^2\theta}(\overline{w_a'^2}+\overline{w_b'^2}-\overline{2u'^2}\cos^2\theta) \tag{1}$$

where v'=transverse velocity fluctuation, u'=longitudinal velocity fluctuation, and w_a', w_b'=velocity fluctuation components in the directions with an angle of θ and −θ to the mainstream, respectively. In the experiments, we chose θ=60°.

Because of the limitations of the laser system, the transverse velocity fluctuation was not directly measured but was obtained with the aid of the results obtained in the direction with an angle of θ and −θ to the main flow. The laser beam was required to turn by an angle θ (or −θ) in the measurements, but this made it difficult to observe the transverse velocity fluctuation very close to the wall. Therefore the data on the transverse flow turbulent velocity very near the wall could only be inferred. In addition, since the optical conditions of observation at different points for the circular pipe are different, in the experiments we used instead the rectangular pipe to ensure the same optical conditions of observations at different measurement points along the transverse axis.

Experimentation

Experiment 1

Using the laser-Doppler split-phase measurement technique, experiments were conducted on particle-laden pipe flows in horizontal and vertical tubes, respectively. Glass particles 0.145–0.175 mm in diameter were used in the experiments. The longitudinal (flow direction, i.e., x direction in Fig. 2) and transverse (perpendicular to flow direction, i.e., y direction in Fig. 2) velocity fluctuations of both the particle-phase and the water-phase were observed along the center line of the measurement section. In experiments, the longitudinal velocity fluctuations of both phases were observed at first. Then, keeping the same flow condition, the velocity fluctuations in both phases in the direction with an angle of 60° and −60° to the main flow were observed; respectively. Finally, the transverse velocity fluctuations were obtained by using Eq. (1) (θ=60°). The experimental results of the horizontal and the vertical pipe flows are shown in Figs. 4 and 5, respectively.

Experiment 2

In the horizontal pipe flow, the turbulence intensity (flow direction) of clear water in the center point of the measurement section was observed at first under the flow condition of having the flow Reynolds number ($\mathsf{R}_f=UR/\nu$, U=cross-section-averaged velocity of pipe flow; R=hydraulic radius of pipe flow; and ν=kinematic viscosity of water) of 14,700. Then, keeping the same flow condition ($\mathsf{R}_f=14{,}700$) and adding the polystyrene particles with a diameter of 0.15–0.20 mm to the flow, the flow turbulence intensities (flow direction) at the same point for different particle concentrations were observed for comparing with that of clear water flow. The results of statistical analysis of a large amount of sampling data showed that the measured value of turbulence intensity of particle-laden flow was lower than that of clear water. Therefore the decrement (ΔE) of flow turbulence intensity (E) was examined, and the values of $\Delta E/E$(%) for different particle concentrations are shown in Fig. 6.

Experiment 3

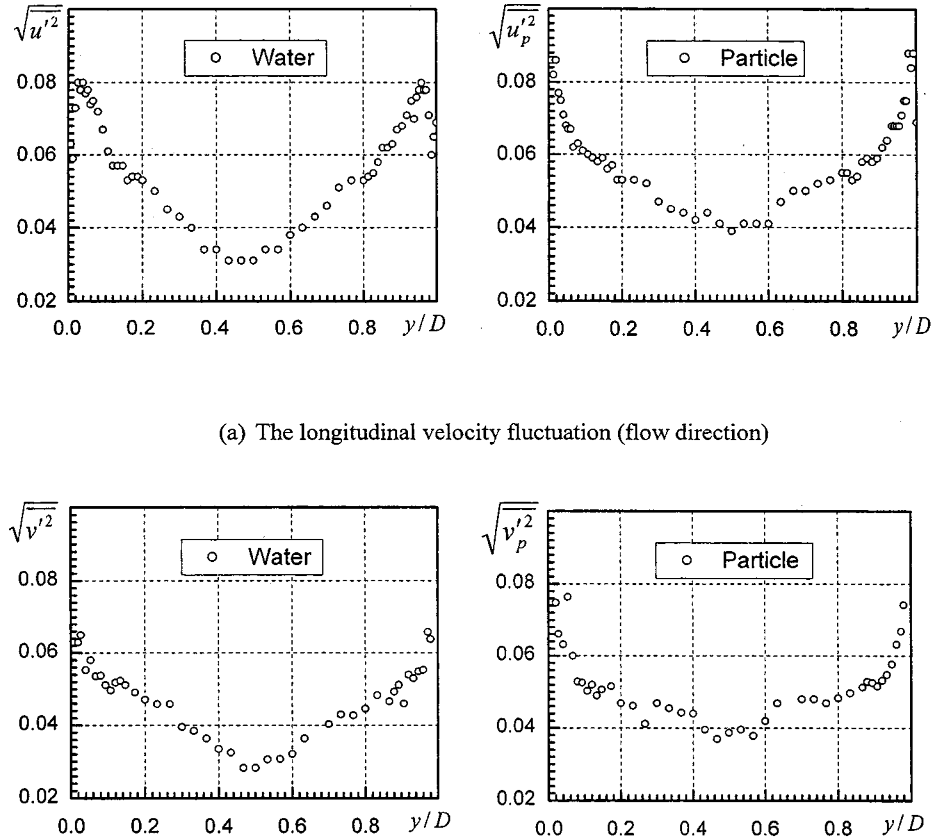
For the horizontal pipe system, two kinds of polystyrene particles of d_p=0.45–0.50 mm and d_p=0.17–0.20 mm were added to the flow, respectively. Then, keeping other conditions constant and only changing the flow rate (flow Reynolds number), the flow turbulence intensity at the center point of the measurement section was observed by the laser-Doppler velocimeter. Similar to Experiment 2, the decrement (ΔE) of flow turbulence intensity, comparing with clear water flow, was examined, and the values of $\Delta E/E$(%) for different flow Reynolds numbers are shown in Fig. 7.

Experimental Results

Velocity Fluctuations of Solid and Liquid Phases

Experimental results of vertical and horizontal pipe flows, plotted in Figs. 4 and 5, respectively, show that longitudinal and transverse velocity fluctuation profiles of both phases along the transverse axis are similar, and exhibit similar characteristics. Except for a thin region near the wall, the velocity fluctuations of both phases in both directions decrease first, reach a smallest value at the pipe center, and then begin to increase. Regardless of the phase, the transverse velocity fluctuation is generally less than the longitudinal velocity fluctuation. The difference between the two phases becomes larger close to the wall. In the mainstream region away from the wall, both gradually become equal and the flow can be regarded as homogeneous turbulent.

Comparing the results of horizontal pipe flow and vertical pipe flow, there exist small differences, especially in the thin region



(a) The longitudinal velocity fluctuation (flow direction)

(b) The transverse velocity fluctuation (perpendicular to flow direction)

Fig. 4. Longitudinal and transverse velocity fluctuations of both phases distributed along transverse axis in the vertical pipe flow

near the wall. These may be caused by different distributions of particle concentrations in both flows. In the vertical flow, the maximum value of the particle concentration occurs at the center of pipe and decreases gradually from the center to the wall. However, in the horizontal flow the maximum value of the particle concentration occurs at the bottom wall of the pipe and decreases gradually from the bottom wall to the top wall. This may be the main reason causing the distribution of velocity fluctuations to be unsymmetrical, especially for the particle phase. The influence of the bottom wall is more than that of the top wall. In addition, because the condition for observation very near the top wall in the horizontal pipe was not very favorable, the data very near the up wall were not observed. This was perhaps the reason that the wall effect near the $y/D=1$ did not appear distinctly in the experimental results.

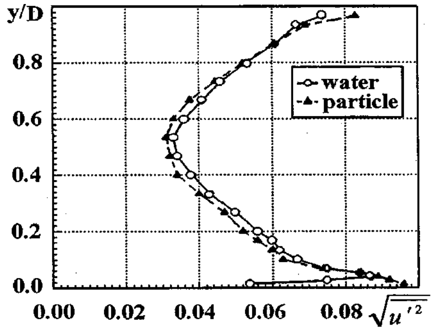
In the experiments, only one transverse velocity fluctuation and its distribution along with one transverse direction were observed. Indeed, because the cross section of the tube was rectangular, the wall effects in both transverse dimensions existed and were different due to different dimensions. The wall effect would be higher along the small dimension. However, it is surmised that the qualitative laws should be similar, although the numerical values may be different.

Comparing the velocity fluctuations of particles and water, one may note three main differences: (1) in the near-wall region, the velocity fluctuation of the particle-phase is generally larger than that of the liquid phase; (2) because of the influence of the wall, the turbulent flow velocity of the liquid phase decreases rapidly near the wall, but this is not true for the particle phase; instead it increases near the wall; and (3) in the mainstream region, the velocity fluctuation of the particle phase is, in general, marginally smaller than that of the fluid phase. However, in a small region around the pipe center, the velocity fluctuation of the particle phase is slightly more than that of the fluid phase in the vertical pipe flow.

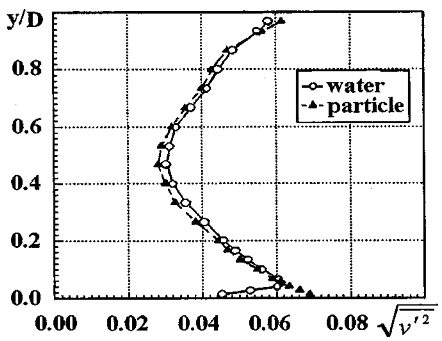
The longitudinal and transverse velocity fluctuations of particles near the wall and around the vertical pipe center are larger than those of the liquid, which cannot be explained by the particles following flow turbulence. According to Liu and Lu (1993), the irregular motion of particles in the solid–fluid flow may have various forms. Besides turbulent fluctuations caused by flow turbulence, there are yet other fluctuation forms which are different from turbulence. It is surmised that the irregular pulsation caused by collision between particles, or particle and wall, is a form of fluctuation which is different from turbulence. The total fluctuation of particles $(\overline{v_p'^2})$ can be regarded as a superposition of turbulent motion $[(\overline{v_p'^2})_T]$ caused by flow turbulence and nonturbulent motion $[(\overline{v_p'^2})_N]$ not caused by flow turbulence (Liu and Lu 1993; Liu 1997), i.e.

$$\overline{v_p'^2} = (\overline{v_p'^2})_T + (\overline{v_p'^2})_N \tag{2}$$

This is the reason that the particles have larger fluctuation intensity than the does the liquid.



(a) Longitudinal velocity fluctuation (flow direction)



(b) Transverse velocity fluctuation (perpendicular to flow direction)

Fig. 5. Longitudinal and transverse velocity fluctuations of both phases distributed in the transverse axis in the horizontal pipe flow

Likewise, according to different fluctuation forms, the fluctuation stress of particles (P) can be divided into turbulence stress (P^T) and nonturbulence stress (P^N), that is

$$P = P^T + P^N \tag{3}$$

Therefore a mechanism for the particle movement in the layer close to the wall is that particles have an intense nonturbulent fluctuation, resulting in the intense fluctuation stress which greatly influences the particle movement in the flow, especially in horizontal flow because of the higher particle concentration near the bottom wall. Bagnold (1954) pointed out that there exist intense discrete force and shear force near the bed in open channel flows. Indeed this is just the result of the nonturbulence stress due to particles near the bottom wall.

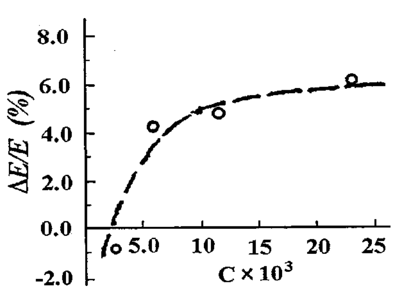


Fig. 6. Variation of $\Delta E/E$ with particles concentration in the horizontal pipe flow (C=particle concentration by volume)

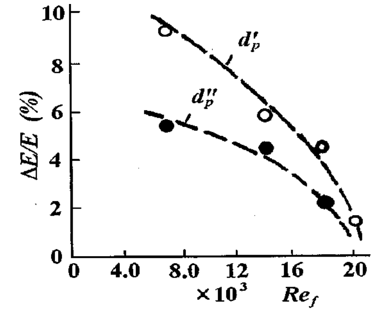


Fig. 7. Variation of $\Delta E/E$ with flow Reynolds number in the horizontal pipe flow

Influence of Particles on Flow Turbulence in Horizontal Flows

The flow turbulence is the result of flow instability and external disturbance, and the particles carried by flow can change the source of disturbance and the stability of flow. The ways in which particles affect turbulent flow can be divided into two types: one is to change the stability of flow, and the other is to change the source of external disturbance. The flow stability is influenced by increasing flow viscosity, extra effective gravity, and buoyancy caused by the particle concentration gradient, relative motion between particles and fluid, and increment of the fluid inertia caused by the increment of the mean specific gravity.

The source of external disturbance is influenced as follows: (1) the shear force is not totally transmitted to the wall to generate vortices anymore because of the existence of particles; (2) a large amount of particles concentrate in the vicinity of the bottom in horizontal flows where the vortices are continually generated; (3) there is a shielding effect of particles on the bottom; and (4) there is collision between particles or between particles and wall. Undoubtedly, all these factors affect the flow turbulence in different ways. The mechanism and the main factors, such as particle concentration, particle diameter, and flow Reynolds number are now analyzed.

Influence of Particle Concentration

The variation of particle concentration influences flow turbulence in various ways. In general, the increment of particle concentration may increase the viscosity of flow, and more particles congregate near the bottom which strengthens the motion of particles on the bottom. At the same time, the impact of more particles intensifies the fluid disturbance. However, for particles of different diameters, the particle concentration has a different influence on the flow turbulence.

Fig. 6 illustrates the decrement of flow turbulent intensity changing with particle concentration. At the beginning, the increment of ΔE is evident as the concentration increases to an average value. Then the increment of ΔE gradually decreases to a very small value. This is due to the effect of the particle concentration affecting the deposition velocity of particles. For particle-laden flows, it is generally accepted that the suspension of particles is sustained by the vertical flow turbulence. Following the analysis of horizontal fluid–solid flow by Azbel (1981), the turbulence energy dissipated on suspension particles, that is, suspension energy, can be expressed as $B \approx (\gamma - 1) g \omega \phi$, where ω=deposition velocity of particles, and ϕ=volumetric particle concentration.

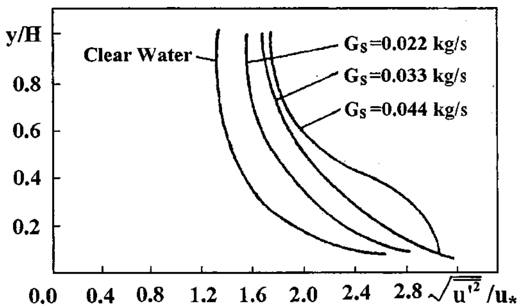


Fig. 8. The flow turbulent intensity profiles for different sediment transport rates in horizontal flow (G_s=sediment transport rate)

When ϕ increases, the viscosity of the medium will increase and ω will decrease. Hence B increases as ϕ will mitigate in high particle concentration.

Our experiments show that particles weaken the flow turbulence. However, the results of experiments, conducted in the Laboratory of High Speed Hydraulics, Chengdu Science and Technology University in China, using coarse sand of $d_{\max}=4$ mm, $d_{50}>1$ mm, shown in Fig. 8, are opposite. These results show that the intensity of flow turbulence intensified due to particles, and the degree of influence on turbulence became more intense as the particle concentration grew higher.

The difference in the results of the two sets of experiments indicates that the effect of variation in the concentration of different particles on the flow turbulence is different. This can be explained as follows: (1) The effect on the viscosity of fluid is different. Fine particles enhance the viscosity more rapidly than do coarse particles: (2) The influence on the vortex generating field near the bottom is different. Because of larger adhesion, finer particles easily conglomerate and may form flocculent structures which lead to vortex generation and mixing becomes difficult. On the other hand, coarse particles have no such effects. (3) The effect on the source of disturbance is different. In one way, the relative motion between particles and fluid can cause a disturbance. The increment of coarse particles largely intensifies the source of disturbance, but such an effect of fine particles is much weaker. In another respect, the compaction between particles also gives rise to the disturbance. The compaction between smaller particles perhaps forms floccus, while the collision between coarse particles generates a large disturbance in the flow. (4) The motion of particles on the bottom intensifies the disturbance. In general, coarse particles moving in the form of bed load are much more than fine particles. Thus the enhancement of bed load motion is mainly due to coarse particles. A large amount of coarse particles roll, skid, and skip on the bed, which is sure to disturb the flow in the near-bed region.

The above analysis shows that the increment of fine particles will suppress the flow turbulence; while the augmentation of coarse particles will give rise to the source of larger disturbance and intensify the flow turbulence. The results also show that different particle concentrations have different influences on the flow turbulence, but the diameter of particles is more important.

Influence of Particle Diameter

Comparison of experimental results shown in Figs. 6 and 8 shows that particles of different diameters have a different influence on the flow turbulence. The above analysis indirectly discusses the results on the influence of particle diameter on flow turbulence. Here, the effect of particle diameter on the source of disturbance and the stability of flow is further analyzed now.

1. The smaller the particle diameter is, the lesser the relative motion between particles and fluid is, and the more difficult it is for the energy carrying vortices to divorce from particles. If the particle diameter becomes larger, the relative motion will increase, which is easy to separate fluid and particles and generate a source of larger disturbance, together with extra turbulence vortices.
2. The smaller the particle diameter is, the stronger the concealing effect on the bottom is, so that the bottom becomes rather smooth, which decreases the disturbance and generally weakens the flow turbulence. If the particles are coarse, there is no concealing effect. Conversely they will enhance the roughness of the bottom resulting in a rougher bed, which largely increases the disturbance and generally intensifies the flow turbulence.
3. In the particle-laden flow, there exists a particle–bottom collision. For small particles, such an effect is quite weak, but for coarse particles, its collision with bottom, its roll and skip on the bottom are strong, and largely intensify the flow disturbance. To summarize, small particles suppress the turbulence but coarse particles intensify it, as shown in Figs. 6 and 8.

Influence of Particles because of Different Flow Reynolds Number

From the experiments shown in Fig. 7, it was also found that the effect of particles on the flow turbulence intensity was different for flows of different Reynolds numbers. For the particles used in the experiments, the measurements showed that the turbulence intensity of particle laden flow was suppressed, compared with that of clear water. As flow Reynolds number R_f decreased, the relative weakening effect of particles on the flow turbulence increased. According to Newitt's semiempirical formula (Govier and Aziz 1972), two kinds of particle-laden flows are in suspension flow with low Reynolds number. When R_f changes, the variation of particle concentration in the mainstream is little. The suspension energy $B[\approx(\gamma-1)g\omega\phi]$ changes a little or does not change at all. But if R_f decreases the turbulence energy P_e decreases correspondingly, so the relatively weakened value of the turbulence intensity B/P_e increases.

Condition for Particles Restraining Turbulence in the Main Stream Region

In the mainstream region far away from the wall, the increase or decrease of the flow turbulence intensity by particles mainly depends on whether the tail vortices separate from particles (Hetsroni 1989, 1993). Theoretically, the condition that particles can only weaken the turbulence and do not cause the tail vortex separation is

$$\mathsf{R}_p=\frac{V_r d_p}{\upsilon_f}<100 \tag{4}$$

where R_p=particle Reynolds number, υ_f=viscosity of fluid, V_r=relative velocity between particles and fluid, and d_p represents the particle diameter.

In Eq. (4) V_r is the key parameter. It is generally assumed that the horizontal relative velocity of particles is zero and the perpendicular relative velocity is equal to the falling velocity, ω. But there exist relative turbulent flow velocities in horizontal and perpendicular directions. Therefore in 2D horizontal flows, V_r=composition of longitudinal relative velocity V_{rl} and perpendicular relative velocity V_{rp}. The particle Reynolds number can be expressed as

$$\mathsf{R}_p = (\mathsf{R}_{pl}^2 + \mathsf{R}_{pp}^2)^{1/2} \tag{5}$$

where $\mathsf{R}_{pl}=V_{rl}d_p/v_f$, $\mathsf{R}_{pp}=V_{rp}d_p/v_f$.

Usually it is not easy to express R_{pl}. Levich (1962) investigated the motion of particles larger than the smallest vortex. From the homogeneous turbulence theory, he derived a formula for the maximum relative velocity in gas–solid flow under the condition that the apparent body force and the gravity are neglected and the resistance coefficient remains constant. In the present study, the apparent body force was added to this formula to evaluate the maximum relative velocity $\tilde{V}_r$ of particles in the solid–liquid flow. The particle Reynolds number $\tilde{R}_\text{p}$ corresponding to $\tilde{V}_r$ can be expressed as

$$\tilde{\mathsf{R}}_p \approx 0.504\left(\frac{\rho_p - \rho_f}{\rho_p + \frac{1}{2}\rho_f}\right)^{1/2}\left(\frac{\rho_p + \frac{1}{2}\rho_f}{\rho_f}\right)^{1/3}\left(\frac{4}{C_d}\right)^{1/3}\left(\frac{d_p}{D_e}\right)^{4/3}\mathsf{R}_f \tag{6}$$

where C_d=resistant coefficient, D_e=flow scale, ρ_f=density of fluid, and ρ_p=density of particles. Here turbulence in the mainstream region is assumed to be homogeneous, so $\tilde{\mathsf{R}}_p$ is the maximum of longitudinal particle Reynolds numbers R_{pl}. It is also the maximum turbulent part of the perpendicular particle Reynolds number R_{pp}. Hence the composite Reynolds number can be written as

$$\mathsf{R}_{pc} = (\mathsf{R}_{p\omega}^2 + 2\tilde{\mathsf{R}}_p^2)^{1/2} \tag{7}$$

where $\mathsf{R}_{p\omega}$ denotes the particle Reynolds number corresponding to the gravitational fall velocity. Because the interrelation of perpendicular turbulent motion in homogeneous turbulence is zero, the term $2\tilde{\mathsf{R}}_p^2$ is a conservative value. In the range $0.4<\mathsf{R}_p<500$, the particle gravitational deposition velocity can be expressed as (Qian and Wan 1986)

$$\omega = \left(\frac{4}{225}\right)^{1/3}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)^{1/3} g^{2/3} v_f^{-1/2} d_p \tag{8}$$

The corresponding particle Reynolds number is

$$\mathsf{R}_{p\omega} = \frac{\omega d_p}{v_f} \approx 0.261\left(\frac{\rho_p}{\rho_f} - 1\right)^{2/3}\left(\frac{g d_p^3}{v_f^2}\right)^{2/3} \tag{9}$$

It is seen from Eqs. (6) and (9) that parameter d_p is expressed in dimensionless forms: d_p/D_e and gd_p^3/v_f^2. It has a significant effect on the condition that the tail vortex does not separate. Other parameters, such as R_f which has a large range and ρ_p/ρ_f, are also important. Eqs. (6) and (9) are applicable to gas–solid flow and vertical flow. This explains why the method introduced by Gore and Crower (1989), in which only a parameter d_p/le (proportional to d_p/D_e) is used to determine whether the turbulence will be weakened or intensified, can be applied to most but not all experimental data. According to Eq. (7), the condition for restraining turbulence is

$$\mathsf{R}_{pc} = (\mathsf{R}_{p\omega}^2 + 2\tilde{\mathsf{R}}_p^2)^{1/2} < 110 \tag{10}$$

On the other hand, particles should be carried by large scale vortices, so partial turbulence energy can be dissipated. The vortex corresponding to Prandtl's mixing length is the large scale vortex carrying energy with the characteristic time (Davies l972), T_p, as

$$T_p \approx 0.4 D_e^2 \mathsf{R}_f^{-7/8} v_f^{-1} \tag{11}$$

The condition that particles respond to the vortex motion is that the characteristic time of the vortex is several times the relaxation time of particles τ^*. Supposing it be two times

$$R = T_p/\tau^* > 2 \tag{12}$$

$$\tau^* = \frac{d_p^2}{18 v_f\, k}\left(\frac{\rho_p + 0.5\rho_f}{\rho_f}\right) \tag{13}$$

where k=revised coefficient of resistance function in the Stokes formula. In the range of $1<\mathsf{R}_p<200$, $k\approx \mathsf{R}_p^{0.34}$. For heavy coarse particles, R_p is replaced by $\mathsf{R}_{p\omega}$. Substituting these into Eq. (12), one obtains

$$R \approx \frac{4.56}{\mathsf{R}_f^{7/8}}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)^{0.227}\left(\frac{\rho_f}{\rho_p + 0.5\rho_f}\right)\left(\frac{D_e}{d_p}\right)^2\left(\frac{g d_p^3}{v_f^2}\right)^{0.227} \tag{14}$$

Here D_e/d_p is the key parameter. In the experiments, it was found that $\mathsf{R}_{pc}<110$ and $R>3.0$. This explains why the particles used in the experiments suppressed the flow turbulence.

To summarize, in the mainstream region of horizontal flow if Eqs. (10) and (12) are satisfied, the particles will suppress the flow turbulence. Both equations have several parameters, the scale ratio of the fluid and particle D_e/d_p is the most important. The flow Reynolds number R_f and the density ratio of particles and fluid ρ_p/ρ_f are also important. In addition, parameter gd_p^3/v_f^2 has a strong influence on the separation of vortices, but has a secondary effect on the dissipation of turbulence energy by particles. The flow satisfying Eq. (12) may not necessarily satisfy Eq. (10); thus the increase or decrease of turbulence depends on the comparison of both aspects.

Effect of Particles on the Loss of Flow Energy in Horizontal Flows

Mechanism of Particle Suspension

In order to clarify how the suspended particles act on the energy loss of water flow, it is first necessary to expound how particles are suspended in the flow. The past investigations discussed the suspension of particles by analyzing the action forces on a single particle. However, the motion of particles in water flow is a kind of group motion. Therefore suspension of particles from the point of view of the momentum equilibrium of group particle motion will be analyzed here. For steady flow, the equation of motion for particles in the vertical direction can be expressed as

$$\frac{\partial(\alpha_p u_p v_p)}{\partial x} + \frac{\partial(\alpha_p v_p v_p)}{\partial y} = -\alpha_p g_p - \frac{\alpha_p}{\rho_p}\frac{\partial p}{\partial y} + \frac{f_y}{\rho_p} + \frac{F_L}{\rho_p} \tag{15}$$

where u_p and v_p=particle velocities in the horizontal and vertical directions, respectively; ρ_p=density of particles; f_y=vertical resistance of the water flow on particles; α_p=fractional number of volume of particles; p=pressure of water flow; and F_L=uplift force of flow acting on particles.

Taking time-averaging of Eq. (15) and neglecting high order small quantities, one obtains

$$\frac{\partial(\alpha_p \overline{v_p' v_p'})}{\partial y} = -\alpha_p g_y - \frac{\alpha_p}{\rho_p}\frac{\partial p}{\partial_y} + \frac{f_y}{\rho_p} + \frac{F_L}{\rho_p} \tag{16}$$

where $\alpha_p=m_p n_p/\rho_p$, m_p=mass of particles, n_p=number density of particles; $\partial p/\partial y=-\rho_f g$, ρ_f=water density. Assuming $F_L=n_p m_p a$

(a=acceleration velocity due to by the uplift force F_L), Eq. (16) can be transformed into the following form:

$$\frac{\partial}{\partial y}(m_p n_p \overline{v_p'^2}) = -m_p n_p g\left(1-\frac{\rho_f}{\rho_p}\right) + f_y + m_p n_p a \qquad (17)$$

On the right side of Eq. (17), $m_p n_p g(1-\rho_f/\rho_p)$ expresses the gravity force of particles under water. The left term of this equation expresses the momentum transport rate of particle fluctuations in the vertical direction. Eq. (17) shows that the gravity and buoyancy forces acting on the particles can be balanced by both the momentum of the fluctuations of the moving particles and the uplift force with which the water flow acts on the particles. Thus it can be concluded that the vertical fluctuation of particles is one of the most important mechanisms raising the particles from the bottom.

The fluctuation of particles may have various forms, such as heat motion, and the fluctuation of particles induced by turbulent flow. Besides these, there is still some random motion taking on other forms. The saltation of particles and their impact on the bottom can also lead to the fluctuation of particles (Liu and Lu 1993).

Influence of the Existence of Particles

It was concluded that suspension of particles depends mainly on the momentum of particle fluctuation in the vertical direction. The particle fluctuation is caused partly by the flow turbulence. Therefore a part of the turbulent kinetics energy of the flow is used to support the suspension of particles. However, it does not directly consume the effective mechanical energy. From this viewpoint, the existence of sediment particles does not affect the loss of flow energy.

While the random motion of particles occurs near the bottom, except for the fluctuation of particles induced by turbulent flow, there is a more important factor, i.e., the saltation of sediment particles and the impact of particles on the bottom. In other words, if there exists the suspension of particles, there must exist the saltation and impingement of particles on the bottom. It is impossible to imagine the existence of particle suspension without particle contact on the bottom. The saltation of particles and the impact on the bottom transmit part of the energy and momentum to the bottom and consume energy. Hence, in order to keep particles in equilibrium (statistically averaged), the effective energy must be continually extracted from the flow. From this viewpoint, the existence of particles greatly increases the loss of flow energy.

On the other hand, particles affect the loss of flow energy through their influence on the flow turbulence. The existence of particles in accordance with different conditions of flow and the properties of particles may have differing influence on turbulence intensity, i.e., the existence of particles may both weaken and increase the turbulence intensity and consequently its effect on the loss of flow energy varies. To that end, consider the equilibrium equation of the flow energy

$$-u\frac{d\tau}{dy} = \tau\frac{du}{dy} - \frac{d}{dy}(\tau u) \qquad (18)$$

where u=longitudinal velocity of particle-laden flow at y, and τ=shear stress at y. In Eq. (18) the left-hand side is the energy provided by flow. The first term on the right-hand side is the loss of energy to overcome the resistance. The second term on the right-hand side is the energy at y in a unit water body to be transmitted downward.

Since the mechanical energy provided by the flow is not equal to the energy loss due to the local resistance, energy comes mainly from the main flow region, while the energy loss is focused in the flow region near the boundary. This reveals that there is an energy transition and a relevant process in certain strata of the flow. The energy deficit in the lower layers may be supplied from the excessive energy in the upper layers. Combining with the turbulent flow configuration, one can visualize that the effective potential energy can be transmitted to the boundary and produce turbulent vortices, which will be defused into the main flow region and will gradually break down into small-sized ones and finally be transformed through viscosity as heat is consumed. Thus the kinetic energy of turbulence comes from the effective potential energy and is finally transformed into heat. It must, however, be emphasized that the kinetic energy of turbulence is originally a medium of the energy transformation process. To take out part of the kinetic energy of turbulence to support the suspension of sediment does not mean an increase of the loss of effective potential energy. Therefore the existence of suspended particles weakening or increasing the intensity of turbulence does not directly translate into the decrease or increase of energy loss.

Nevertheless, the change of turbulence intensity can affect the variation of the local loss of flow energy. The weakening of turbulence intensity (if the dimensional size is not changed) means the decrease of effective viscosity. When the shear stress remains unchanged, it means the velocity gradient will increase and the local dissipation of mechanical energy will increase. When the velocity gradient is unchanged, the shear stress and local dissipation of mechanical energy decrease. In other words, under certain conditions the weakening or increasing of turbulence intensity will lead to the local decrease or increase of the energy loss. However, considering the total energy loss (not equivalent to the local mechanical dissipation), it is possible that the energy loss of particle-laden flow is greater, equivalent to, or smaller than the energy loss of clear water flow. It depends on the final results of the resultant action. Generally speaking, the weakening of turbulence intensity mostly leads to the decrease of the loss of flow energy, while the enhancement of turbulence intensity mostly leads to the increase of the loss of flow energy.

It is seen that there exist diversified complicated interactions between particles and flow, and all of these interactions influence the loss of the flow energy in different ways. Therefore, whether the existence of particles will increase or decrease the energy loss of flow depends on the final result of the resultant action. In other words, the effect of particles on the loss of flow energy may vary in accordance with the difference of particles and flow conditions.

Conclusions

1. There is a difference between fluctuation intensities and forms of particles and liquid. Except for the fluctuation caused by the flow turbulence, the particle phase has other nonturbulent fluctuations. Especially in the thin region near the wall, the particle phase has intense nonturbulent fluctuation, resulting in the fluctuation stress, which greatly influences the particle movement.
2. The factors affecting the flow turbulence vary with the conditions of flow and particles (concentration and diameter). In general, fine particles weaken the flow turbulence, and coarse particles increase the flow turbulence.

3. The effect of particles on the flow turbulence depends on the particle diameter, particle concentration, and flow Reynolds number. An initial condition of particles restraining flow turbulence in the mainstream region is derived.
4. The vertical fluctuation of particles near the bottom is one of the main mechanisms that generates particle suspension in flow, which leads to the loss of flow energy. At the same time, the existence of particles also influences the energy loss by changing the flow turbulence. Although the increase or decrease of flow turbulence intensity is not equal to the increase or decrease of the loss of flow energy, the variation of flow turbulent intensity indeed influences the variation of local flow energy loss. Generally, the decrease of turbulence intensity leads to the decrease of flow energy loss, and the increase of turbulence intensity increases the loss of flow energy. For the total loss of flow energy, both increase and decrease of the flow energy loss due to particles may occur.

Acknowledgment

This research was financially supported by the Key Project of the Chinese Natural Science Foundation (No. 10332050).

Notation

The following symbols are used in this paper:

a = acceleration velocity due to by the uplift force F_L;
$\boldsymbol{B}$ = turbulence energy dissipated on suspension particles;
C_d = resistant coefficient;
D = diameter of pipe;
D_e = flow scale;
$d_{\max}$ = maximum diameter of particles;
d_p = diameter of particle;
d_{50} = median grain size of particles;
E = flow turbulence intensity;
F_L = uplift force of flow acting on particles;
f_y = vertical resistance of the particles to water flow;
g = gravitational acceleration;
g_y = gravitational acceleration exponent in the y direction;
k = revised coefficient of resistance function in the Stokes formula;
l_e = characteristic length of flow;
m_p = the mass of particles;
n_p = number density of particles;
P = fluctuation stress of particles;
P^N = nonturbulence stress of particles;
P^T = turbulence stress of particles;
P_e = turbulence energy;
p = pressure of water flow;
R = parameter defined by Eqs. (14) and (16) as well;
R_f = flow Reynolds number;
R_p = particle Reynolds number;
$\widetilde{\mathsf{R}}_p$ = particle Reynolds number corresponding to $\widetilde{V}_r$;
R_{pc} = $(\mathsf{R}_{pw}^2+2\widetilde{\mathsf{R}}_p^2)^{1/2}$;
R_{pl} = particle Reynolds number corresponding to V_{rl};
R_{pp} = particle Reynolds number corresponding to V_{rp};
R_{pw} = particle Reynolds number corresponding to the deposition velocity of particles;
T_p = characteristic time of large scale vortex carrying energy;
u = flow velocity in the horizontal (or longitudinal) direction;
u' = turbulent flow velocity in the horizontal (or longitudinal) direction;
u_p = particle velocity in the horizontal (or longitudinal) direction;
u_p' = particle velocity fluctuation in the horizontal (or longitudinal) direction;
V_r = relative velocity of particles;
v = flow velocity in the vertical (or transverse) direction);
v' = turbulent flow velocity in the vertical (or transverse) direction;
v_p = particle velocity in the vertical (or transverse) direction;
v_p' = particle velocity fluctuation in the vertical (or transverse) direction;
$\widetilde{V}_r$ = maximum relative velocity of particles;
V_{rl} = composition of longitudinal relative velocity of particles;
V_{rp} = composition of perpendicular relative velocity of particles;
w_a' = turbulent flow velocity components in the directions with an angle of θ;
w_b' = turbulent flow velocity components in the directions with an angle of $-\theta$;
x = the coordinate along in the horizontal (or longitudinal) direction;
y = the coordinate along in the vertical (or transverse) direction;
α_s = fractional number of volume;
γ = specific weight of particles;
ΔE = decrement of flow turbulence intensity;
v_f = viscosity of fluid;
ρ_f = density of fluid;
ρ_p = density of particles;
τ = shear stress at y;
τ^* = relaxation time of particles;
ϕ = volumetric particle concentration; and
ω = deposition velocity of particles.

References

Aísa, L., Garcia, J. A., Cerecedo, L. M., Palacín, I. G., and Calvo, E. (2002). “Particle concentration and local mass flux measurements in two-phase flows with PDA. Application to a study on the dispersion of spherical particles in a turbulent air jet.” *Int. J. Multiphase Flow*, 28(2), 301–324.

Azbel, D. (1981). *Two-phase flow in chemical engineering*, Cambridge University Press, Landon.

Bagnold, R. A. (1954). “Experiments on a gravity-free dispersion of large solid particles in a Newtonian fluid under shear.” *Proc. R. Soc. London, Ser. A*, 225(1332), 49–63.

Bagnold, R. A. (1962). “Auto-suspension of transported sediment, turbidity currents.” *Proc. R. Soc. London, Ser. A*, 265, 315–319.

Best, J., Bennett, S., Bridge, J., and Leeder, M. (1997). “Turbulence modulation and particle velocities over sand beds at low transport rates.” *J. Hydraul. Eng.*, 123(12), 1118–1129.

Cao, Z. X., Egashira, S., and Carling, P. A. (2003). “Role of suspended-sediment particle size in modifying velocity profiles in open channel flows.” *Water Resour. Res.*, 39(2), 1029–1043.

Davies, J. T. (1972). *Turbulence phenomena*, Academic, New York, 58.

Elata, C., and Ippen, A. T. (1961). “Dynamics of open channel flow with suspensions of neutrally buoyant particles.” *Technical Rep. 45*, Hy-

drodynamic Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.
Gore, R. A., and Crower, C. T. (1989). “Effects of particle size on modulating turbulent intensity.” *Int. J. Multiphase Flow*, 15(2), 179–285.
Govier, G. W., and Aziz, K. (1972). *The flow of complex mixture in pipes*, Van Nostrand Reinhold, New York, 649.
Hetsroni, G. (1989). “Particles-turbulence interaction.” *Int. J. Multiphase Flow*, 15(2), 735–746.
Hetsroni, G. (1993). “The effect of particles on the turbulence in boundary layer.” *Particulate two phase flow*, M. C. Rocco, ed., Butterworth-Heinemann, Wobum, Mass., 244–264.
Lee, S. L., and Durst, F. (1982). “On the motion of particles in turbulent duct flows.” *Int. J. Multiphase Flow*, 8, 125–146.
Levich, V. G. (1962). *Physicochemical hydrodynamics* (translated from Russian by Scripta Technica, Prentice-Hall, Englewood Cliffs, N.J.).
Liu, Q. Q. (1997). “The mechanics properties of sediment movement in layers close to the bed.” *J. Basic Sci. Eng.*, 5(1), 56–66 (in Chinese).
Liu, Q. Q. (1998). “LDV measurements and experimental study of water and sediment two-phase flow.” *J. Sediment Res.*, 2, 71–79 (in Chinese).
Liu, Q. Q., Chen, L., and Liu, D. Y. (1996) “ Effect of existence of sediment particles on the energy loss of flow.” *Int. J. Sediment Res.*, 11(3), 18–24.
Liu, D. Y., and Lu, Z. M. (1993). “Various kinds of random motion and stress in two-phase flows.” *Proc., 2nd Int. Conf. on the Fluid Mechanics*, Peking University Press, Beijing, 782–788.
Ljus, C., Johansson, B., and Almstedt, A. E. (2002). “Turbulence modification by particles in a horizontal pipe flow.” *Int. J. Multiphase Flow*, 28(7), 1075–1090.
Lu, Z. M., Li, G. D., and Peng, W. S. (1988). “LDA measurements of bubble-water two-phase flow.” *Acta Mech. Sin.*, 20(6), 489–495 (in Chinese).
Lu, Z. M., Liu, Q. Q., Liu, D. Y., and Yang, X. Z. (1996). “The behavior and criterion of turbulence suppression effect of the particles in an horizontal liquid-solid flow.” *Acta Mech. Sin.*, 28(3), 291–297 (in Chinese).
Lyn, D. A. (1992). “Turbulence characteristics of sediment-laden flows in open channels.” *J. Hydraul. Eng.*, 118(7), 971–988.
Monte, J. S., and Arthur, T. I. (1973). “Interaction of two dimensional turbulent flow with suspended particles.” *Rep. No. 164*, *Lab. Water Resources and Hydrodynamics*, Massachusetts Institute of Technology, Cambridge, Mass.
Muller, A. (1973). “Turbulence measurements over a movable bed with sediment transport by laser anemometry.” *15th IAHR Congress*, International Association for Hydraulic Research, Istanbul, Turkey.
Nguyen, A. V., and Fletcher, C. A. G. (1999). “Particle interaction with the wall surface in two-phase gas-solid particle flow.” *Int. J. Multiphase Flow*, 25(1), 139–154.
Nino, Y., and Garcia, M. H. (1996). “Experiments on particle-turbulence interactions in the near-wall region of open channel flow: Implications for sediment transport.” *J. Fluid Mech.*, 326, 285–319.
Ohba, K., and Yuhara, T. (1979). “Velocity measurements of both phase in two-phase flow using laser doppler velocimeter.” *Proc., IMEKO Symp.*, Tokyo, 181.
Ooms, G., and Jansen, G. H. (2000). “Particles-turbulence interaction in stationary, homogeneous, isotropic turbulence.” *Int. J. Multiphase Flow*, 26(11), 1831–1850.
Qian, N., and Wan, Z. H. (1986). *Mechanics of sediment motion*, Scientific Press House of China, Beijing (in Chinese).
Rashidi, M., Hestroni, G., and Baneree, B. N. (1990). “Particles-turbulence interaction in a boundary layer.” *Int. J. Multiphase Flow*, 16(6), 935–946.
Sommerfeld, M., and Huber, H. (1999). “Experimental analysis and modeling of particle-wall collisions.” *Int. J. Multiphase Flow*, 25(6-7), 1457–1489.
Tsuji, Y., and Morikawa, Y. (1982). “LDV measurements of an air-solid two-phase flow in a horizontal pipe.” *J. Fluid Mech.*, 120, 385–409.
Van Ingen, C. (1981). “Observation in a sediment-laden flow by use of Laser Doppler Velocimeter.” *Rep. No. KH-r-42*, W. M. Kech. Lab of Hydrol. and Water Resour., California Institute of Technology, Pasadena, Calif.
Xingkui, W., and Ning, Q. (1989). “Turbulence characteristics of sediment-laden flow.” *J. Hydraul. Eng.*, 115(6), 781–800.