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BRIEF COMMUNICATION

EFFECT OF PARTICLE SIZE ON MODULATING TURBULENT INTENSITY

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INTRODUCTION

Gas–solid flows are important to many industrial processes such as pulverized coal combustors and fluidized beds. In these and other processes, gas–particle interactions have a dominating influence on heat and mass transfer.

While gas–solid flows have been the focus of extensive research for many years there does not yet exist a consensus on the effect of particles on changing the turbulent intensity of the carrier phase. This paper brings together the work of various researchers and proposes a simple physical model to explain the increase or decrease of turbulent intensity caused by the addition of particles. A critical parameter appears to be the ratio of particle diameter to a turbulent length scale, d_P/l_e. The length scale associated with the fluid phase, l_e, is the integral length scale or the characteristic length of the most energetic eddy when only one phase is present.

As shown later, a critical value of this ratio offers a demarcation of particle size which causes the turbulent intensity of the carrier phase to either increase or decrease with the addition of particles to the flow. While not having complete information for all particle sizes the trend has been found to hold for gas–solid, gas–liquid, liquid–solid and liquid–gas flows in pipes and free jets at various orientations.

RESULTS

For the carrier phase (without particles) the works of Wyganski & Fiedler (1969) and Hutchinson *et al.* (1971) are used to find the turbulent length scales of the fluid. Hutchinson *et al.* (1971) demonstrated that the l_e/R ratio across a pipe in fully developed flow was approximately constant ($l_e/R \simeq 0.2$) except near the wall, as shown in figure 1. As shown in the figure this ratio holds for various Reynolds numbers. Note that l_e is the characteristic length of the most energertic eddy and R is the pipe radius.

For single-phase jet flows, Wyganski & Fiedler (1969) demonstrated that (in the notation of Wyganski & Fiedler) $\Lambda_f/x = 0.039$, where Λ_f is the integral length scale (henceforth noted as l_e) and x is the axial distance from the jet exit.

Using these results for single-phase flows one can compile the results from various investigators, as presented in figure 2. The percentage change in turbulent intensity is defined as

$$\frac{\sigma_{TP} - \sigma_F}{\sigma_F} \times 100,$$

where σ is the turbulent intensity of the fluid based on the local time-averaged velocity, $\sigma = \sqrt{\overline{u'^2}}/U_m$ and the subscripts TP and F refer to the two-phase and single-phase flows, respectively. All values were taken along the centerline. From the figure it can be seen that a value of

$$\frac{d_P}{l_e} \simeq 0.1$$

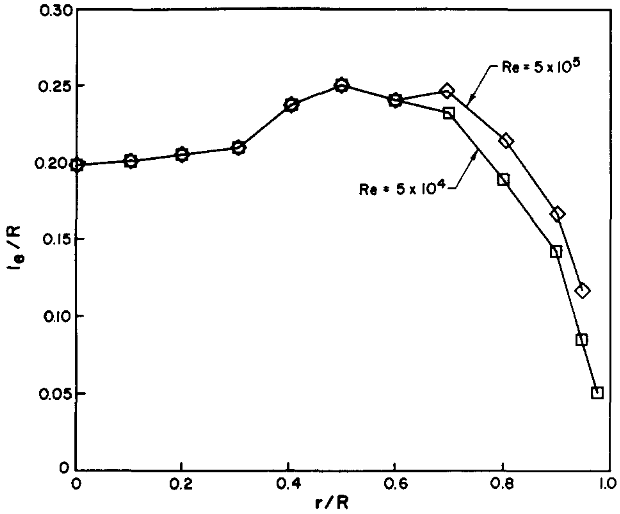


Figure 1. Characteristic fluid length scale as function of radial location [from Hutchinson *et al.* (1971)].

offers a demarcation where, at larger values of d_P/l_e, the addition of particles will cause an increase in the carrier-phase turbulent intensity and at lower values a decrease.

Descriptions of the various investigations can be found in table 1, where the density ratio of the dispersed phase to that of the continuous phase (S), the volume concentration (ϕ) and flow Reynolds number (Re) are listed. With the exception of Hetsroni & Sokolov (1971), Serizawa *et al.* (1975) and Wang *et al.* (1987) the investigators used laser-Doppler anemometers with various techniques to reduce "cross-talk". Hetsroni & Sokolov (1971), Serizawa *et al.* (1975) and Wang *et al.* (1987) used hot-wire anemometers with a special technique to eliminate errors from droplet and gas impingement on the wire. As can be seen from the table, the range of experimental observation is quite extensive. Included are gas–solid, gas–liquid, liquid–solid and liquid–gas flows. Flow geometries include axisymmetric jets and pipes for various orientations; flow Reynolds number variations from 8000 to 100,000; density ratio variations from 0.0012 to 2500; and volume concentration variations from 10^{-6} to 0.2. Presented in table 1 are typical values of the various

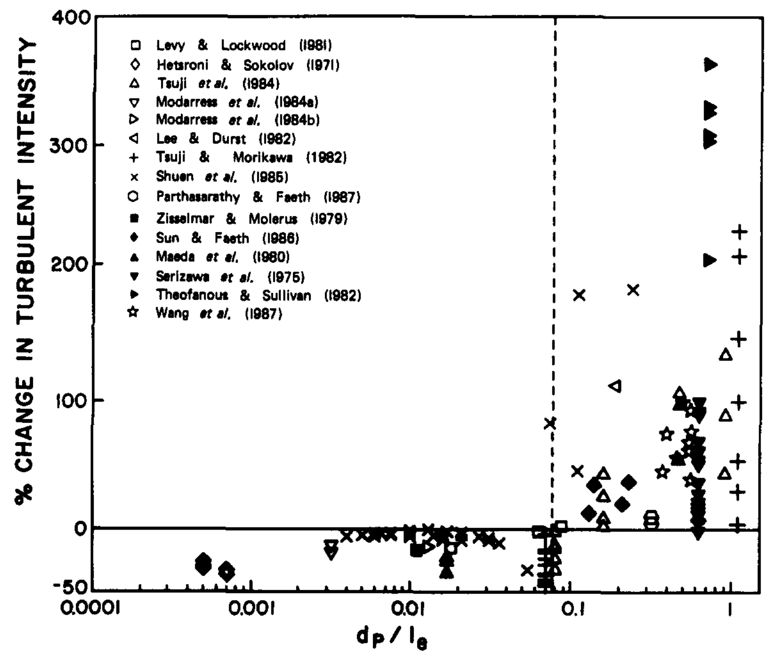


Figure 2. Change in turbulent intensity as function of length scale ratio.

Table 1. Experimental parameters

Reference	Geometry	S	ϕ	Re
Levy & Lockwood (1981)	Gas–solid downward jet	2000	6×10^{-4}	20,000
Hetsroni & Sokolov (1971)	Gas-liquid horizontal jet	775	2.5×10^{-6}	83,300
Tsuji *et al.* (1984)	Gas–solid upward pipe	850	5×10^{-3}	22,500
Modarress *et al.* (1984a)	Gas–solid downward jet	2500	2×10^{-4}	13,300
Tsuji & Morikawa (1982)	Gas–solid horizontal pipe	833	4×10^{-3}	20,000
Shuen *et al.* (1985)	Gas–solid downward jet	2200	2×10^{-4}	19,000
Parthasarathy & Faeth (1987)	Liquid–solid downward jet	2.5	0.03	9000
Modarress *et al.* (1984b)	Gas–solid downward pipe	2500	3.5×10^{-4}	17,000
Lee & Durst (1982)	Gas–solid upward pipe	2080	1×10^{-3}	8000
Zisselmar & Molerus (1979)	Liquid–solid horizontal pipe	2.5	0.04	100,000
Sun & Faeth (1986)	Liquid–gas upward jet	0.001	0.05	9000
Maeda *et al.* (1980)	Gas–solid upward pipe	7500	1×10^{-4}	20,000
Theofanous & Sullivan (1982)	Liquid–gas upward pipe	0.001	0.08	20,000
Serizawa *et al.* (1975)	Liquid–gas upward pipe	0.001	0.17	26,000
Wang *et al.* (1987)	Liquid–gas upward & downward pipe	0.001	0.2	30,000

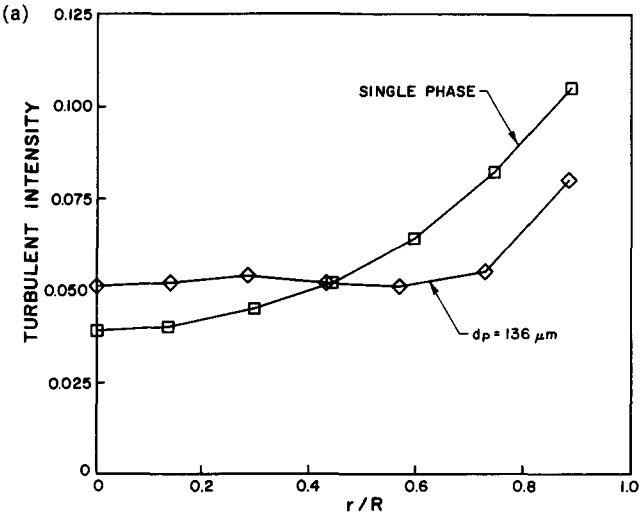
parameters. Generally, each investigator examined a range of parameters. It should be noted that bubble size information for Wang *et al.* (1987) was obtained from Lee (1988).

The investigation of Shuen *et al.* (1985) reported the properties of free jets for a large range of downstream locations ($1 < x/d < 50$, where d is the jet diameter). Close to the jet exit, the results of Wyganski & Fiedler (1969) are not valid. At $x/d = 1$ the characteristic length scale should still be approximated by pipe flow (the potential core of free jets generally extends to $x/d \simeq 5$). At this location the result from Hutchinson *et al* (1971) was used to reduce the data. Free jet results were used for values taken at $x/d > 10$. No values between $x/d = 1$ and $x/d = 10$ were used since there is no information on the turbulent length scale in this region. It should also be noted that for the downstream region (i.e. for $x/d > 10$) the turbulent intensities were taken from the results of their stochastic separated flow model which is, in essence, a curve fit of the data through this region. This was done to cut down on the scatter present in the experimental data.

A proposed explanation for the trend depicted in figure 2 follows. The small particles, which are much smaller than the most energetic eddy, will follow the eddy for at least part of its lifetime. Part of the eddy's energy will be imparted to the particle since the eddy, through the drag force, will be moving the particle. The turbulent energy of the eddy is therefore transformed into the kinetic energy of the particle and the turbulent intensity will be reduced. The larger particles will tend to create turbulence (in its wake) near the scale of the most energetic eddy, thus increasing the turbulent intensity of the gas. In this case energy is transferred from the mean flow, which is moving the particles, to the turbulent kinetic energy.

Results from three investigations are not included in figure 2. Two of these are the studies by Soo *et al.* (1960) and Boothroyd (1967) who found both increases and decreases in the turbulent intensities for flows with $d_P/l_e < 0.1$. The authors pointed out that the scatter in the data was due to their experimental procedure [i.e. Soo *et al.* (1960) used a photographic technique and Boothroyd (1967) used a sampling probe to measure the concentration of tracer gas injected at various points from which the level of turbulence was assessed]. Their conclusions were that there was no discernible change in the turbulent intensity for their particular loading and geometry.

Also not included in figure 2 are two sets of data from Maeda *et al.* (1980) for glass particles. The reason for their exclusion is as follows. The present authors feel that the glass particles may have agglomerated, possibly due to electrostatic charging, while the other set of data (copper beads) did not. As pointed out in Tsuji *et al.* (1984), with continual pumping of the particles through a testing apparatus a static charge can build up on the particles which may or may not result in agglomeration (Tsuji 1988). It is noted that the glass particles will be susceptible to this effect while copper is not. It was found that the glass, while having a $d_P/l_e < 0.1$, increased the turbulent intensity and the copper decreased it even though the glass (in one case) had a smaller diameter (the glass beads appear to have a larger effective diameter). Further verification of this explanation is found by comparing the velocity and turbulent intensity profiles of Maeda *et al.* (1980) with those of Tsuji *et al.* (1984), Tsuji & Morikawa (1982) and Lee & Durst (1982). Lee & Durst (1982) and



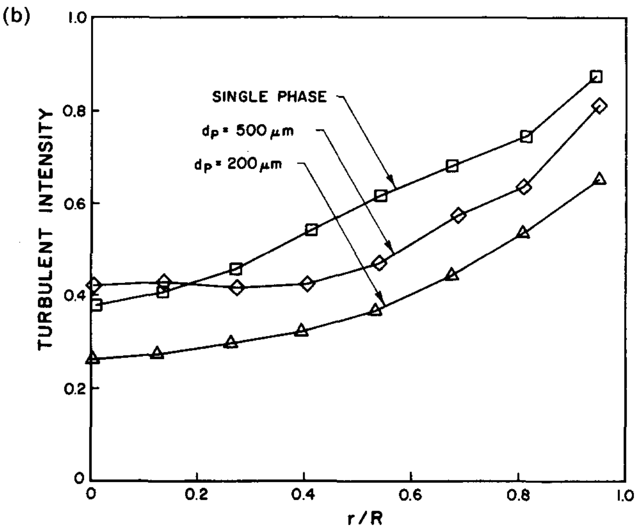


Figure 3. (a) Turbulent intensity profile of Maeda *et al.* (1980), $d_P = 136\,\mu$m, mass loading = 0.54. (b) Turbulent intensity profile of Tsuji *et al.* (1984), $d_P = 200$ and $500\,\mu$m, mass loading = 1.3.

Tsuji *et al.* (1984) found for small particles ($\sim 200\,\mu$m) that there is a point at approx. $r/R \simeq 0.8$ where the mean particle velocity is faster than the mean fluid velocity (even though the flow was upward). For larger particles ($> 500\,\mu$m) no such point was found. No such point was found in the investigation of Maeda *et al.* (1980) even though they used particle sizes $< 200\,\mu$m and density ratios approximately equivalent to those used in Tsuji *et al.* (1984) and Lee & Durst (1982). The same comparisons can be made in examining turbulent intensity profiles. That is, for comparable concentrations, the turbulent intensity profiles of Maeda *et al.* (1980) for glass particles are closer in shape to those of the $500\,\mu$m particles of Tsuji *et al.* (1984) and Tsuji & Morikawa (1982) than the shape of the profiles for the $200\,\mu$m particles (as demonstrated in figure 3).

It should also be mentioned that some data points of Theofanous & Sullivan (1982) are not included in figure 2 because they did not fit onto the graph. For the same value of d_P/l_e (i.e. 0.70) they found increases in turbulent intensity of up to 700%.

Theofanous & Sullivan (1982) derived two expressions for the turbulent intensity. One, was a function of ϕ, d_P, ρ_P/ρ_G, U_m and D, and the other depended on ϕ, ρ_P/ρ_G, U_m, and D. Both equations contained an empirical constant which takes into account the radial distribution of turbulence energy in their one-dimensional model. They claimed that the constants are universal and compared their data (liquid–gas flow) to that of Lee & Durst (1982) (gas–solid flow) to

Table 2. Percentage change in turbulent intensity

Source	$d_P(\mu m)$	ϕ	Measured	Equation (19)	Equation (23)
Theofanous & Sullivan (1982)	4000	0.04	220	220	280
	4000	0.07	310	280	290
	4000	0.18	340	360	290
	4000	0.03	380	360	510
	4000	0.06	500	510	600
	4000	0.09	600	610	650
	4000	0.12	720	700	700
Lee & Durst (1982)	800	1.2×10^{-3}	113	132	127
Tsuji *et al.* (1984)	2780	8.0×10^{-3}	137	66.1	116
	2780	5.8×10^{-3}	89.3	52.2	98.4
	2780	1.6×10^{-3}	43.6	8.5	25.9
	501	5.3×10^{-3}	43.6	88.2	107.7
	501	4.6×10^{-3}	26.1	70.6	90.1
	501	2.3×10^{-3}	8.9	23.9	40.3
	501	1.3×10^{-3}	2.3	12.2	28.1
	243	3.9×10^{-3}	−2.1	67.8	67.8
	243	2.4×10^{-3}	−23.8	33.7	40.2
	243	1.7×10^{-3}	−32.6	17.9	24.1
	243	1.1×10^{-3}	−15.1	17.9	16.3
	243	6.4×10^{-4}	−13.1	0.0	−25.8

demonstrate the applicability of the expressions (and constants) to liquid–gas and gas–solid flows. One of their expressions [equation (19)], however, does not allow for the turbulent intensity of the carrier phase to be reduced which (see figure 2) is clearly the case in some instances. The other expression allows for a decrease but does not model the phenomena correctly (table 2). Comparisons of their analytic results with their own data, the data of Lee & Durst (1982) and Tsuji *et al.* (1984) (which was not available when Theofanous & Sullivan published their results) are shown in table 2. The wide discrepancies with the data of Tsuji *et al.* (1984) are obvious, particularly with the smaller diameter particles. The universality of the constants used in their expressions is very much in doubt. Equations (19) and (23) in table 2 refer to equation numbers found in Theofanous & Sullivan (1982).

DISCUSSION

There are two possible sources of errors in reducing the data for figure 2. The first of these is the characteristic length, as given by Wyganski & Fiedler (1969) and Hutchinson *et al.* (1971). As in most turbulence measurements, there can be found in the literature a range of values for the integral length scale. The present authors feel that the ones chosen are the most accurate and best characterize the flow configurations of the multiphase investigations.

The other question is how the length scale of the flow changes with the addition of particles. Tsuji *et al.* (1984) found that there are no appreciable differences in the frequency power spectrum for large values of d_P/l_e in pipe flows. For smaller values, though, there is conflicting evidence. For pipe flows Tsuji & Morikawa (1982) and Tsuji *et al.* (1984) found that the addition of particles decreased the power spectrum at low frequency but increased it at higher values. The opposite trend, though, was found by Hetsroni & Sokolov (1971) for jet flows. With the wide range of flow parameters examined the authors feel that l_e does not change dramatically with the addition of particles, at least through the range of parameters examined.

This paper examines only particle–fluid interactions. There are other forces that will play a role (of varying degree) in any flow. They are, for example, particle–wall interactions, fluid–wall interactions and particle–particle interactions. In interactions involving particles there is the possibility for direct contact of one particle with another particle, particles in the wake of other particles and particles in contact with the wall. These added interactions can lead to much more complicated results than presented here. For example, Zisselmar & Molerus (1979) found that, for a given particle size, the turbulence intensity at the centerline was reduced (which follows the trend given in figure 2). As measurements were taken very close to the wall ($r/R < 0.994$) this trend was reversed and the turbulence intensity was increased for certain values of particle concentration.

Tsuji *et al.* (1984) found cases where the turbulence intensity was increased on the centerline, in accordance with the data given in figure 2, but as one nears the wall the trend is again reversed and turbulence intensity is decreased. In the previous case one could explain the behavior by realizing that the eddies will be decreasing in size near the wall and d_P/l_e will be getting larger, thus changing the effect of the particles on the turbulence. No such explanation is available for the latter case. The authors feel that near the wall (where *near the wall* is relative to particle size) the present explanation is incomplete as different interactions may dominate the phenomena.

CONCLUSION

In summary, the ratio $d_P/l_e \simeq 0.1$ provides an estimate of whether the relative turbulent intensity of the carrier phase will be increased or decreased by the addition of the second phase when particle–fluid interactions are dominant. It should be noted that the critical diameter/length scale ratio refers to only the question of increasing or decreasing the turbulent intensity and does not relate to the magnitude of the change. The amount of change will be affected by various parameters such as, concentration, density ratio, flow Reynolds number and flow configuration.

As noted previously the trend seems to be valid for a wide range of flow conditions. While all flows examined do fall into the correct region it is not possible to verify the critical d_P/l_e for all cases since only a limited range of particle sizes were examined. The strongest evidence is for gas–solid flows in pipes and jets.

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