A critical analysis of turbulence modulation in particulate flow systems: a review of the experimental studies

Abstract: In multiphase particulate systems, the turbulence of the continuous phase (gas or liquid) is modulated due to interactions between the continuous phase and the suspended particles. Such phenomena are non-trivial in the essence that addition of a dispersed phase to a turbulent flow complicates the existing flow patterns depending on the physical properties of the particles leading to either augmentation or attenuation of continuous phase turbulence. In the present study, this aspect has been comprehensively analysed based on the available experimental data obtained from the well-studied turbulent flow systems such as channel and pipes, free jets and grids. Relevant non-dimensional parameters such as particle diameter to integral length scale ratio, Stokes number, particle volume fraction, particle momentum number, and particle Reynolds number have been utilised to characterise the reported turbulence modulation behavior. Some limitations of these commonly used dimensionless parameters to characterise turbulence modulation are discussed, and possible improvements are suggested.

Keywords: dimensionless parameters; multiphase flows; particles; turbulence modulation

1 Introduction

Macroscale multiphase flows ubiquitously encountered in the process industries are inherently turbulent due to high Reynolds numbers. Such process systems include but are not limited to multiphase contactors such as chemical reactors, dryers, absorption columns, and pneumatic conveying systems which are widely used in the chemical, minerals, metallurgical, energy, food and beverage, and pharmaceutical industries. Understanding the dispersed and continuous phase interactions in turbulent flows is a well-regarded challenge in the field of multiphase flow science. The presence of a dispersed phase (drops, bubbles, or particles) modifies the continuous phase turbulence characteristic such as turbulence intensity and the associated eddy length and time scales which is defined as turbulence modulation. In contrast, effect of the continuous phase turbulence on the distribution of dispersed phases is referred to as turbulence dispersion (Crowe 2000; Hetsroni 1989). Turbulence modulation has a significant impact on mass, momentum and heat transport processes and needs to be optimised for appropriate design and satisfactory performance of the industrial process systems.

Multiphase contactors involving all three phases (gas, solid, and liquid) are widely used in the chemical process industries, which include but are not limited to fluid catalytic cracking, bitumen coking, fast pyrolysis of biomass, chemical vapor deposition, and spray drying. The resulting turbulence due to continuous and dispersed phase interactions is quite effective in controlling the performance of these multiphase contactors in terms of augmenting mixing at both macro and micro scales involving both axial and radial dispersion and interphase heat and mass transport processes. For example, in the mineral separation context involving flotation, it has been demonstrated that recovery of fine particles (<20 μm) requires a substantial dispersed state of bubbles and particles by means of introducing significant turbulence in the system through mechanical agitation or shearing by the gas flow. The turbulence energy dissipation rate favours physical contacts...
between bubbles and particles and enhances particle floatability (Schubert 2008). At higher solid loading, slurry viscosity, however, increases, which in turn reduces turbulent energy dissipation rate and has a negative effect on the particle-bubble collision efficiency.

Specific to the particle-laden systems, which is the primary focus of this study, the particulate phase is known to contribute to the modulation of continuous phase turbulence through interphase momentum exchange. Details of turbulence modulation mechanisms in the presence of particles are well discussed in the literature (Balachandar and Eaton 2010; Bovin et al. 2000; Crowe 2000; Elghobashi and Truesdell 1992; Gore and Crowe 1989; Hetsroni 1989; Hoque et al. 2018a; Hoque et al. 2016; Hwang and Eaton 2006; Ljus et al. 2002; Poelma et al. 2007; Sheen et al. 1994). The turbulence modulation observed in the particle-laden systems is known to be influenced by five interrelated mechanisms, which are: (i) energy transfer through the drag force, (ii) particle-eddy interactions, (iii) turbulence production caused by wake formation and vortex shedding, (iv) energy transfer resulting from particle trajectory crossings (where a particle falls through an eddy due to a significant difference in velocity between the particle and the turbulent eddy), and (v) the added fluid mass that moves along with the particle (Lightstone and Hodgson 2004; Yuan and Michaelides 1992). Among these, two primary mechanisms for turbulence modulation are widely encountered – (a) energy dissipation from eddies accelerating particles (attenuates turbulence), and (b) flow disturbance due to the presence of wakes around the particles or shedding of vortices from particles (enhances turbulence).

The aforesaid mechanisms of turbulence modulation in the presence of solid particles are dependent on several parameters which include particle size, shape, volume fraction, and dimensionless numbers such as Reynolds number (ratio of inertia to viscous force), Stokes number (ratio of particle response time to fluid response time), particle diameter to integral length scale ratio, and particle to fluid density ratio (Eaton 2009b; Eaton and Fessler 1994; Elghobashi 1991, 1994, 2004; Elghobashi and Truesdell 1993; Gore and Crowe 1989; Hetsroni 1989; Hoque et al. 2016; Hussainov et al. 2000; Joshi et al. 2017; Kulick et al. 1994; Pan and Banerjee 1996; Poelma et al. 2007; Rani et al. 2004; Rashidi et al. 1990; Saber et al. 2016; Vreman 2007, 2015). Despite the use of these ratios, any definite trend in the reported turbulence modulation is not entirely evident yet (Balachandar and Eaton 2010).

The quantitative understanding of the influence of particles on turbulence modulation has been elusive because of the complex multi-scale nature of the problem. Also, there is an inherent difficulty in carrying out experiments in dense particulate systems to obtain sufficiently complete information to allow development of competent mathematical descriptions of the complex multiphase interactions and flow physics at the various length scales. Arguably, the effect of various system parameters and underlying physical mechanisms of particles-modulated turbulence is yet to be fully understood.

Our literature review indicates that studies on the comprehensive analysis of turbulence modulation in particulate systems are rather limited (Balachandar and Eaton 2010; Crowe et al. 1996; Gouesbet and Berlemont 1998; Guha 2008; Kuerten 2016; Loth 2000; Mashayek and Pandya 2003; Saber et al. 2015; Shaw 2003; Shirolkar et al. 1996; Subramaniam 2013; Voth and Soldati 2017). A brief summary of previous reviews on turbulent dispersed multiphase flow is presented in Table 1.

From Table 1, it is clear that the previous reviews largely focus on the interaction mechanisms of particles and continuous phase flow based on numeral analysis; however, no generality in the reported turbulence modulations in different flow systems is available. In the present study, we endeavored to bridge this knowledge gap to categorically study the turbulence modulation behavior in different flow systems by systematically analysing the previous experimental studies. A mapping method is presented to classify the turbulence augmentation and attenuation behavior with five different non-dimensional quantities: particle diameter to length scale ratio, Stokes number, volume fraction, particle momentum number and particle Reynolds number. The effect of these parameters on the turbulence characteristics is discussed for both gas–solid and liquid–solid flows in channels and pipes, free jets, and grid systems. One critical question remains is there any single dimensionless parameter that can fully capture the effect of particles on the modulation of continuous phase turbulence intensity.

With the above stated motivation, the paper is organised as follows – Section 2 summarises the focus of earlier studies on turbulence modulation in the presence of solid particles; Section 3 presents a comprehensive analysis of the previous turbulence data in particle-laden systems based on relevant non-dimensional parameters and finally, in Section 4, we comment on the turbulence modulation trends and identify future challenges and propose possible research directions in future.

2 Turbulence modulation in particulate systems: a general overview of the past studies

We note that until the 1980s, most of the work on turbulence modulation was primarily experimental; however, in recent
Table 1: Summary of the previous review studies on turbulent dispersed multiphase flows.

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>References</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shirolkar et al. (1996)</td>
<td>Different modelling techniques, such as Eulerian and Lagrangian particle dispersion models, were reviewed to describe the problem of particle dispersion in dilute flows. In addition, applications of the turbulent particle dispersion model for pulverised-coal flames were discussed to provide insight into the implementation of dispersion models.</td>
</tr>
<tr>
<td>2</td>
<td>Crowe et al. (1996)</td>
<td>Numerical models such as turbulence energy-dissipation model, large-eddy simulations, direct numerical simulations, and discrete vortex models for particulate flows were reviewed. The applications of these models to simulate the particulate flows due to fluid-particle interactions and carrier phase modulation were discussed.</td>
</tr>
<tr>
<td>3</td>
<td>Gouesbet and Berlemont (1998)</td>
<td>Both Eulerian and Lagrangian approaches to predict and/or simulate the dispersion behavior of discrete particles in turbulent flows were reviewed. From numerous validations carried out by comparing theoretical results and experimental data, the authors concluded that both approaches were suitable for the purpose.</td>
</tr>
<tr>
<td>4</td>
<td>Loth (2000)</td>
<td>The advancements in computational approaches (such as Eulerian and Lagrangian models) for two-phase flow motion were reviewed in the context of engineering applications. In this review, they classified the computational approaches by their treatment of the continuous phase (surrounding liquid or gas) and of the dispersed-phase (solid particles, droplets, or bubbles). The most appropriate point-volume descriptions for interphase transfer of momentum were described based on the available experimental data.</td>
</tr>
<tr>
<td>5</td>
<td>Mashayek and Pandya (2003)</td>
<td>Various existing analytical descriptions for predicting particles or liquid droplets laden turbulent flows were reviewed. The main aim was collision-less dispersed phase flows; however, the two-way coupling effects were also considered and discussed. The review of various methods was carried out by dividing them into two main categories such as (a) Lagrangian description (includes direct numerical simulation (DNS), large-eddy simulation, and stochastic modelling) and (b) Eulerian description (includes Reynolds averaged Navier–Stokes (RANS) and probability density function (pdf) modelling). The applications of these models for understanding and</td>
</tr>
<tr>
<td>6</td>
<td>Guha (2008)</td>
<td>The physical processes responsible for the transport and deposition of particles and their theoretical modelling were reviewed. Both laminar and turbulent processes were considered, emphasising the physical understanding of the various transport mechanisms. The computational methods for determining particle motion and deposition were discussed, including stochastic Lagrangian particle tracking and a unified Eulerian advection–diffusion approach. The theory presented includes Brownian and turbulent diffusion, thermophoresis, inertial impaction, gravitational settling, electrical forces, and the effects of surface roughness and particle interception. The article describes two example applications: the deposition of particles in the human respiratory tract and deposition in gas and steam turbines.</td>
</tr>
<tr>
<td>7</td>
<td>Balachandar and Eaton (2010)</td>
<td>Both experimental (LDA, PDA, and PIV) and computational techniques (Dusty gas and equilibrium Eulerian approaches, Eulerian approach, Lagrangian point-particle approach, LES, DNS) for dispersed multiphase turbulent flows were reviewed, including their strengths and limitations and opportunities for the future. This review also covered three critical aspects of dispersed phase flows such as (a) the preferential concentration of particles, droplets, and bubbles; (b) the effect of turbulence on the coupling between the dispersed and carrier phases and (c) the modulation of carrier-phase turbulence in the presence of particles or bubbles.</td>
</tr>
<tr>
<td>8</td>
<td>Subramaniam (2013)</td>
<td>This review aimed to provide a comprehensive and understandable account of the theoretical foundation, modelling issues, and numerical implementation of the Lagrangian–Eulerian approach for multiphase flows. It was noted that the numerical convergence of Lagrangian–Eulerian implementations is crucial to the success of the Lagrangian–Eulerian modelling approach. This review shows how the numerical convergence and accuracy of a Lagrangian–Eulerian implementation can be established using grid-free estimators and computational particle number density control algorithms.</td>
</tr>
</tbody>
</table>
times, more emphasis has been given to numerical simulations. Mainly, three systems have been studied extensively, e.g., jet flows, pipe and channel flows, and grid-generated flows. A brief review of the turbulence modifications in these systems is first presented in the subsequent subsections.

### 2.1 Jet flows

Two-phase turbulent jet flows ubiquitously appear in several engineering applications, which include spray combustions, internal combustion engine injections, automobile exhaust plumes, and pulverized coal combustors. These classes of particulate flows are quite complex due to the presence of finely suspended particles that continuously interact with the continuous phase. The physical parameters that are responsible for turbulence modulation involve flow characteristics (characteristic length, particle size, particle-to-fluid density ratio, mass loading (ratio of mass flow rate of particle and fluid), and any external body forces acting on the particles. Details of the operating conditions and measurement techniques used in the previous studies are summarised in Table 2.

From Table 2, it can be noted that most of the studies till 2014 were conducted using the single-point measurement techniques at jet Stokes number, $St_{k_0} > 9$, implying particle response time scale much larger compared to the fluid time scale (here $St_{k_0} = \frac{\rho_p d_p^2 U_b}{18\mu D}$, where $\rho_p =$ density of the particle, $d_p =$ diameter of the particle, $U_b =$ jet bulk velocity, $D =$ diameter of the pipe and $\mu =$ viscosity of the continuous phase). A typical experimental setup used for turbulence measurement in jet flow is shown in Figure 1.

In the system shown in Figure 1, Sheen et al. (1994) studied the effect of particle size and mass loading ratio in a jet flow ($St_{k_0} > 180$) and compared their results with a single-phase jet. It was noted that the turbulent kinetic energy in the dissipation range was smaller than those of a single-phase jet and turbulence intensity attenuated with the decreasing particle size and increasing mass loading ratio.

Under the condition $St_{k_0} >> 1$, particles exhibit a relatively weak response to turbulent motions. Notably, these measurements only cover a limited region of the flow field and do not provide useful information such as spatial correlations (Liepmann and Gharib 1992), proper orthogonal decomposition (Bi et al. 2003), and identification of particle clusters (Birzer et al. 2011). Only three recent studies (Lau and Nathan 2014, 2016; Park and Park 2021) report the jet Stokes number ($St_{k_0} \sim 1$), which is very relevant to the application of direct-fired pulverized coal burners (Jenkins and Mullinger 2011; Nathan et al. 2012; Smoot and Smith 2013). In these applications, Stokes number varies in the range from 0.2 to 5.0 involving particle diameter $d_p \sim 50–100 \mu m$, and particle density $\rho_p \sim 1200–1700 kg/m^3$.

Particle size distribution in jet flow is another critical aspect in turbulence modification. Among the previous studies summarised in Table 2, only Mostafa et al. (1989) used mono-disperse particle size distribution (standard deviation <5%), whereas Fleckhaus et al. (1987) and Har-dalupas et al. (1989) employed somewhat wider particle size distribution with a standard deviation less than 15%.

It can be noted that a wide range of particle size distribution can lead to masking of important details of the

<table>
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<tr>
<td>9</td>
<td>Saber et al. (2015)</td>
<td>The main mechanisms influencing turbulent modulation in the presence of spherical and non-spherical particles were reviewed. This work highlighted the need for more numerical and experimental work with higher accuracy than obtained so far and the need to resolve the flow near the surface of particles with the aim to re-evaluate the quantitative effect of different parameters on turbulent modulation. The review revealed that non-spherical particles have a more adverse effect on turbulence as compared to spherical ones for the same ambient conditions</td>
</tr>
<tr>
<td>10</td>
<td>Kuerten (2016)</td>
<td>Existing numerical simulation methods (such as particle-resolved DNS, Lagrangian point-particles and Eulerian methods) for particle-laden turbulent flows were discussed. This review puts the emphasis on the intermediate class of methods, the Euler–Lagrange methods in which the continuous phase is described by an Euler-Lagrange approach and the dispersed phase in a Lagrangian way with equations of motion for each individual particle</td>
</tr>
<tr>
<td>11</td>
<td>Voth and Soldati (2017)</td>
<td>The complex interaction between the anisotropic particles and turbulent fluid flows was reviewed using the models used to describe non-spherical particle motion, along with numerical and experimental methods for measuring particle dynamics. This review also covers the mathematical models widely used to describe kinematics and the dynamics of anisotropic particles, as well as the forces and torques acting between particles and the fluid</td>
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</tbody>
</table>
Comparison with the previously published studies. It is noted that no earlier study has reported a full description of the inlet flow conditions, such as detailed profiles of the mean and fluctuating velocity components and concentration field at the nozzle exit. Absence of such details in the two-phase turbulent flows has been recognised as a key drawback to the advancement of the multiphase computational fluid dynamics (CFD) models (Balachandar and Eaton 2010).

### 2.2 Pipe and channel flows

The two-phase particulate flows in the pipe and channel geometries are ubiquitous in several engineering applications varying from coal gasifiers to pneumatic conveying systems and multiphase chemical reactors (Capcelatro et al. 2014) such as riser and downer flows in the fluid catalytic cracking unit for producing transportation fuels, sediment transport in rivers (Ninto and Garcia 1996), and inhalation of

<table>
<thead>
<tr>
<th>References</th>
<th>Flow direction</th>
<th>Carrier phase</th>
<th>Particle type</th>
<th>Particle diameter $d_p$ (μm)</th>
<th>Particle density $ρ_p$ (kg m$^{-3}$)</th>
<th>Stokes number $St_0$</th>
<th>Mass loading, $ϕ_m$ (–)</th>
<th>Reynolds number $Re$</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modarress et al. (1984a)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>50</td>
<td>2990</td>
<td>≈13.5</td>
<td>0.32 and 0.85</td>
<td>13,300</td>
<td>LDA</td>
</tr>
<tr>
<td>Shuen et al. (1985)</td>
<td>Downward</td>
<td>Gas</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&gt;110</td>
<td>0.2–0.66</td>
<td>17,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Fleckhaus et al. (1987)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>64, 132</td>
<td>1020</td>
<td>&gt;120</td>
<td>0.3</td>
<td>30,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Tsuij et al. (1988)</td>
<td>Downward</td>
<td>Gas</td>
<td>Polystyrene particles</td>
<td>170, 243, 500 and 1400</td>
<td>LDA</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Gore and Crowe (1989)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>40, 80 and 200</td>
<td>2420, 2950 and 2950</td>
<td>≥10</td>
<td>0.13–0.86</td>
<td>13,000</td>
<td>PDA</td>
</tr>
<tr>
<td>Hetsroni (1989)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>210, 460 and 780</td>
<td>2500 and 1020</td>
<td>=11–14</td>
<td>0.2–1.0</td>
<td>5700</td>
<td>PDA</td>
</tr>
<tr>
<td>Hardalupas et al. (1989)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>10–45</td>
<td>2600</td>
<td>&gt;180</td>
<td>1.0</td>
<td>20,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Mostafa et al. (1989)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>100–110</td>
<td>72</td>
<td>9, 13, 6</td>
<td>0.08</td>
<td>13,100</td>
<td>PDA</td>
</tr>
<tr>
<td>Sheen et al. (1994)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>210, 460 and 780</td>
<td>3950</td>
<td>11–21</td>
<td>0.3–0.62</td>
<td>&gt;30,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Prevost et al. (1996)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass particles</td>
<td>210, 460 and 780</td>
<td>3950</td>
<td>11–21</td>
<td>0.3–0.62</td>
<td>&gt;30,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Fan et al. (1997)</td>
<td>Downward</td>
<td>Gas</td>
<td>Silica gel</td>
<td>72</td>
<td>1250</td>
<td>9, 13, 6</td>
<td>0.22, 0.8</td>
<td>≥54,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Frishman et al. (1999)</td>
<td>Downward</td>
<td>Gas</td>
<td>Synthetic corundum powders</td>
<td>23 and 32</td>
<td>2000</td>
<td>20</td>
<td>0–3.6</td>
<td>5700</td>
<td>LDA</td>
</tr>
<tr>
<td>Gillandt et al. (2001)</td>
<td>Downward</td>
<td>Gas</td>
<td>Spherical silica</td>
<td>160</td>
<td>800 to 1820 and 2444, 2815</td>
<td>1820 and 1030</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mando (2009)</td>
<td>Downward</td>
<td>Gas</td>
<td>Glass and polystyrene</td>
<td>10, 20 and 40</td>
<td>1200</td>
<td>0.3, 1.4 and 11.2</td>
<td>0.4</td>
<td>10,000–20,000</td>
<td>PIV/PN</td>
</tr>
<tr>
<td>Lau and Nathan (2014)</td>
<td>Downward</td>
<td>Gas</td>
<td>Polymer spheres</td>
<td>10, 20 and 40</td>
<td>1200</td>
<td>0.3–22.4</td>
<td>0.4</td>
<td>10,000–20,000</td>
<td>PIV/PN</td>
</tr>
<tr>
<td>Lau and Nathan (2016)</td>
<td>Downward</td>
<td>Gas</td>
<td>Polymer spheres</td>
<td>10, 20 and 40</td>
<td>1200</td>
<td>0.3–22.4</td>
<td>0.4</td>
<td>10,000–20,000</td>
<td>PIV/PN</td>
</tr>
<tr>
<td>Park and Park (2021)</td>
<td>Upward jet with crossflow</td>
<td>Gas</td>
<td>Silicon spherical particles</td>
<td>6, 53.6 and 205.5</td>
<td>2330</td>
<td>0.01–27.42</td>
<td>–</td>
<td>1170–5200</td>
<td>PIV</td>
</tr>
</tbody>
</table>

PIV, particle image velocimetry; PN, planar nephelometry; PTV, particle tracking velocimetry; LDA, laser Doppler anemometry; PDA, phase Doppler anemometry.
aerosol to decongest human nasal airways (Kleinstreuer and Zhang 2010) just to mention a few. The characteristics of turbulent pipe and channel flows in the presence of the particles are quite complex due to various physical phenomena, which include particle-particle and particle-wall interactions (linear and rotational motion of particles), particle-fluid interactions (drag, lift, virtual mass, and Basset history force), and particle settling and deposition due to gravity.

The topic of particle-laden pipe and channel flows has been studied comprehensively in the literature (Alajbegović et al. 1994; Caraman et al. 2003; Choi and Chung 1983; Fan et al. 1997; Govan et al. 1989; Hosokawa and Tomiyama 2004; Kafori et al. 1998; Kameyama et al. 2014; Kiger and Pan 2002; Kulick et al. 1994; Kussin and Sommerfeld 2002; Lee and Durst 1982; Liljegren and Vlachos 1990; Ljus et al. 2002; Mena and Curtis 2020; Rashidi et al. 1990; Sato and Hishida 1996; Shokri et al. 2017; Suzuki et al. 2000; Tsuji and Morikawa 1982; Tsuji et al. 1984; Varaksin et al. 2000; Zisselmar and Molerus 1979). It is noted that the magnitude of turbulence intensity is either augmented or attenuated depending on the particle size. More specifically, small particles tend to reduce turbulence intensity, while large particles tend to increase turbulence intensity (Gore and Crowe 1989; Tsuji and Morikawa 1982; Tsuji et al. 1984).

A detailed overview of the previous experimental investigations in particle-laden turbulent flows are summarised in Table 3. Based on the continuous phase, such as gas (air) or liquid (water), the earlier studies summarised in Table 3 can be classified into two main categories – (a) gas–solid and (b) liquid–solid flows, respectively, which are further categorised in horizontal and vertical flow configuration with further sub-categorisation of upward and downward flow for the latter.

For horizontal pipe systems (Figure 2) involving both spherical and non-spherical particles, turbulence intensity attenuates close to the pipe wall while it augments at the center of the pipe (Lee and Durst 1982; Ljus et al. 2002).

The same outcome is also observed for the horizontal channel systems (Figure 3) which shows significant attenuation in the mean velocity of the continuous phase in the presence of particles even at a low mass loading ratio (Kiger and Pan 2002; Kussin and Sommerfeld 2002). Also, the turbulent kinetic energy significantly increases above that of the continuous fluid phase, and follows Kolmogorov’s universal slope $-5/3$ in the inertial subrange (Kolmogorov 1941).

Micro-roughness at the flow walls (<10 μm) has a significant influence on the turbulence levels leading to attenuation. In a DNS (direct numerical simulation) study, Vreman (2015) found that apart from the energy dissipation from the eddies, turbulence intensity in a vertical channel is also attenuated by the non-uniformity of the mean feedback (force exerted by particles on the fluid) force, both for channels with smooth walls and walls with small roughness (10–20 μm). For heavy particles ($\rho_p = 8800$ kg/m$^3$) and higher mass loading (mass loading $= 0.8$), the mean particle velocity is typically flatter than the mean fluid velocity which in turn increases the mean relative velocity between particles and fluid phase in the wall-normal direction. The increased relative velocity leads to non-uniformity of the mean feedback force due to higher wall-normal velocity fluctuations which leads to attenuation in turbulence. Similar results were not found in a study by Benson et al. (2005), which involved a much higher wall roughness (250 μm). Lower mass loading (mass loading $= 0.15$), and relatively lighter particles ($\rho_p = 2500$ kg/m$^3$).

Varaksin et al. (2000), Caraman et al. (2003), and Borée and Caraman (2005) investigated the downward gas–solid pipe flow at $Re < 8000$. Tsuji et al. (1984) measured the turbulent flow statistics in a gas–solid upward pipe flow at higher Reynolds number ($Re = 8000$ and 23,000). They found that energy distribution remains unchanged at different wavenumbers for the larger size of particles (>500 μm), while energy is redistributed for smaller size particles (<200 μm). In downward pipe flow systems, turbulence modulation occurs in streamwise as well as in the radial direction. Varaksin et al. (2000) reported higher streamwise turbulence intensity in the presence of particles, but the lateral turbulence intensity was observed lower than the single-phase flow. In contrast, Caraman et al. (2003) reported augmentation in the single-phase streamwise fluctuating velocity in the presence of particles; but no alteration along the radial direction. This could be attributed to an order of
Table 3: Summary of previous experimental studies on particle-laden pipe and channel flows.

<table>
<thead>
<tr>
<th>References</th>
<th>Flow direction</th>
<th>Type of wall</th>
<th>Carrier phase</th>
<th>Particle type</th>
<th>Particle diameter, $d_p$ (µm)</th>
<th>Particle density, $\rho_p$ (kg m$^{-3}$)</th>
<th>Mass loading, $\phi_m$ (--)</th>
<th>Volume fraction, $\phi_v$ (--)</th>
<th>Reynolds number, Re (--)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zisselmar and Molerus (1979)</td>
<td>Horizontal</td>
<td>-</td>
<td>Water</td>
<td>Glass particles</td>
<td>53</td>
<td>2.5 $\times$ 10$^{-3}$</td>
<td>0.007–0.024</td>
<td>0.017–0.056</td>
<td>100,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Lee and Durst (1982)</td>
<td>Upward</td>
<td>-</td>
<td>Gas</td>
<td>Glass particles</td>
<td>100–800</td>
<td>2100</td>
<td>0.55–0.71</td>
<td></td>
<td>8000</td>
<td>LDA</td>
</tr>
<tr>
<td>Tsuji and Morikawa (1982)</td>
<td>Horizontal</td>
<td>-</td>
<td>Gas</td>
<td>Plastic particles</td>
<td>200 and 3400</td>
<td>1000</td>
<td>0.29–0.77</td>
<td>0.5–4 $\times$ 10$^{-3}$</td>
<td>&lt;40,000</td>
<td>LDV</td>
</tr>
<tr>
<td>Rashidi et al. (1990)</td>
<td>Horizontal</td>
<td>-</td>
<td>Water</td>
<td>Polystyrene and glass copper</td>
<td>120–1100, 28, 25, 50, 90 and 70</td>
<td>1020 and 2500, 700, 2500 and 8800</td>
<td>0.03–1</td>
<td>5 $\times$ 10$^{-5}$ to 2 $\times$ 10$^{-4}$</td>
<td>2500–7500</td>
<td>High speed camera</td>
</tr>
<tr>
<td>Fessler et al. (1994)</td>
<td>Vertical</td>
<td>Rough</td>
<td>Gas</td>
<td>Lycopodium, glass and copper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13,800</td>
<td>Digitising photographs</td>
</tr>
<tr>
<td>Alajbegović et al. (1994)</td>
<td>Upward</td>
<td>-</td>
<td>Water</td>
<td>Ceramic and polystyrene glass and copper</td>
<td>1790 and 2320</td>
<td>2400</td>
<td>3 $\times$ 10$^{-4}$ – 0.08</td>
<td>0.009–0.036</td>
<td>5 $\times$ 10$^{-5}$ to 2 $\times$ 10$^{-4}$</td>
<td>42,000–68,000</td>
</tr>
<tr>
<td>Kulick et al. (1994)</td>
<td>Vertical</td>
<td>Rough</td>
<td>Water</td>
<td>Glass and copper</td>
<td>50, 90 and 70</td>
<td>2500, 2500 and 8800</td>
<td>0.02–0.8</td>
<td></td>
<td>13,800</td>
<td>LDA</td>
</tr>
<tr>
<td>Taniere et al. (1997)</td>
<td>Horizontal</td>
<td>Smooth</td>
<td>Gas</td>
<td>Glass and PVC</td>
<td>60 and 130</td>
<td>2500 and 1430</td>
<td>0.006–0.001</td>
<td>5 $\times$ 10$^{-6}$</td>
<td>6260 and 6700</td>
<td>LDA</td>
</tr>
<tr>
<td>Kaftori et al. (1998)</td>
<td>Horizontal</td>
<td>Rough</td>
<td>Water</td>
<td>Polystyrene</td>
<td>100, 275, 50 and 900</td>
<td>1.05</td>
<td>–</td>
<td>2 $\times$ 10$^{-4}$ and 1</td>
<td>5000–14,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Varaksin et al. (2000)</td>
<td>Downward</td>
<td>-</td>
<td>Gas</td>
<td>Glass particles</td>
<td>50</td>
<td>2550</td>
<td>0.04–0.55</td>
<td></td>
<td>15,300</td>
<td>LDA</td>
</tr>
<tr>
<td>Ljus et al. (2002)</td>
<td>Horizontal</td>
<td>-</td>
<td>Gas</td>
<td>Polystyrene and pulp</td>
<td>100–800</td>
<td>1000</td>
<td>0.03 and 0.1</td>
<td></td>
<td>82,100 and 13,000</td>
<td>LDA</td>
</tr>
<tr>
<td>Kussin and Sommerfeld (2002)</td>
<td>Horizontal</td>
<td>Rough</td>
<td>Gas</td>
<td>Glass particles</td>
<td>62–1000</td>
<td>2500</td>
<td>0.1–1</td>
<td>4 $\times$ 10$^{-4}$ to 4 $\times$ 10$^{-3}$</td>
<td>30,805, 42,585 and 57,284</td>
<td>PDA</td>
</tr>
<tr>
<td>Khalitov and Longmire (2003)</td>
<td>Vertical</td>
<td>Smooth</td>
<td>Gas</td>
<td>Glass particles</td>
<td>20–160</td>
<td>2500</td>
<td>0.1</td>
<td>5 $\times$ 10$^{-5}$</td>
<td>4500</td>
<td>PIV</td>
</tr>
<tr>
<td>Caraman et al. (2003)</td>
<td>Downward</td>
<td>-</td>
<td>Gas</td>
<td>Glass particles</td>
<td>60</td>
<td>2470</td>
<td>0.1</td>
<td>5 $\times$ 10$^{-5}$</td>
<td>5300</td>
<td>PDA</td>
</tr>
<tr>
<td>Hosokawa and Tomiyama (2004)</td>
<td>Upward</td>
<td>-</td>
<td>Water</td>
<td>Ceramic particles</td>
<td>1000–4000</td>
<td>3200</td>
<td>0.002–0.006</td>
<td>0.007–0.0018</td>
<td>15,000</td>
<td>LDV</td>
</tr>
<tr>
<td>Benson et al. (2005)</td>
<td>Vertical</td>
<td>Smooth, rough</td>
<td>Gas</td>
<td>Glass particles</td>
<td>150</td>
<td>2500</td>
<td>0.15</td>
<td>7 $\times$ 10$^{-5}$</td>
<td>13,800</td>
<td>LDA</td>
</tr>
<tr>
<td>Borée and Caraman (2005)</td>
<td>Downward</td>
<td>-</td>
<td>Gas</td>
<td>Glass particles</td>
<td>60 and 90</td>
<td>2470</td>
<td>0.1–0.52</td>
<td>(0.5–5) $\times$ 10$^{-4}$</td>
<td>5300</td>
<td>PDA</td>
</tr>
<tr>
<td>Wu et al. (2006)</td>
<td>Horizontal</td>
<td>Smooth</td>
<td>Gas</td>
<td>Polythene</td>
<td>60 and 110</td>
<td>1000</td>
<td>5 $\times$ 10$^{-4}$ to 4 $\times$ 10$^{-2}$</td>
<td>6 $\times$ 10$^{-7}$ to 4.8 $\times$ 10$^{-5}$</td>
<td>6826</td>
<td>PIV</td>
</tr>
<tr>
<td>Li et al. (2012)</td>
<td>Horizontal</td>
<td>Smooth</td>
<td>Gas</td>
<td>Polythene</td>
<td>60</td>
<td>1030</td>
<td>0.00025–0.0005</td>
<td>0.006</td>
<td>19,500</td>
<td>PTV</td>
</tr>
<tr>
<td>Kameyama et al. (2014)</td>
<td>Upward/ downward</td>
<td>-</td>
<td>Water</td>
<td>Glass particles</td>
<td>625 and 755</td>
<td>2590</td>
<td>0.002</td>
<td>0.006</td>
<td>4000 and 5600</td>
<td>PIV</td>
</tr>
<tr>
<td>Saber et al. (2016)</td>
<td>Horizontal</td>
<td>-</td>
<td>Gas</td>
<td>Glass particles</td>
<td>50</td>
<td>2500</td>
<td>–</td>
<td>5 $\times$ 10$^{-4}$ and 8 $\times$ 10$^{-4}$</td>
<td>320,000</td>
<td>PIV/PTV</td>
</tr>
<tr>
<td>Shokri et al. (2017)</td>
<td>Upward</td>
<td>-</td>
<td>Water</td>
<td>Glass particles</td>
<td>500, 1000 and 2000</td>
<td>2500</td>
<td>–</td>
<td>0.1, 0.4 and 0.8</td>
<td>6020 and 9320</td>
<td>PIV</td>
</tr>
<tr>
<td>Fong et al. (2019)</td>
<td>Vertical</td>
<td>Smooth</td>
<td>Gas</td>
<td>Glass particles</td>
<td>50</td>
<td>2500</td>
<td>0.006–0.1</td>
<td>3 $\times$ 10$^{-4}$ to 5 $\times$ 10$^{-5}$</td>
<td>200,000</td>
<td>LDA/PDA</td>
</tr>
<tr>
<td>Mena and Curtis (2020)</td>
<td>Upward</td>
<td>-</td>
<td>Water</td>
<td>Glass and steel particles</td>
<td>500–5000</td>
<td>2400 and 7750</td>
<td>–</td>
<td>0.70–2.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PIV, particle image velocimetry; PN, planar nephelometry; PTV, particle tracking velocimetry; LDA, laser Doppler anemometry; LDV, laser Doppler velocimetry; PDA, phase Doppler anemometry.
magnitude difference in the particle concentration used in these two studies (see Table 3) and further clarified in Borée and Caraman (2005) which showed at higher particle concentrations, the fluctuations in the particle velocity in radial direction exceeded those of the continuous gas medium.

Similar outcomes have been obtained for the liquid medium as well. Suzuki et al. (2000) notes that the turbulent fluctuations in any direction in a downward channel flow were higher in presence of ceramic particles compared to liquid phase (water). A later study by Kameyama et al. (2014) also shows the turbulent fluctuations in both the radial and streamwise directions are equal to or higher than those of the liquid phase (water) in both upward and downward flows in presence of glass particles.

In the case of the vertical channel flow system (see Figure 4), Kulick et al. (1994) performed experiments using particles size smaller than the Kolmogorov’s length scale (~170 µm) at the centerline of the channel.

It was noted that the fluctuating streamwise fluid velocity in the particle-laden channel flow significantly attenuates with larger particle mass loading, particle inertia (Stokes number), and distance from the wall. The turbulence was attenuated by as much as 75% at the channel centerline by the highest inertia particles. Similarly, the wall-normal fluctuating fluid velocity also experienced a similar degree of attenuation with increasing mass loading and particle inertia. Measurements of the streamwise velocity power spectra at the centerline of the channel revealed that the highest inertia number particles amplified the energy at high wavenumbers while attenuating the lower wavenumber range. Perhaps the most unexpected result showed that the gas-phase streamwise velocity power spectra were distorted non-uniformly in the presence of the particles. The spectra exhibited a localized dip in power, beginning at lower frequencies with increasing mass loading, indicating that the particles may change the turbulence structurally at length scales much larger than the particle diameter.

Particle Reynolds number (Re_p) was incorporated by Paris (2001) in a later turbulent flow analysis built upon the experimental work of Kulick et al. (1994). Two particle size classes were used with approximately the same Stokes number but differing in particle Reynolds number by a factor of 2 (Re_p = 8 and 18). Extensive measurements on the channel center plane showed strong attenuation of turbulence which was in close agreement with Kulick’s data (Kulick et al. 1994). The spanwise turbulence intensity also showed similar levels of attenuation. Two mechanisms were proposed to explain the observed reduction in the turbulent kinetic energy – direct dissipation of gas-phase turbulent kinetic energy due to particle drag effect and modulation of transport mechanisms of the gas-phase turbulent kinetic energy.

There is a comprehensive body of literature on the numerical modelling of channel flows which although is not the direct focus of this study, is briefly reviewed as they provide useful insights to the underlying mechanisms of turbulence modulation. These studies involve mainly two approaches – point-particle model (Eaton 2009a; Li et al. 2001; Liu et al. 2017; Muramulla et al. 2020; Vreman 2015; Wang 2010; Wang and Zhao 2020; Wang et al. 2019; Wang et al. 2020b; Wang et al. 2020c; Zhao et al. 2010a; Zhao et al. 2013; Zhou et al. 2020) and interface-resolved DNS approaches (Ardekani et al. 2017; Gao et al. 2013a; Garcia-Villalba et al. 2012; Kajishima et al. 2001; Lucci et al. 2010; Peng and Wang 2019; Picano et al. 2015; Santarelli and Fröhlich 2015; Shao et al. 2012; Ten Cate et al. 2004; Uhlmann 2008; Wang et al. 2016; Wu et al. 2011; Yu et al. 2017; Zhu et al. 2020b).

The point-particle model is appropriate for small particles that are smaller than the Kolmogorov length scale, but it does not account for the effects of particle wakes. Therefore, it is generally found that turbulence is reduced in point-particle simulations. Li et al. (2001) found that in a downward channel flow, particles tend to enhance turbulence at low mass loading, but suppress it at high mass loading. Studies by Zhao et al. (2010a) and Zhao et al. (2013) show that for large particle inertia (Stokes number), the streamwise velocity fluctuations increase, while the spanwise and wall-normal velocity fluctuations decrease. The numerical study of Liu et al. (2017) shows that in a vertical channel flow, the turbulence is significantly weakened as the Stokes number increases. Turbulence is also reduced in vertical channel specifically in an upward flow scenario when particle loading is increased. It is argued that this reduction is caused by the decay in the turbulent kinetic energy (TKE) generation instead of the increase in the turbulent energy dissipation rate caused by the particles (Muramulla et al. 2020).

Figure 2: Schematic of a horizontal pipe flow system: (1) smoothly shaped inlet section, (2) aluminum pipe, (3) removable pipe section, (4) venturi tube, (5) Plexiglas section, (6) “etoile” straightener, (7) bellow, and (8) fan (reprinted from Ljus et al. (2002), with permission from Elsevier).
The interface-resolved approach has also been widely used for studying the turbulence modulation behavior by particles larger than the Kolmogorov length scale (Bala-chandar and Eaton 2010; Maxey 2017; Tenneti and Sub-ramaniam 2014). When examining wall-bounded flows, it was found that neutrally buoyant particles decrease the maximum streamwise velocity fluctuation near the wall by reducing the intensity of large-scale vortices while increasing the spanwise and wall-normal velocity fluctuations in the near-wall region by creating small-scale vortices (Picano

Figure 3: Schematic of horizontal channel flow systems: (a) open loop (reprinted from Kiger and Pan (2002), with permission from Elsevier); and (b) closed loop (reprinted from Kussin and Sommerfeld (2002), with permission from Elsevier).
In absence of enough data on liquid phase turbulence modulation at high Reynolds number, it is noted that extrapolation of particle motion in gas-to-liquid flows at similar Reynolds number is not straightforward due to the significant difference in the ratio of particle to fluid density and viscosity and particle Stokes number (Shokri et al. 2017). Due to such difference in the particle and fluid properties, it is expected that different flow regimes will be encountered during such extrapolation. It might be possible to use certain models or empirical correlations to predict particle behavior in a liquid medium based on gas flow data, but such extrapolations are likely to have limited accuracy and would require careful validation through experimental data.

Therefore, the experimental studies on liquid–solid flows at high Re are required to focus on three main points: (i) determine the extent to which fluid turbulence is modulated in the presence of particles, (ii) determine if the current methodologies for predicting turbulence modulation are accurate, and (iii) determine the magnitudes of the particle streamwise and radial fluctuations compared to those of continuous (liquid) phase (Shokri et al. 2017).

### 2.3 Grid-generated flows

Grids are a special category of turbulence-generating device which are known to produce nearly homogenous and isotropic turbulence. A summary of previous experimental works addressing particle-laden grid turbulent flows are summarised in Table 4.

Studies on turbulence modulation in the grid systems in the presence of particles are somewhat limited (Geiss et al. 2004; Hoque et al. 2016; Hussainov et al. 2000; Poelma et al. 2007; Schreck and Kleis 1993; Yang and Shy 2005). Most of these studies involved a static grid in a wind or water tunnel system, which allows simplification in physical as well as mathematical analyses (Pope 2000). A schematic of the static vertical grid system is illustrated in Figure 5, which was used in the work of Poelma et al. (2007).

In this system, turbulence is generated by placing a static grid in a vertically oriented water channel system. The mean flow is in the upward direction while particles are introduced from the top of the system and removed by employing a fine filter in the return pipe. Experiments were conducted at different locations downstream from the grid at a given mean velocity.

Alternatively, a vertical/horizontal oscillating grid system was used to generate nearly homogeneous and isotropic turbulence inside an enclosed tank (Hoque et al. 2016; Yang and Shy 2005). For instance, a schematic of vertical (Yang and
For both negatively and neutrally buoyant particles, Schreck and Kleis (1993) found that the turbulence intensity augmented with increasing particle mass loading ratio (-0.4 %–1.5 %); however, the reverse effect was reported by Hussainov et al. (2000) for larger mass loading ratio (10 %). Later, Geiss et al. (2004) observed that the continuous phase turbulence intensity only changed with a minimum particle mass loading (0.058 %–0.37 %); however, the reverse effect was reported by Geiss et al. (2004). Furthermore, Geiss et al. (2004) reported that the original isotropic turbulence produced by the grid inside the wind tunnel was modulated to anisotropic turbulence in the presence of different sizes of particles. Later this observation was confirmed by Poelma (2004); however, it was not observed in an earlier study by Schreck and Kleis (1993).

The spectral analysis of Hussainov et al. (2000) showed that the presence of particles ($d_p < 700 \mu m$) does not affect the energy spectra (no clear cross-over observed between no-particle and with-particle cases); however, some changes were apparent at the smaller scales. In the presence of particles, energy transfer to smaller scales was enhanced, which was manifested in the so-called right shift of the spectrum. This observation agrees well with the experimental spectra reported by Schreck and Kleis (1993); however, a clear cross-over was apparent in the latter study. The presence of observed cross-over is attributed to the large

### Table 4: List of experimental studies addressing particle-laden grid turbulence flows.

<table>
<thead>
<tr>
<th>References</th>
<th>Geometry</th>
<th>Carrier phase</th>
<th>Particle type</th>
<th>Particle diameter $d_p$ (µm)</th>
<th>Particle density $\rho_p$ (kg m$^{-3}$)</th>
<th>Reynolds number Re (-)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schreck and Kleis (1993)</td>
<td>Grid generated turbulence</td>
<td>Water</td>
<td>Neutrally buoyant plastic and glass particles</td>
<td>600–700</td>
<td>1045 and 2400</td>
<td>15,600</td>
<td>LDV</td>
</tr>
<tr>
<td>Hussainov et al. (2000)</td>
<td>Grid generated turbulence (vertical)</td>
<td>Gas</td>
<td>Glass particles</td>
<td>700</td>
<td>2500</td>
<td>3045 and 6340</td>
<td>LDA</td>
</tr>
<tr>
<td>Geiss et al. (2004)</td>
<td>Grid generated turbulence</td>
<td>Gas</td>
<td>Glass particles</td>
<td>120, 240 and 480</td>
<td>2500</td>
<td>7900</td>
<td>PDA</td>
</tr>
<tr>
<td>Yang and Shy (2005)</td>
<td>Vertical oscillating grid system</td>
<td>Gas</td>
<td>Copper, glass and lead particles</td>
<td>12, 40 and 24</td>
<td>8800, 2500 and 11,300</td>
<td>73, 120 and 202</td>
<td>PIV</td>
</tr>
<tr>
<td>Poelma et al. (2007)</td>
<td>Grid generated turbulence</td>
<td>Water</td>
<td>Polystyrene, glass and ceramic particles</td>
<td>275, 509, 280 and 153</td>
<td>1050, 2450 and 3800</td>
<td>3750</td>
<td>PIV and PTV</td>
</tr>
<tr>
<td>Hoque et al. (2016)</td>
<td>Horizontal oscillating grid system</td>
<td>Water</td>
<td>Glass particles</td>
<td>1000, 3000, 5000 and 8000</td>
<td>2500</td>
<td>12–64</td>
<td>PIV</td>
</tr>
</tbody>
</table>

PIV, particle image velocimetry; LDV, laser Doppler velocimetry; PTV, particle tracking velocimetry; LDA, laser Doppler anemometry; PDA, particle Doppler velocimetry.

Shy 2005) and horizontal (Hoque et al. 2016) grid systems are shown in Figures 6 and 7, respectively.

Both of these systems consist of a pair of grids. Both grids can be moved in-and-out instead of side-to-side at a given frequency and are able to generate stationary and nearly isotropic turbulent flow field in the fluid region between the two grids. The advantage of this system is turbulence intensity level is comparatively high and not affected by the mean flow. This is due to the fact that net flow in this system is zero; hence no mean flow is present. This feature is useful if a Lagrangian measurement technique is deployed, for instance, tracking particles over a period of time to study the dispersion properties. Note that all of these studies involved particle-laden systems ($d_p < 1000 \mu m$) except Hoque et al. (2016), which specifically focused on the turbulence modulation behavior in the presence of a single stationary particle of larger sizes ($d_p \sim 1000–8000 \mu m$).

Only a few studies have so far investigated the effect of particles on the modulation of homogenous and isotropic turbulence using a static grid system (Geiss et al. 2004; Hussainov et al. 2000; Poelma et al. 2007; Schreck and Kleis 1993). The major difference between these studies is the selection of phase density ratio; for instance, the first two studies used solid particles in a wind tunnel (density ratio $\sim 10^2$), while the latter two studies used solid particles in a water tunnel (density ratio $\sim 1.0$). These experimental studies can be classified into two categories based on their aims: (i) the effect of particle mass loading on continuous phase turbulence intensity, and (ii) the effect of particles on the energy spectral slope, i.e., deviation from Kolmogorov's $-5/3$ slope.
particle Stokes number based on the hypothesis that large Stokes number particles are not affected by the fluid flow hence a two-way coupling is not applicable (Poelma and Ooms 2006). Geiss et al. (2004) did not observe any significant changes in the energy spectrum slope; however, Poelma et al. (2007) reported a less steep slope in the inertial region of the spectrum compared to Kolmogorov’s $-5/3$ slope due to the presence of particles. The rate of production of turbulence was also found to increase in the presence of particles, and observation was explained using a mathematical model.

In a vertical oscillating grid system (see Figure 6), Yang and Shy (2005) found a significant change in the turbulence intensity at both large and small scales, depending on the particle size and density. They note: (i) for particles ($\sim 12 \mu m$, $St_k = 0.36$), turbulence intensity decreases at large
scale and increases beyond the Taylor microscale (in both horizontal and vertical velocity spectrum), (ii) for particles (∼40 µm, St\textsubscript{k} = 1.0), an enhancement in turbulence intensity occurs in both horizontal and vertical directions at scales smaller than the Taylor microscale; however, no modulation is observed at large scales and (iii) for particles (∼24 µm, St\textsubscript{k} = 1.9), the turbulence intensity at both large and small scales is enhanced along the vertical direction, however in contrast along the horizontal direction, attenuation occurs at large scales while augmentation occurs at small scales.

More recently, Hoque et al. (2016) studied the effect of a single stationary coarse-size particle in a nearly homogeneous and isotropic flow field generated by a pair of horizontal oscillating grids (see Figure 7). The main motivation for using a stationary particle was to quantify the local flow modulations in the vicinity of the particle by time-resolved PIV measurement. Energy spectrum analysis showed that the continuous phase energy was enhanced both at small and large scales; however, the maximum energy enhancement occurred primarily in the inertial subrange region. For the particle size (∼1000 µm) smaller than the integral length scale of the system, change in the energy dissipation rate was insignificant. However, when particle size (∼3000–8000 µm) was larger than the integral length scale, the energy dissipation rate significantly increased.
2.4 Fluidized beds

The fluidized beds are extensively used in various process industry applications that include coal and biomass combustion and gasification, production of fine powders and ceramic materials, alumina calcination, and fluid catalytic cracking of heavy vacuum gas oil to produce lower molecular weight transport fuels to name a few. These systems exhibit excellent hydrodynamics due to their capability to work in different flow regimes with varying turbulence intensity (Grace 2000) and have the benefits of (a) enhanced liquid/gas–solid contacts, (b) excellent control over heat and mass transfer rates, (c) low particle aggregation and segregation, and (d) high solid flux rate (Grace and Bi 1997). The fluidized beds are generally superior to other multiphase reactors (such as a stirred tank) for carrying out various liquid–solid, gas–liquid, and gas–solid–liquid processes due to these aforesaid benefits for the same power consumption (Ghatage et al. 2014b).

In fluidized bed systems, the operating parameters that govern the turbulence intensity include fluid superficial velocity, particle size, shape and density (Joshi 1983) which produce several flow regimes as illustrated in Figure 8a–h.

When the superficial gas velocity is low, the drag force on each particle is also low, resulting in a stationary state (i.e., a packed bed, see Figure 8a). However, as the superficial gas velocity reaches a critical value ($U_{cf}$), the upward drag force on the particles becomes equal to the downward net gravitational force causing the particles to become suspended in the fluid. This phenomenon is known as fluidization, and the bed exhibits fluid-like behavior (see Figure 8b). Increasing the superficial velocity beyond $U_{cf}$ results in a uniform expansion of the bed, known as “smooth
fluidization or homogeneous regime” (Figure 8c), with the bed pressure drop remaining proportional to the weight of particles per unit area. As the superficial velocity is increased beyond the minimum bubbling velocity \( U_{mb} \), bubbles start to form (see Figure 8d). Further increase in the fluid velocity causes an increase in bubble generation frequency and coalescence, leading to slugging if the bubble diameter approaches the column diameter. The shape of the slugs can be either round-nosed or flat-nosed (see Figure 8e and f). With a further increase in the fluid velocity, the upper boundary of the bed becomes less distinct, and bubbles begin to break up resulting in “turbulent fluidization” (see Figure 8g). The fluidization regimes depicted in Figure 8d–g are also referred to as the “heterogeneous or aggregative fluidization” regime. At even higher fluid velocities, the particles undergo “pneumatic transport” as shown in Figure 8h.

In general, the fluidized bed can be either operated in a homogeneous state (particulate fluidization), characterized by the even distribution of phases throughout the equipment, or in a heterogeneous state (aggregative fluidization), characterized by the uneven distribution of phases and the random occurrence of “bubbles” of the continuous phase within the system. The higher rates of heat, mass and momentum transfer and better mixing can be obtained in the heterogeneous regime due to higher interphase momentum exchange (particles–fluid as well as particles–particles) leading to high turbulence intensity.

There is a significant body of literature involving both experimental (Briens and Ellis 2005; Didwania and Homsy 1981; Duru and Guazzelli 2002; Fraguío et al. 2007; Gao et al. 2022; Ghatage et al. 2014b; Ghatage et al. 2013; Haam et al. 2000; Joshi et al. 2001; Kashyap et al. 2011; Kulkarni et al. 2001; Reddy et al. 2013; Shaikh and Al-Dahhan 2007; Thorat and Joshi 2004; Valverde et al. 2003; Wei et al. 2021; Zenit et al. 1997; Zhang et al. 1997) as well as numerical studies (Batchelor 1988; Bhole and Joshi 2005; Duru et al. 2002; Ghatage et al. 2014a; Gibilaro et al. 1986; Homsy et al. 1980; Joshi et al. 2001; Koch and Sangani 1999; León-Beccerril and Liné 2001; Nedelchev and Shaikh 2013; Peng et al. 2014; Reddy and Joshi 2009; Shnip et al. 1992; Zhao et al. 2022) to characterize fluidized beds by quantifying the bed expansion behavior, particle settling velocity, and regime transition conditions. It is noted that turbulence in the fluidized bed systems in general is quantified by the global energy dissipation rate through computing the specific power input in the system. Nevertheless, velocity measurements in the fluidized bed systems are scarcely reported due to obvious difficulties, specifically in the dense systems. Hence, modulation of turbulence intensity in fluidized bed systems is not generally available in the reported studies.

3 Turbulence modulation: effect of governing parameters

3.1 Particle diameter to integral length scale ratio

In a pioneering work on turbulence modulation in two-phase systems, Gore and Crowe (1989) collated previous experimental data on jet and pipe flows (1971–1987) and classified turbulence modulation into two categories: (i) augmentation and (ii) attenuation, by proposing a ratio of particle diameter to the integral length scale given as \( \frac{d_p}{l} \). Here, \( d_p \) is the particle diameter and \( l \) is the integral length scale given as \( l = \frac{u_{rms}^2}{\varepsilon} \), where \( u_{rms} \) is the root-mean-square velocity, and \( \varepsilon \) is the energy dissipation rate of the flow system. They noted a threshold of \( \frac{d_p}{l} \) parameter at \( \frac{d_p}{l} = 0.1 \) below which turbulence intensity always decreased while
the values above it, had an opposite effect. Change in continuous phase turbulence intensity in the presence of a dispersed phase is given by:

\[ \Delta = \frac{I_{DP} - I_{CP}}{I_{CF}} \times 100 \]  \hspace{1cm} (1)

where \( I = \frac{\sqrt{\overline{u'^2}}}{u} \); \( u' \) is fluctuating velocity and \( U \) is mean velocity along the centerline of the flow system is the turbulence intensity, and the subscripts DP and CP denote the dispersed and continuous phase, respectively.

In their work, it was shown that the percentage change of turbulent intensity depends on a length scale ratio given by \( d_p/l \) (see Figure 9).

All the experimental data of Figure 9 were taken along the centerline of the flow geometry, and the integral length scale was determined from an empirical relationship assuming \( UR = 0.2 \) (Hutchinson et al. 1971), where \( R \) is the radius of the pipe. As shown in Figure 9, turbulence intensity decreased for \( d_p/l < 0.1 \), while it increased for \( d_p/l > 0.1 \). Particles smaller than the integral length scale, i.e., the largest eddy size, suppress the continuous phase turbulent intensity because particles will follow the eddy for at least a part of their lifetime. The eddy shares a portion of its energy with particles through the drag force. Therefore, its energy is transformed into particle kinetic energy with an apparent reduction in the turbulence intensity.

Figure 10 presents the experimental data from reported studies post 1989 for different flow geometries, namely jets (Sheen et al. 1994), pipe (Ljus et al. 2002), and channels (Kaftori et al. 1998; Kiger and Pan 2002; Kulick et al. 1994; Kussin and Sommerfeld 2002; Rashidi et al. 1990) involving particles as the dispersed phase. It is evident that the ratio of \( d_p/l \sim 0.1 \) does not change even after adding the experimental data of channel flow.

However, this ratio in Hoque et al. (2016) was found to be \( \sim 0.41 \) (see Figure 11) for grid turbulence systems with a stationary particle as opposed to 0.1 earlier reported in Gore and Crowe (1989). It is noted that due to the nearly zero mean flow characteristics of the oscillating grid system; a modified definition was used to estimate the turbulence intensity for the continuous and dispersed phase as follows (Hoque et al. 2016):

\[ I = \sqrt{\frac{u_{rms}^2 + v_{rms}^2}{2}} \]  \hspace{1cm} (2)

where \( u_{rms} \) and \( v_{rms} \) denote as the root mean square (RMS) velocity components in horizontal and vertical directions, respectively.

Note that Equation (2) has dimension as opposed to the usual form of turbulence intensity which is dimensionless (see how turbulence intensity is calculated in Equation (1) in the presence of the mean velocity of the system). For details, continuous and dispersed phase turbulence intensity estimation, please see Supplementary Tables S1 and S2.

In Figure 11, it appears that the smaller particle of size (\( \sim 160–700 \mu m \)) used in the studies (Poelma et al. 2007;...
Schreck and Kleis (1993; Yang and Shy 2003) cause suppression of turbulence intensity compared with the larger particle size (∼1000–8000 µm). The continuous and dispersed phase turbulence intensity of these studies are summarised in Supplementary Tables S3–S7. The particle size of 1000 µm appears to set the demarcation boundary between the turbulence augmentation and attenuation regimes. The mechanism for turbulence modulation for particles larger than the integral length scale of the system (Hoque et al. 2016) is different from that created by smaller particles. The apparent difference could be attributed to the fact that, unlike smaller particles, larger particles are not accelerated by eddies; instead, they produce wakes through boundary layer separation and enhance the continuous phase turbulent intensity. However, it is worth pointing out that an oscillating grid system in the presence of a single particle, as reported by Hoque et al. (2016), differs from that of a typical particle-laden flow. This difference arises due to the stationary state of the particle and, therefore, the momentum exchange does not cause any change to particle motion. In the threshold case involving a 1000 µm particle, it was observed that turbulence intensity remained almost unchanged at nearly zero value. This observation supports the fact that energy containing larger eddies do not interact with particle sizes smaller than the integral length scale of the system (Hoque et al. 2016). In a specific scenario where a
particle is kept stationary in an oscillating flow field (see the supplementary document in Hoque et al. 2016), turbulence modulation occurs through both shear and pressure component of the drag force.

Although the $d_p l$ ratio appears to be a parameter to quantify turbulence modulation, the classification map proposed by Gore and Crowe (1989) (see Figure 9) based on this criterion, however, has been critically assessed in several studies (Ferrante and Elghobashi 2003; Lucci et al. 2011; Tanaka and Eaton 2008) with a view that this parameter does not incorporate the effect of particle density and other flow characteristics. For this reason, alternative criteria such as Stokes number and particle momentum number have been proposed to quantify the turbulence modulation phenomenon in more detail.

### 3.2 Stokes number

The role of Stokes number on the continuous phase turbulence intensity has drawn much research attention and still is a debated topic, specifically in the context of correctly determining the modulation of turbulence intensity. For instance, Abdelsamie and Lee (2012), Ferrante and Elghobashi (2003), and Yang and Shy (2005) demonstrated that Stokes number could be utilised as a parameter to quantify the turbulence modulation for small particles while this was shown to be not appropriate for larger particles (Lucci et al. 2010; Tanaka and Eaton 2008).

To elucidate the significance of Stokes number on turbulence modulation, we first focus on the various levels of particle–fluid interactions. Elghobashi (1994) first classified the modulation of turbulence intensity with the Stokes number based on both experimental and numerical results available at the time and presented a regime map showing various levels of interactions of the particles with the fluid medium.

Later, Elghobashi (2006) proposed an updated classification map (see Figure 12) based on particle concentration (volume fraction of particles) and Stokes number. The first regime on this map comprises dilute particle systems (particle volume fraction $<10^{-6}$), which exhibits one-way phase coupling. In this regime, particle dispersion behavior depends on the continuous phase turbulence, while the momentum transfer from particle phase to continuous phase is deemed to be insignificant due to the low concentration of the particles implying no turbulence modulation occurs.

In the second regime, the particle volume fraction is intermediate ($10^{-6} \leq \phi_v \leq 10^{-3}$), implying that the transfer of momentum from particles to the continuous phase and vice versa is significant (two-way coupling), which contributes to turbulence modulation. In this regime, there are two zones (A and B) for a given value of $\phi_v$, which depends on the value of the Stokes number at the wall $St_K$. The transition between the two zones occurs at about $St_K \approx 10$. In zone A, the DNS study of Ferrante and Elghobashi (2003) showed that for a fixed $\phi_v$, effect of particles on the continuous phase turbulence level varies significantly as a function of $St_K$, wherein the particle Reynolds number, $Re_p \leq 1$ within the range of $0.01 \leq St_K \leq 10$. This phenomenon of zone A, as depicted in Figure 12 is discussed in the subsequent section. At the same time, an enhancement of turbulence production (i.e., zone B) is observed when the value of $\tau_f$ increases (for the exact value of $\phi_v$), and when the particle Reynolds number increases to over 400, vortex shedding appears.

In the third regime, the particle volume fraction is greater than $10^{-3}$ (dense systems), and consequently, particle-particle interactions become inevitable. In this region, besides the two-way coupling between a particle and continuous fluid, inter-particle interactions are also considered hence this region is known as the four-way coupling zone.

Zone A of the updated classification map (see Figure 12) was reclassified by Elghobashi (2006) based on the DNS study of Ferrante and Elghobashi (2003). The DNS study was carried out in an isotropic flow system for 80 million particles much higher compared to previous studies (Bovin et al. 2000; Druzhinin and Elghobashi 1999; Elghobashi and Truesdell 1993; Squires and Eaton 1990; Sundaram and Collins 1999). Particles in this study

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**Figure 12:** Classification map of particle-laden turbulent flows (reprinted from Elghobashi (2006), with permission from Springer).
were selected in size range from 30 to 94 µm, much smaller than the Kolmogorov length scale of the system (0.043–0.134 times of the Kolmogorov length scale). In their study, zone A was further categorized into three sub-regions: micro-particles \((0.01 \leq St_K \leq 0.1)\), intermediate or ghost particles \((0.1 \leq St_K \leq 1.0)\), and large particles \((St_K \geq 1.0)\).

Based on the DNS study of Ferrante and Elghobashi (2003), a schematic representation of different mechanisms for these three types of particles is presented in Figure 13.

The net rate of spectral kinetic energy \(E(t)\) in an isotropic turbulent flow due to the presence of particles can be written as:

\[
\frac{dE(t)}{dt} = T(t) - \varepsilon(t) + \psi_p(t) \tag{3}
\]

where \(T(t)\) is the net result of the spectral energy-transfer rate, \(\varepsilon(t)\) is the viscous dissipation rate, and \(\psi_p(t)\) is the change in energy due to particle–fluid drag.

In case of the micro-particles \((0.01 \leq St_K \leq 0.1)\), the net rate of turbulent energy transfer \(E(t)\) in Equation (3), can be written as a competition between the rate of viscous energy dissipation \(\varepsilon(t)\) and change in energy due to particle–fluid drag force \(\psi_p(t)\), as follows:\(^1\)

\[
\frac{dE(t)}{dt} = -\varepsilon(t) + \psi_p(t). \tag{4}
\]

Due to low inertia, micro-particles exhibit a small response time in the low Stokes number region and get trapped within the vortical structures of adjacent fluid and get transported (see Figure 13a). In a DNS study, Ferrante and Elghobashi (2003) noted that both specific energy dissipation rate and turbulent kinetic energy are enhanced in the presence of micro-particles. In large Stokes number cases, particle’s relaxation time \(\tau_p\) is greater than the dissipation time scale based on Kolmogorov’s length scale of the continuous phase \(\tau_{\eta}\). Elghobashi and Truesdell (1992) pointed out that large particles are not responsive to the surrounding fluid velocity fluctuations, and they intersect the fluid streamlines (see Figure 13b). Large particles attenuate both turbulent kinetic energy and energy dissipation rate relative to their values in a single-phase flow system.

Another class of particles called the ghost particles in the intermediate Stokes number regime modifies the continuous phase turbulence such that the turbulence kinetic energy remains unchanged; however, the energy dissipation rate is larger than the single-phase flow. Elghobashi (2006) introduced another region between the ghost and large particles, which is referred to as “critical particle” region \((St_K \approx 0.1)\). These particles were noted to have higher preferential accumulation in between the low vorticity and high strain rate regions compared to the ghost and large particles. While interacting with the smallest vortical structure,
i.e., Kolmogorov’s length scale, a critical size particle ($d_p < \eta$) is ejected from the center of these flow structures due to centrifugal force and rotates along their periphery (Figure 13c). Consequently, the core of these flow structures remains relatively free of particles. Due to the significant inertia of the particles accumulated at the periphery, the turbulent kinetic energy of these eddies attenuates.

In Figure 14, variations in turbulent intensity are presented against Stokes number for different particle diameters. This figure includes the experimental data from the channel flows (Kaftori et al. 1998; Kiger and Pan 2002; Kulick et al. 1994; Kussin and Sommerfeld 2002) and jet flows (Mando 2009) obtained at various operating conditions and orientations (horizontal and vertical).

In the range of $St_K < 0.01$, negligible attenuation ($<10\%$) of turbulence intensity is evident from the data reported by Kaftori et al. (1998) for 100 $\mu$m size particles. In the intermediate range ($0.01 < St_K < 1.0$), turbulence augmentation ($\sim 10\%$) is apparent from the data of Kaftori et al. (1998) for 275 $\mu$m size particle, $\sim 20\%$ augmentation reported in Kulick et al. (1994) for 50 and 70 $\mu$m particle and negligible effect in Kiger and Pan (2002) for 195 $\mu$m size particle. For $St_K > 1.0$, reported experimental data (Kussin and Sommerfeld 2002; Mando 2009) indicate that turbulent intensity does not follow any definite trend, and both augmentation and attenuation behavior is noted. Figure 14 shows that $St_K$ possibly is not a rigorous parameter to account for the systematic variation in the turbulence intensity, which seems to hold true at least for the channel and jet flow cases and is in agreement with earlier findings (Tanaka and Eaton 2008).

Contrary to the turbulence intensity data presented in Figure 14, it can be noted that Stokes number can demarcate the turbulence augmentation and attenuation regimes for the grid-generated turbulence (see Figure 15). The analyzed data sets fall into two distinct groups: (a) for the range $0.01 \leq St_K < 9.0$ wherein the turbulence intensity is attenuated in the presence of the smaller particles (diameter range: 160–500 $\mu$m) (Poelma et al. 2007; Yang and Shy 2005) and (b) for $St_K \geq 9.0$ wherein turbulence intensity is augmented in the presence of larger particles (diameter range: 1000–8000 $\mu$m) (Hoque et al. 2016).
There are, however, a few known issues with the selection of the Stokes number as an identifier of turbulence modulation, specifically in defining the appropriate length scale required to estimate both fluid and particle response time. For the fluid phase, either Kolmogorov’s scale or the integral time scale of the continuous phase can be selected to determine the fluid response time as $\tau_f = l_f/\bar{u}'$, where $l_f$ is a flow length scale which is system-specific and deserves a careful examination (Monchaux et al. 2012).

There are two contributing parameters to the inertial effects in the definition of Stokes number which are particle diameter and density, respectively. It is noted that these two parameters cannot be interchanged, one with the other, to represent the same particle dynamics (Qureshi et al. 2008). They should be distinguished when dealing with the finite-size particles ($d_p > \eta$) where slip velocity is not negligible. This aspect is further confirmed in the numerical studies of Lucci et al. (2010) and Lucci et al. (2011), which showed that different size particles having identical relaxation times can have a distinct influence on the continuous phase flow.

3.3 Particle concentration

In the literature, particle concentration is described both in terms of volume fraction and mass loading (ratio of mass flow of particles to that of continuous phase fluid) parameter. It is commonly hypothesised that the continuous phase flow is not influenced by particles if present in a low volume fraction ($\phi_v < 10^{-3}$). In this case, particles are considered to be passively advected. Conversely, above this threshold, the continuous phase flow is significantly affected by the presence of particles. In addition, particle–particle collisions are also needed to be accounted for solid volume fractions $>10^{-3}$. It was previously shown in Figure 12 that increasing particle volume fraction ($\phi_v$) (ratio of the volume of the dispersed phase to continuous phase) leads to turbulence modulation such that the momentum lost or gained by the solid phase is no longer negligible. This subset of particle-laden flows has not been investigated as thoroughly as particle dispersion by turbulence primarily because of the difficulty in obtaining reliable laboratory measurements for an exhaustive range of particle volume fractions (Squires and Eaton 1990). Furthermore, fewer studies (Ferrante and Elghobashi 2003; Lucci et al. 2010; Lucci et al. 2011) are available on the so-called two-way coupling (see Figure 12) problem and need to be explored further to expand the theoretical understanding of volume fraction effect.

In Figure 16, change in turbulence intensity is plotted against the dispersed phase volume fraction parameter for channels, pipes, and free jets flow system. These datasets show both attenuation and augmentation of turbulent

![Figure 16: Dependency of turbulence intensity on particle volume fraction for channel, pipe, and jet flow system.](image-url)
intensity parameter which is randomly scattered over the \( I - \phi_v \) plane. Based on Figure 12, it is intuitive to expect a negligible effect of the presence of particles in turbulence in low, i.e., one-way coupling region when \( \phi_v < 10^{-6} \), however, Wu et al. (2006) found that the turbulence of the continuous phase in a horizontal rectangular channel flow is modulated even at very low values of \( \phi_v \left( 10^{-5} \right) \) (see Figure 16). These observations were also reported by Guo et al. (2004), Kiger and Pan (2002), Kullick et al. (1994) and Taniere et al. (1997). It may be noted that some previous studies (Eaton and Fessler 1994; Elghobashi 1994, 2006) assumed that modulation of turbulence would be insignificant in presence of such small mass loading ratio.

In the two-way coupling region \( (10^{-6} < \phi_v < 10^{-3}) \), both attenuation and augmentation in the turbulence intensity can be observed in the presence of particles (Kaftori et al. 1998; Levy and Lockwood 1981; Mando 2009; Modarress et al. 1984b; Rashidi et al. 1990; Saber et al. 2016; Sheen et al. 1994; Wu et al. 2006) (see Figure 16). In this regime, several factors are known to contribute to the energy dissipation rates, such as (a) particle–fluid interactions, (b) wake production behind the large particles due to the vortex shedding, and (c) enhancement of the energy dissipation rate owing to the no-slip condition at the vicinity of the particle surface (Balachandar and Eaton 2010).

In Figure 16, the experimental results of jet flows (Mando 2009; Sheen et al. 1994) show attenuation in turbulence intensity at \( \phi_v < 2 \times 10^{-5} \), while an augmentation was apparent at \( \phi_v > 2 \times 10^{-4} \) for large particles \( (d_p > 200 \mu m) \). In contrast, channel flow experiments (Kaftori et al. 1998; Rashidi et al. 1990) indicate both attenuation \( (d_p < 120 \mu m) \) and augmentation \( (d_p > 800 \mu m) \) in the presence of particles. Wu et al. (2006) claimed significant augmentation of turbulence intensity in the two-way coupling region due to the presence of small particles \( (d_p < 100 \mu m) \).

Tanaka and Eaton (2010) investigated the modulation of small-scale turbulent structures in a homogeneous and isotropic chamber with particles \( (\phi_v = 5.5 \times 10^{-5} \text{ to } 4.7 \times 10^{-5}) \) using PIV measurement. Their analysis showed a disagreement between the turbulent kinetic energy (TKE) modulated by the particles to the TKE dissipation rate in contrast with the earlier measurements that showed the dissipation level was reduced to approximately the same extent as the TKE. Tanaka and Eaton (2010) attributed this discrepancy to the inadequate dissipation measurement techniques used in previous research.

To counter the incorrect notion that there is little impact of turbulence attenuation on small-scale turbulence, Tanaka and Eaton (2010) investigated this phenomenon further by analysing the two-point correlations and subgrid-scale TKE for various spatial resolutions. They observed the presence of particles caused a decrease in the two-point correlations for most cases indicating small-scale turbulence structures were affected by the particles. These apparently conflicting findings suggest there are two distinct mechanisms at play at small scales. Firstly, as large-scale turbulence is reduced, there is less energy transferred down the cascade for small scales to dissipate. Secondly, the local disruption of turbulence around the heavy particles generates additional small-scale energy and dissipation rate. For the particle sizes and flow parameters examined in Tanaka and Eaton (2010), these two mechanisms roughly balance each other out at small scales.

Additionally, Tanaka and Eaton (2010) conducted high-resolution PIV measurements near particles to gain further insight into the modification of turbulence by examining changes in the dissipation rate between particle-laden and unladen cases. They found that the TKE was attenuated close to the particles by a factor of approximately two in the region of strong reduction extending out to around twice the particle diameter. Furthermore, strong energy dissipation approximately three times of the unladen case was observed around the particles, which is consistent with the fully resolved direct numerical simulations (DNS) by Burton and Eaton (2005). The significant attenuation in TKE is attributed to the large density difference between the fluid and particles \( (\rho_f/\rho_p \sim 10^3) \), which prevents the particles from following the turbulent velocity fluctuations. Consequently, in such particle-laden turbulent regimes, the momentum of these high-inertia particles is hardly influenced by the fluid motion. Instead, particles experience strong shear stress through no-slip condition at the particle surface which results in strong energy dissipation around particles implying particles act as TKE dampers.

Finally, in the four-way coupling region \( (\phi_v > 10^{-3}) \), interactions among the particles, such as collision, attrition, and agglomeration, become significant in addition to the fluid–particle interactions. Balachandar and Eaton (2010) observed that in a dense granular flow regime, collisions among the particles become more critical compared to interactions with the interstitial fluid. In Figure 16, the experiments carried out in jet (Levy and Lockwood 1981; Modarress et al. 1984a) and pipe (Modarress et al. 1984b; Tsuji and Morikawa 1982; Tsuji et al. 1984; Zisselmar and Molerus 1979) flows were performed at a volume fraction above 0.001. The data indicate both attenuation and augmentation of turbulence intensity; however, no definite trend is noted. This behavior could be attributed to the more complex particle-turbulence interactions in this region due to the higher particle volume fraction which are difficult to characterise by only Stokes number, particle volume fraction, and length scale ratios.
Modulation of turbulence in the grid systems (both active and passive) in the presence of particles is summarised in Figure 17.

Noticeably, turbulence augmentation is only observed in the two-way coupling region, while turbulence attenuation is evident in both one-way and four-way coupling regions. It is noted that turbulence augmentation occurs only in the presence of large-size particles \( (d_p \geq 1000 \, \mu m) \). In contrast, the effect of small particles \( (d_p \leq 700 \, \mu m) \) on turbulence modulation is relatively insignificant. It is essential to mention that due to the low level of velocity fluctuations in the grid-generated flow system, reported turbulence intensity values might have significant variations (Balachandar and Eaton 2010). Although in Figure 16, no discernible trend between the turbulent modulation and particle volume fraction could be established due to a greater degree of scattering in the data, clustering of data points in the particle volume fraction range between \( 10^{-6} \) and \( 10^{-4} \) indicates turbulence suppression can occur on either side of this range.

### 3.4 Particle momentum number

Tanaka and Eaton (2008) proposed a non-dimensional number called particle momentum number \( \text{Pa}_{\text{St}} \) to assess the effect of particle phase as turbulence promoter or dampener. This number for particle-laden flow according to (Tanaka and Eaton 2008) can be written as:

\[
\text{Pa}_{\text{St}} = \text{St}_{\text{K}} \text{Re}_l^2 \left( \frac{\eta}{l} \right)^3
\]

Figure 17: Dependency of turbulence intensity on particle volume fraction for grid generated turbulence systems.

Figure 18: Mapping of the previous turbulence modification experiments based on (a) \( \text{Pa}_{\text{St}} \) and \( \text{Re}_l \), and (b) \( \text{Pa}_{\text{Re}} \) and \( \text{Re}_l \). The open and closed symbols represent the turbulence intensity augmentation and attenuation, respectively (reprinted from Tanaka and Eaton (2008), with permission from American Physical Society).
Tanaka and Eaton (2010) suggested two different mechanisms causing turbulence augmentation – (a) superposition of wakes at large $\text{Pa}_\text{St}$ and (b) preferential particle concentration around the strong vortical structures at small $\text{Pa}_\text{St}$ (Yang and Shy 2005).

Using the similar set of experimental data, Figure 18b represents the plot $\text{Re}_l$ versus $\text{Pa}_{\text{Re}}$ and shows a similar trend to Figure 18a. Noted that Tanaka and Eaton (2010) estimated the value of $\text{Pa}_{\text{Re}}$ based on the Equation (6). The particle Reynolds number ($\text{Re}_p$) in Equation (6) was estimated by assuming the slip velocity can be approximated by the particle terminal velocity due to the difficulty in obtaining $\text{Re}_p$ directly from the previous experimental studies. From the data presented in Figure 18b, it is evident that turbulence attenuation occurs in the range $3 < \text{Pa}_{\text{Re}} < 200$. Since turbulence modulation has some dependency on $\text{Re}_l$ as well, another regime demarcation may be considered. In Figure 18b, the dotted line shows $\text{Re}_l = 1.5 \times 10^3 \text{Pa}_{\text{Re}}^{1/2}$ and therefore, the classification can be described as $\text{Re}_l < 1.5 \times 10^3 \text{Pa}_{\text{Re}}^{1/2}$ or $\text{Pa}_{\text{Re}} < 3$ for the augmentation cases, and $\text{Re}_l > 1.5 \times 10^3 \text{Pa}_{\text{Re}}^{1/2}$ and $\text{Pa}_{\text{Re}} > 3$ for the attenuation cases.

This dependency of the turbulence modulation on the particle momentum number has been investigated for the grid turbulence system. The experimental data of the grid turbulence system in the presence of particles ranging from 160 µm to 8000 µm are plotted in Figure 19 on $\text{Pa}_{\text{St}_l}$ – $\text{Re}_l$ plane where the open and close symbols show the turbulence attenuation and augmentation cases, respectively. A critical particle momentum number $\text{Pa}_{\text{St}_l} \sim 3.0$ can be noted above which an augmentation in the turbulence intensity and below which attenuation is quite apparent. This classification map can be used to choose the correct operating parameters for any future particle-laden flow experiments and, thus, to generate tailor-made turbulence intensity in the grid-generated turbulence systems.

### 3.5 Particle Reynolds number

In general, particle Reynolds number ($\text{Re}_p = \frac{d_p \text{U}_T}{\nu}$, where $\text{U}_T$ is the terminal settling velocity of the particle in quiescent fluid) defined as the ratio of the inertial to viscous forces, is
extensively used to quantify turbulence modulation in the presence of particles. It governs the type of boundary layer present on particles (laminar or turbulent) and occurrence of vortex shedding. In an earlier study by Hetsroni (1989), experimental data from Gore and Crowe (1989) was utilized to propose that particles with low Re\(_p\) values have a tendency to suppress turbulence intensity of the continuous fluid, while particles with high Re\(_p\) values exceeding 400, tend to enhance turbulence intensity possibly due to vortex shedding. It should be noted that Hetsroni (1989) did not use the conventional definition of Re\(_p\) for particles, but instead, introduced an alternative definition based on the density difference and slip velocity between the fluid and the particle which can be written as follows:

$$\text{Re}_p = \frac{(\rho_p - \rho_f)(u - u_p)d_p}{\mu_f}$$ (7)

where \(\mu\) is the dynamic viscosity, \(\rho\) is the mass density, \(u\) is the velocity, \(d_p\) is the particle diameter, and the subscript \(p\) and \(f\) denote the particle and fluid, respectively.

The analysis reported by Hetsroni (1989), however was limited to the previous studies (1971–1987) on the pipe and jet flows. It was of interest, therefore, to present the experimental data from the reported studies post 1989 for different flow geometries, namely jets (Mando 2009; Sheen et al. 1994), channels (Kafftiri et al. 1998; Rashidi et al. 1990; Saber et al. 2016; Wu et al. 2006) involving particles as the dispersed phase (see Figure 20). It is noted that particle Reynolds number was challenging to obtain from most of the previous studies in absence of any information on the slip velocity. In view of this, in the present study; slip velocity was approximated by the particle terminal settling velocity. The following equations were used to estimate the terminal settling velocity (Wang and Fan 2013):

$$U_T = 0.153 \frac{d_p^{1.14}}{\delta^{0.71}} \frac{(\rho_p - \rho_f)^{0.71}}{\mu_f^{0.39} \rho_f^{0.29}}; \text{for } 1 \leq \text{Re}_p \leq 500$$ (8)

and

$$U_T = 1.76 \sqrt{\frac{gd_p(\rho_p - \rho_f)}{\rho_f}}; \text{for } \text{Re}_p \geq 500$$ (9)

Figure 20 shows that both attenuation and augmentation of turbulent intensity can occur over a range of particle Reynolds number up to 1000.

This observation indicates there is no clear, strong correlation between Re\(_p\) and changes in the turbulent intensity. However, when focusing on the work of Mando (2009), it becomes evident that turbulence attenuation is more prominent at low Re\(_p\) values, while augmentation only
occurs at values above $Re_p \approx 110$, exclusively at $Re_p$ values higher than approximately 400. Mando (2009) argued that wake instability occurs at $Re_p \approx 130$ while vortex shedding begins at $Re_p \approx 270$, indicating that increase in the turbulent intensity cannot be solely attributed to vortex shedding. If this were the case, the lower critical value of vortex shedding formation at $Re_p \approx 270$ should have demarcated the increasing and decreasing turbulence regimes.

Figure 21 illustrates the variations in turbulence intensity with particle Reynolds number defined as $Re_p = \left( \frac{u_{rms} dp}{\nu} \right)$ in the range of 1–106 for the grid turbulence system in both multi-particles and single particle systems (Hoque et al. 2016). It is apparent that even after replacing the parameter $dp/l$ with $Re_p$ in the abscissa, the two regimes of turbulence enhancement (top part) and attenuation (bottom part) are distinctly demarcated by $Re_p = 10$, corresponding to the particle size of 1000 µm, as previously shown in Figure 11 (Section 3.1).

The available studies indicate that vortex shedding occurs at relatively higher particle Reynolds number ($Re_p > 400$) in pipe and jet flows, Hetsroni (1989); and $Re_p > 300$ in a sinusoidally oscillating free stream, Mittal (2000). In the study of Hoque et al. (2016), the $Re_p$ based on the root mean square velocity was below the reported threshold values for vortex shedding, but $Re_p$ based on the instantaneous velocity was higher than these thresholds. This was confirmed in Hoque et al. (2016) (see the supplementary document in Hoque et al. (2016); particularly Figure A2a–h) showing spatial distribution of the instantaneous velocity in the presence of a particle. The distribution revealed that a small fraction of velocity was in the range of 0.15–0.18 m/s corresponding to $Re_p$ in the range of 450–540 which exceeds the reported thresholds for vortex shedding.

Hoque et al. (2016) also observed strong accelerating and decelerating flow components, flow reversal, and chaotic flow directions dominated by the fluctuating components over local mean flow (~3–9 times of the local mean flow) (see the supplementary document in Hoque et al. (2016); particularly Figure A1a–h). Based on these observations, it appears that both wake oscillations and vortex shedding mechanisms may be valid for the oscillating grid system even in the low Reynolds number range. Nevertheless, a confirming DNS study on the oscillating grid system would be necessary to support this postulation in future.

4 Concluding remarks and recommendations for future work

4.1 Summary

The present study brings out the current knowledge on turbulence modulations in particulate flow systems. Available published literature on the experimental measurements involving gas–solid, gas–liquid, and liquid–solid flows in three different systems, namely channels and pipes, free jets, and grids, have been critically analysed and characterised using five dimensionless parameters, namely length scale ratio, dispersed phase volume fraction, Stokes number, particle momentum number and particle Reynolds number. Arguably, it can be inferred that to date no single dimensionless number has emerged that unequivocally describes the influence of particles on the modulation of continuous phase turbulence intensity. Current understandings of turbulence modulation in particulate systems are summarised in the following remarks:

1. The turbulence modulation classification figure reported by Gore and Crowe (1989) has been updated by

![Figure 21](image-url)
incorporating the experimental data of channel flows. A critical value of \( d_p/l \approx 0.1 \) was obtained, below which the turbulence intensity was considerably attenuated. However, above the value of 0.1, turbulence intensity was observed to augment. In contrast, a different critical value (\( d_p/l \approx 0.41 \)) was found using the oscillating grid turbulence experimental data. However, the classification figure based on the ratio of \( d_p/l \) does not describe the effect of changing particle material density on turbulence modulation.

(2) The experimental data of jet, pipes and channel flow suggest that turbulent intensity is attenuated or remains unchanged in the Stokes number range \( 0.01 < St_k < 60 \), wherein the particle size varied in the range from 50 to 1800 \( \mu \)m. However, the turbulence intensity either attenuates or augments when the Stokes number is larger than 60. In contrast, a much lower critical threshold value of Stokes number \(-9.0\) is noted for the grid generated turbulence systems.

(3) No definite trend is observed between the turbulence intensity parameter and particle volume fraction for other flow systems except grid systems. For these systems, a specific regime of turbulence augmentation between \( 10^{-2} \) and \( 10^{-4} \) and turbulence suppression on either limit of this range is observed.

(4) A threshold value of particle momentum number \( Pa_{St_k} \sim 3 \) is noted to identify turbulence modulation in the grid systems. This value differs significantly from Tanaka and Eaton (2008), wherein a minimum value between \( 10^2 \) and \( 10^3 \) was obtained.

(5) In flow systems other than grid systems, no clear relationship is observed between the turbulence intensity parameter and the particle Reynolds number. For grid systems, a critical \( Re_p \) value of 10 is identified, below which turbulence intensity significantly reduces.

4.2 Current challenges and future perspectives

Based on the present findings, the following points are noted to elaborate on the current challenges and future research direction in this area:

(1) Determining turbulence kinetic energy dissipation rate is crucial to understand the modulation of continuous phase turbulence in presence of particles. However, a precise measurement of this parameter is still challenging as it involves estimation of the velocity gradient in all three flow directions. There are inherent complexities involved in the velocity field measurement in particulate flow systems due to several factors, which include (a) heterogeneous distribution of solid phase fraction, which makes local measurements, such as pressure taps and optical fibers inadequate, (b) different flow regimes (bubbling, slugging, turbulent and circulating) (c) wide variations in velocity and acceleration (d) flow disturbance due to intrusive measurements and (e) system opacity due to high solid concentrations.

(2) For dilute particulate systems, generally non-invasive particle image velocimetry (PIV) is utilised; however, there are known issues with the conventional planar PIV measurement, which requires an isotropic assumption. It is also known that the spatial resolution of the PIV system directly affects such estimations (Paris and Eaton 1999). In multiphase flows, the energy dissipation rate significantly changes at the vicinity of the particles. To resolve the local flow field surrounding a single-particle, PIV measurements with a high spatial resolution are required (Tanaka and Eaton 2007). Hoque et al. (2016) reported the first single-particle experiments in grid-generated turbulence as an exploratory study. Stereo and tomographic PIV measurements can be utilised to resolve the velocity field in three directions. Tomography along with shadowgraphy technique can also be utilised to reconstruct the interface of dispersed phases such as bubbles and particles (Elsinga et al. 2006; Gao et al. 2013b; Scarano 2012; She et al. 2021). However, it is still very challenging to capture the velocity field around the smaller size particles due to resolution issues that would need further attention in future studies.

(3) Novel measurement techniques need to be applied to obtain meaningful velocity field information for dense particulate systems. High-speed X-ray tomography has been used to investigate optically thick systems (Liu et al. 2009), although spatial resolution in X-ray tomography is still limited.

The electrical capacitance tomography (ECT) technique, on the other hand, has been utilised to quantify volume fraction and phase distribution in gas–solid flow systems both in 2D and 3D configurations (Banaei et al. 2015; Breault et al. 2020; Cong et al. 2012; Grudzien et al. 2012; Jaworski and Dyakowski 2001; Li et al. 2018; Tu and Wang 2020; Wang and Yang 2020; Wang et al. 2012; Wang et al. 2020a; Weber et al. 2018; Zhang et al. 2014; Zhao et al. 2010b; Zhao et al. 2016; Zhu et al. 2003; Zhu et al. 2020c). This method offers multiple benefits including (i) fast-speed imaging, (ii) no radiation, (iii) robust measurement, (iv) non-intrusive and non-invasive, (v) low cost, and (vi) withstand high operating pressure (up to 150 bar) and temperature (up to 300 °C). However, ECT still suffers from inadequate temporal resolution (>>1 mm) (Poelma 2020).
Magnetic resonance imaging (MRI) technique is capable of measuring the three-dimensional temporal velocity field in particulate systems with a resolution of ~0.5 mm (Elkins et al. 2009; Gladden and Alexander 1996; Kutovskyy et al. 1996; Sankey et al. 2009; Sederman et al. 1997; Tayler et al. 2012). However, this technique is quite slow to acquire the images and also expensive in terms of hardware requirements. Further development on these techniques will be required for the cost-effective acquisition of high-speed spatio-temporally resolved data.

Positron emission particle tracking (PEPT) involving tracking of a radiolabelled tracer particle by a positron emission tomography (PET) camera has been successfully applied in recent times to quantify the hydrodynamics of the solid phase in different opaque systems, such as dish-washing machines (Pérez-Mohedano et al. 2015), spouted bed roasters (Al-Shemmeri et al. 2021), milling equipment (Yu et al. 2015) and mineral flotation tanks (Cole et al. 2022; Masa et al. 2021; Masa et al. 2022; Waters et al. 2008). PEPT measurement produces time series data based on the tracer particle location, which can be used to determine the system hydrodynamics. The tracers used in PEPT are either representative particles that work as proxies for the real particles of interest – often indirectly activated Fan et al. (2006a) and Cole et al. (2014) – or identical to the particles studied – often directly activated (for more information on tracer activation, the readers are referred to Boucher et al. (2017) and Fan et al. (2006b).

(4) More careful experiments need to be conducted for a wide range of particle sizes, volume fractions, and particle Reynolds numbers to establish a classification map for the grid-generated turbulence system.

(5) Further experiments are required in oscillating grid systems in the presence of different sizes of stationary particles to determine the validity of the length scale ratio $d_p/l \sim 0.41$ (Hoque et al. 2016) to assess turbulence intensity modulation.

(6) Recognising the limitations of experimental measurements in dense particulate systems and the increasing availability of more computational power at the current state, fully resolved direct numerical simulations (DNS) (Schneiders et al. 2017; Vreman 2016; Vreman and Kuerten 2018) of the systems down to the Kolmogorov length scale will be required to obtain useful insights into the underlying physical mechanisms of turbulence modulation.

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### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$D$</td>
<td>diameter of the pipe (mm)</td>
</tr>
<tr>
<td>$d_p$</td>
<td>diameter of the particle (µm)</td>
</tr>
<tr>
<td>$E(t)$</td>
<td>spectral kinetic energy ($m^2/s^3$)</td>
</tr>
<tr>
<td>$I$</td>
<td>turbulence intensity (–)</td>
</tr>
<tr>
<td>$l$</td>
<td>integral length scale (mm)</td>
</tr>
<tr>
<td>$P_{\delta,\delta}$</td>
<td>particle momentum number (–)</td>
</tr>
<tr>
<td>$R$</td>
<td>radius of the pipe (m)</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number (–)</td>
</tr>
<tr>
<td>$Re_p$</td>
<td>particle Reynolds number (–)</td>
</tr>
<tr>
<td>$Re_i$</td>
<td>Reynolds number based on the integral length scale (–)</td>
</tr>
<tr>
<td>$S_{St0}$</td>
<td>jet Stokes number (–)</td>
</tr>
<tr>
<td>$S_{St}$</td>
<td>particle Stokes number (–)</td>
</tr>
<tr>
<td>$S_{St}^*$</td>
<td>Stokes number based on wall parameter (–)</td>
</tr>
<tr>
<td>$T(\delta)$</td>
<td>net result of the spectral energy-transfer rate ($m^2/s^3$)</td>
</tr>
<tr>
<td>$U_f$</td>
<td>terminal settling velocity (m/s)</td>
</tr>
<tr>
<td>$U_b$</td>
<td>jet bulk velocity (m/s)</td>
</tr>
<tr>
<td>$U_{it}$</td>
<td>critical value of superficial velocity (m/s)</td>
</tr>
<tr>
<td>$U_{min}$</td>
<td>minimum bubbling velocity (m/s)</td>
</tr>
<tr>
<td>$U$</td>
<td>mean velocity along the centerline of the flow system (m/s)</td>
</tr>
<tr>
<td>$u'$</td>
<td>fluctuating velocity (m/s)</td>
</tr>
<tr>
<td>$\bar{v}_{rms}$</td>
<td>root mean square velocity in horizontal direction (m/s)</td>
</tr>
<tr>
<td>$\bar{v}_{rms}$</td>
<td>root mean square velocity in vertical direction (m/s)</td>
</tr>
</tbody>
</table>

### Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>energy dissipation rate ($m^2/s^3$)</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>density of the particle (kg/m$^3$)</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>density of the fluid (kg/m$^3$)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>particle relaxation time (s)</td>
</tr>
<tr>
<td>$\tau_t$</td>
<td>dissipation time of the continuous phase turbulence (s)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Kolmogorov’s length scale (m)</td>
</tr>
<tr>
<td>$\phi_f$</td>
<td>volume fraction (–)</td>
</tr>
<tr>
<td>$\psi(\ell)$</td>
<td>viscous dissipation rate ($m^2/s^3$)</td>
</tr>
<tr>
<td>$\Delta \psi(\ell)$</td>
<td>change in energy due to the particle-fluid drag ($m^2/s^3$)</td>
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### References


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