

Turbulent Modulation in Particulate Flow: A Review of Critical Variables

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Received 29 July 2015; accepted 13 October 2015; published 16 October 2015

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Abstract

A review of the main mechanisms influencing turbulent modulation in the presence of spherical and non-spherical particles is presented. The review demonstrates 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 reveals that non-spherical particles have more adverse effect on turbulence as compared to spherical ones, for the same ambient conditions.

Keywords

Two Phase Flow, Turbulent Modulation, Non-Spherical Particle, Stokes Number, Particle Reynolds Number, Length Scale, Density Ratio

1. Introduction

Turbulent flows can be found everywhere in nature and industry, but a unifying theory of turbulence does not exist. When spherical particles are suspended into such a flow, the flow becomes even more intricate and the resulting interactions between the particles and turbulent structures are not fully understood. For non-spherical particles that often appear in fluids in industrial processes, like paper making, iron ore pelletization, pneumatic conveying [1], cyclone filters [2] [3], and biomass gasification and combustion, the interactions of the particles and the fluid in turbulent flow are extremely complex while theories exist for creeping flow [4]-[8]. In turbulent flow, the particles will wobble or move chaotic, depending on their size and density [9]. Hence, the carrier phase turbulence alters the dispersed phase translational and rotational motion and the particles influence the detailed and overall flow of the carrier phase.

It is important to study turbulent modulation, or in other words the influence of the dispersed phase on the

carrier phase due to its large effect on the behavior and performance of many industrial systems involving solid-gas flow. Already in the middle of the former century, researchers high-lighted that the presence of particles can significantly influence the rate of, for instance, heat transfer and chemical reaction. Such features can be explained with turbulent modulation. The study of turbulent dispersion in two-phase flows has a long history as described for spherical particle motion in [10] and for non-spherical particle motion in [11] while studies on the physics of how the particles effect the fluid turbulence has gained less attention over the last few decades [12] and is still an open topic. To achieve a valuable mathematical description for issues such as turbulent combustion or chemical processes involving solid-gas flow for computational fluid dynamic CFD codes, the knowledge and understanding of the mutual interaction between phases should be improved before additional relationships such as chemical reactions are included.

In two phase two-way coupling flow several mechanisms contribute to the modification of the turbulence like additional dissipation caused by the particles, the transfer of a portion of particle kinetic energy to the carrier phase, turbulence due to vortex shedding behind the particles and increase of dissipation due to no-slip boundary conditions at the surface of the particles. Secondary motion, due to the higher degree of freedom of motion, associated with non-spherical particles can transfer kinetic energy into Turbulent Kinetic Energy TKE in more moods than spheres. The importance of each of these mechanisms for turbulent modulation will now be discussed regarding both rigid spherical and non-spherical particles.

2. Two-Phase Flow Turbulence Modulation

The addition of particles to the carrier phase tends to affect the TKE, dissipation rate, and turbulence intensity. Many researchers have categorized the alterations in turbulence into augmentation and attenuation and suggested correlations that quantitatively describe these phenomena. In general, observations suggest that small particles attenuate the turbulence of the carrier phase and large particles amplify it [13]. It can be argued that a heavy particle sinking in a fluid at rest will transfer its potential energy to the fluid around it and that particles moving in turbulent flow maybe seen in a similar manner where both kinetic and potential energy may be transferred to the surroundings. On the other hand, heavy particle in turbulent flow needs energy if they are to be moved in the direction of flow but it is not obvious how the TKE production and dissipation will be affected. In vertical up-flow, gravity and buoyancy will play major roles and heavy particles attenuate the kinetic energy. A point-particle approach is a sound tactic when the particle diameter dp is smaller than the Kolmogorov length scale η . For a large number of particles fully resolved simulations are, however, not possible to carry out [10] [14]. In the case of non-spherical particles, the shape effect of particles on the solid-liquid turbulence interaction has been investigated for particles with a diameter almost equal to the Taylor micro-scale and with a small relative density, $\rho_p/\rho_f \approx 1$ [15]. One result was attenuation in TKE of 3% and 15% for prolate ellipsoidal particles and spherical particles, respectively. A spectral analysis showed that the ellipsoidal particles distributed more TKE to the smaller scales with less energy loss than the spherical particles. Capone [16] injected rod-like particles into a fully developed water jet, which resulted in a significant change in turbulent structure. Mandø [17] investigated turbulence intensity modulation for spheres, discs and prolate ellipsoids. The results indicate that the discs and the prolate spheroids cause more attenuation than the spherical particles. In most of non-spherical particle studies, particles dampen turbulence more than spherical particles and amplify turbulence less than spherical particles. This may partly be related to non-suitable parameters used to compare spherical and non-spherical particles or related to the preferential orientation and rotation of particles that affect the formation of the wake behind the particles. A summary of published results on different types of particles is presented in Table 1.

3. Scaling of Turbulence Modulation

In the context of turbulence modulation the carrier phase may be characterized and described by its physical properties in addition to the turbulent length and time scales, dissipation and TKE of the flow. The dispersed phase, in its turn, can in addition to particle shape be described by particle density, size, surface and volume/mass fraction. Hence, a number of relationships can be formed that may be of importance. For qualitative evaluation of turbulence modulation the Stokes number St , the particle Reynolds number $Rep = (u_f - u_p)dp/\nu$, and the ratio of dp to turbulent length scales are frequently applied. Here also η may play a role. To determine the magnitude of the modulation, the mass loading ratio and volume fraction of particles may be used. Recently,

Table 1. Previous experimental work.

Reference	Flow configuration	Dimension mm	Fluid velocity m/s	Carrier phase	Particles material	Particle density kg/m ³	Particle equivalent Dia. mm	Particle shape	Seeding particle μm	Volume fraction	Mass loading	Measuring technique
Knowles, Kiger 2012 [44]	rectangular glass horizontal	218 - 268 micron		water	soda lime glass	2500		spherical	hollow silver-coated glass spheres 15			PIV
Bellani <i>et al.</i> 2012 [27]	rectangular tank	800 × 800 × 1620	0	water	hydrogel that is 99.5% water	1020	ds = 8 le = 16 de = 8	spherical & ellipsoidal	10 silver coated glass particles	0.0014		Stereo-PIV
Li 2012 [39]	horizontal channel	30 × 300 × 6000	6.64	air	Polythene	1030	0.06	spherical	5		10 ⁻⁴ to 10 ⁻³	PIV
Capone <i>et al.</i> 2015 [16]	horizontal jet	Dia. 70 × 2200		water	Polyamide 6.6	1130 - 1150	l = 0.32 d = 0.024	rod-like	10		2 × 10 ⁻³ & 6 × 10 ⁻³	PIV
Goswami 2011 [42]	vertical channel	40 × 380		air	glass	2500	0.06, 0.08, 0.12, 0.14	spherical	1 - 2	9:15 × 10 ⁻⁵	0.19	PIV
TANAKA 2010 [43]	nearly spherical chamber			air	glass and polystyrene	2500, 2500, 1000	0.5, 0.25, 0.25	spherical	Aluminum dioxide particles 0.3		0.12 - 0.41	PIV
Li 2010 [38]	horizontal channel	30 × 300 × 6000	6.644	air	Polythene	1030	0.60, 0.11	spherical	5 - 10	0, 2.85 × 10 ⁻⁷ , 1.14 × 10 ⁻⁶ , 5.7 × 10 ⁻⁶	0, 2.5 × 10 ⁻⁴ , 1 × 10 ⁻³ , and 5 × 10 ⁻³	PIV
Lu 2009 [45]	horizontal pipe	75 Dia.	12.0	air	glass	2550	0.11	spherical			1.6%	LDA
Zhou 2009 [46]	vertical water tank	500 × 500 × 1000	0	water	Polystyrene	1050 - 1077	2.78 - 7.94	spherical and cylindrical			single particle	PIV
Mandø 2009 [17]	vertical jet	Dia. 40	7	air	glass, polystyrene	2500, 1030	0.88 - 1.820, 2.444, 2.815	spherical, disk, Prolate spheroid	1		0 - 21.9 g/s	LDA
Mathisen <i>et al.</i> 2008 [47]	vertical	42 Dia	6, 7, 8, & 9	air	ZrO ₂ (Zirconium oxide) & glass	3800 & 2500	0.530 & 0.518	spherical		0.150, 0.200, 0.250		LDA & PIV
Zhang <i>et al.</i> 2007 [48]	45 inclined circular pipe	40 Dia.		air	polypropylene, PP	1123	2.80	spherical		0.16		ECT, PIV
Lain Sommerfeld 2007 [49]	horizontal channel	6000 × 35 × 350	up to 30	air	quartz and duroplastic	2650, 1480	0.185 and 0.24	non-spherical	4		up to 2 kg/kg air	(PDA)
Hwang 2006 [30]	nearly spherical chamber			air	glass	2500	0.165	spherical			0.3	PIV
Wu <i>et al.</i> 2006 [36]	horizontal channel	30 × 300 × 6000	6.603	air	Polythene	1030	0.06, 0.11	spherical	5 - 10	6 × 10 ⁻⁷ -4.8 × 10 ⁻⁵	5 × 10 ⁻⁴ 4 × 10 ⁻²	PIV
Geiss <i>et al.</i> 2004 [28]	vertical downward channel	200 × 200	10	air	glass	2500	0.12, 0.24, 0.48	spherical	1	8.5 × 10 ⁻⁵ , 6.1 × 10 ⁻⁴ , 4.1 × 10 ⁻⁴	0.177, 1.272, 0.855	PDA
Ljus 2002 [50]	horizontal pipe	104 × 10,000	12&19	air	polyacrylate, pulp	1000	0.1 - 0.8 & 3 with AR = 50	spherical & fiber			0.01 0.1	hot film
Lain <i>et al.</i> 2002 [51]	horizontal air channel	35 × 3,506,000	up to 30	air	glass	2500	0.06, 0.1, 0.195, 0.625, 1	spherical	4		2	PDA
Kiger Pan 2002 [52]	horizontal channel	40 × 360 × 4880	0.595	water	glass	2600	0.18 - 0.212	spherical			4 × 10 ⁻³	PIV

Tanaka and Eaton [18] introduced a new dimensionless particle momentum number derived from the particle-laden Navier-Stokes Equations. For non-spherical particles additional parameters are introduced to describe new features that come into play like particle shape, aspect ratio and mass distribution.

4. Stokes Number

The Stokes number $St = \tau_p / \tau_g$ denotes how well the particles are able to follow alterations in the magnitude and direction of the flow where τ_p is the time it takes for a particle to accelerate from rest to a velocity being 63% of the ambient flow velocity and τ_g is the carrier phase time scale. For St less than unity the particles just follow the streamlines while for St larger than one the particles detach from the flow. For particles of $St \approx 1$, St can be used to describe the alteration of the carrier phase turbulence. For small particles $dp \sim \eta$, observations yield an increases in the rate of TKE dissipation and a corresponding reduction of turbulence for $St = O(1) \sim O(10)$, hence the particles extract the turbulent energy from the flow and dissipate it. Elgobashi *et al.* [19] used a two-way coupling approach to study the TKE production and dissipation for a system with small spherical particle, $Re_p \leq 1$ and St based on the Kolmogorov time scale $\tau_\eta \approx O(10^{-2})$ to $O(10^1)$. The aim was to update previous results, especially regarding small particles, Zone A in Figure 1, and they found that TKE and its dissipation rate ε are function of St . Luo Fan *et al.* [20] studied a two phase solid-gas jet flow by developing a DNS technique with a two-way coupling method at moderate Re and $St = 0.01, 1$ and 50 . They found attenuation in TKE for the cases that were studied.

The particles will not be able to follow the motion of smaller eddies perfectly as their size increases and they will follow eddies of larger scale, more frequency [21]. Larger particles lead to increase in TKE, as detected by [22]. The reason to this may be vortex shedding behind the particle. For very high St or particles with diameter around the Taylor length scale, St cannot be used to describe the characteristics of the turbulent modification [23]-[25]. The particle relaxation time definition based on the analytical solution of Stokes equation for creeping flow (for particle falling from rest in stagnant fluid) can be safely applied to small particles of $dp \sim \eta$ following the Kolmogorov theorem, $Re_\eta \sim 1$. For larger particles inertia becomes important and the carrying phase has no obvious influence on the motion of the particles [26]. In this region, where inertia is significant, the assumptions, $Re_\eta \sim 1$, for which relaxation time scales have been derived is no longer valid. Mandø [17] investigated particles with $St = 10 - 1000$. For $10 < St < 60$, the turbulent intensity TI is attenuated or stay unchanged as shown in Figure 2. Increasing St over 60 may however result in as well amplification as attenuation of TI and notice that the attenuation can be substantial. Based on a review, Tanaka and Eaton [18] could not find any trend for turbulent modification that is independent on the fluid studied, as shown in Figure 3.

The discussion, so far, on St is based on the assumption of spherical particles. For non-spherical particles additional mechanism with coupled translational and rotational motion should be included. To exemplify, on top of

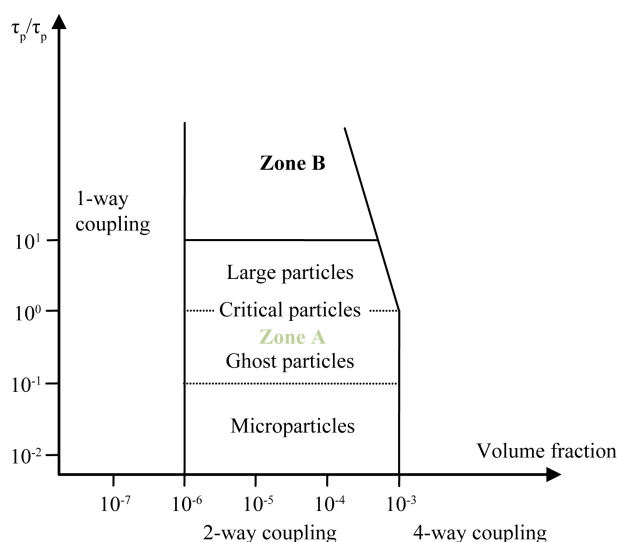


Figure 1. Classification map for St [19].

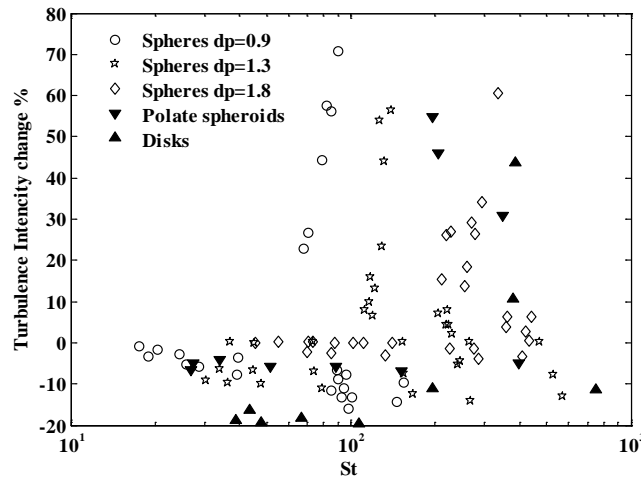


Figure 2. Relation between TI and St for different particles [17]; Note that particles size are in mm.

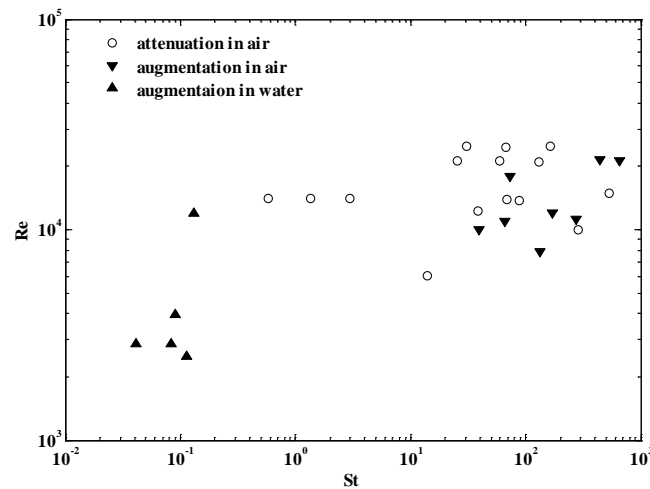


Figure 3. Turbulent modulation as function of St and Re for air and water [18].

the translational relaxation time scale there is a rotational relaxation time scale that is strongly depend on the rotation axis of the particle making it rather difficult to define a single relaxation time [27].

5. Particle Reynolds Number & Reynolds Number

Reynolds number $Re = u_f L / \nu$ is the ratio of fluid inertia fluid viscosity and Re_p can be identified as the ratio of inertia to viscosity in the fluid close to the surface of the particle. Re_p decides the nature of the flow around a particle, the type of boundary layer around the particle (laminar or turbulent) and the occurrence of vortex shedding. In general, studies yield turbulent attenuation for low Re_p and turbulent amplification for $Re_p \geq 400$ [28]. The latter may be explained with a transfer of some of the flow kinetic energy into turbulence through vortex shedding. Geiss [28] found significant turbulence production also for Re_p less than 400. Mandø [17] measured in most cases a decrease in TI when adding spherical particles of $Re_p < 200$ while for $Re_p > 400$, nearly all measurements on spherical particles gave an amplification in TI, see Figure 4 where the variation in TI is plotted as a function of Re_p for spherical and non-spherical particles. Mandø [17], and the reference therein, argued that wake instability occurs at $Re_p \approx 130$ and vortex shedding start at $Re_p \approx 270$, which give the indication that the increase in TI could not be solely because of vortex shedding, otherwise, the lower critical value of vortex shedding formation $Re_p \approx 270$ would have been the value which distinguishes between increasing and decreasing in

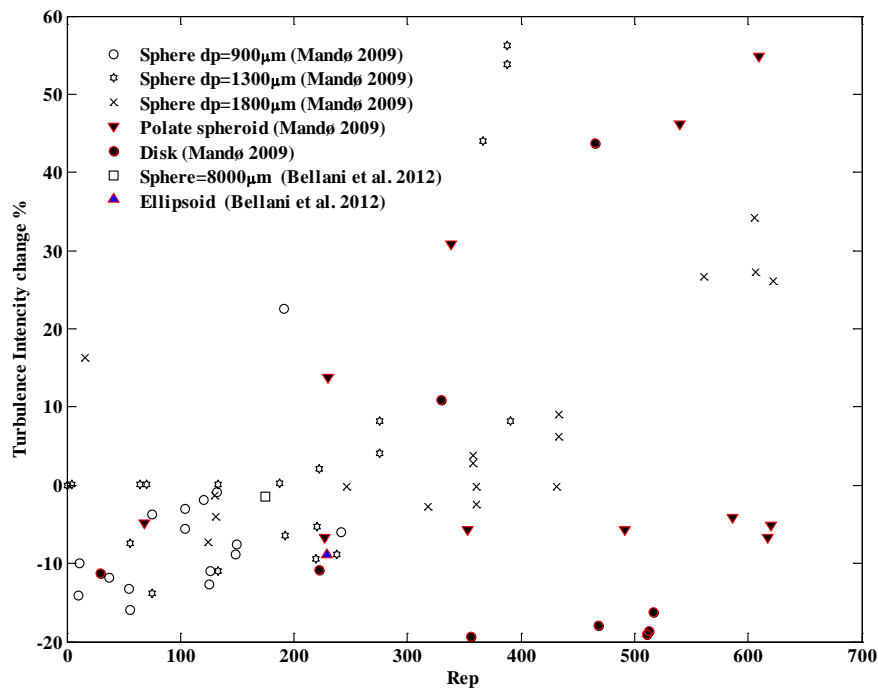


Figure 4. Alteration in TI as function of Re_p when adding spherical and non-spherical.

turbulence. Non-spherical Re_p is a function of the equivalent particle diameter and sphericity. The magnitude of vortex shedding now also becomes dependent on the rotation and orientation of the particle axis with respect to the mean flow direction.

In turbulent flow, length scales are affected by the turbulent Reynolds number Re_p . Tanaka, Eaton [18] found that Reynolds number based on the integral length scale Re_L^2 relates to the ratio of dp and η since Re_L sets η . Reynolds number and the shape of the particles have a major influence on the secondary motion related to non-spherical particle. The particles may move in different ways like slow motion in orbits, translating with maximum cross-section aligned normal to the flow and large periodic swings around the mean path or chaotic tumbling [11]. All these motions will affect the interaction between the two phases.

6. Length Scales

When particles with $dp \sim \eta$ are added to the flow experiments yield that TKE decreases considerably as compared to a case without particles. This implies that dp/η is an important non-dimensional variable. However, Eaton [29] argued that most experimental works leading to this conclusion have been conducted with velocities in the range of 10 - 50 m/s and with a large length scale in the order of 10 - 50 mm. With the resulting rather narrow Re range it is not clear if it is correct to scale dp with. On the other hand, Eaton concluded that for $dp \sim \eta$ turbulent eddies may be distorted by individual particles rather than be effected by a cloud of particles. The strong decrease in TKE is thus partly a reflection of local dissipation of turbulence around individual particles. Hwang and Eaton [30] examined isotropic turbulent with no mean flow in a tank with particles where $dp \sim \eta$ and found attenuation in TKE of as much as 35% - 40%. Mandø [31] and Gore and Crowe [32] reported that it is better to use the ratio of dp to the characteristic length of the most energetic eddy, Le , of the single phase to scale the turbulent modulation. Poelma *et al.* [33] argued that Le and η have a fixed ratio so these length scales will play the same role. This conclusion was based on experiments with spherical particle in solid-gas, solid-liquid and gas-liquid turbulent upward and downward jet and pipe flow. Gore [32] analyzed about 15 studies in order to categorize the modification of the TI at the central region of the flow with usage of the dp/Le ratio. A critical value of $dp/Le \approx 0.1$ was observed, as illustrated in Figure 5, and over this value the relative TI was considerably increased. Gore and Crowe [34] also summarized that with the range of parameters examined there was no large influence of adding particles on Le .

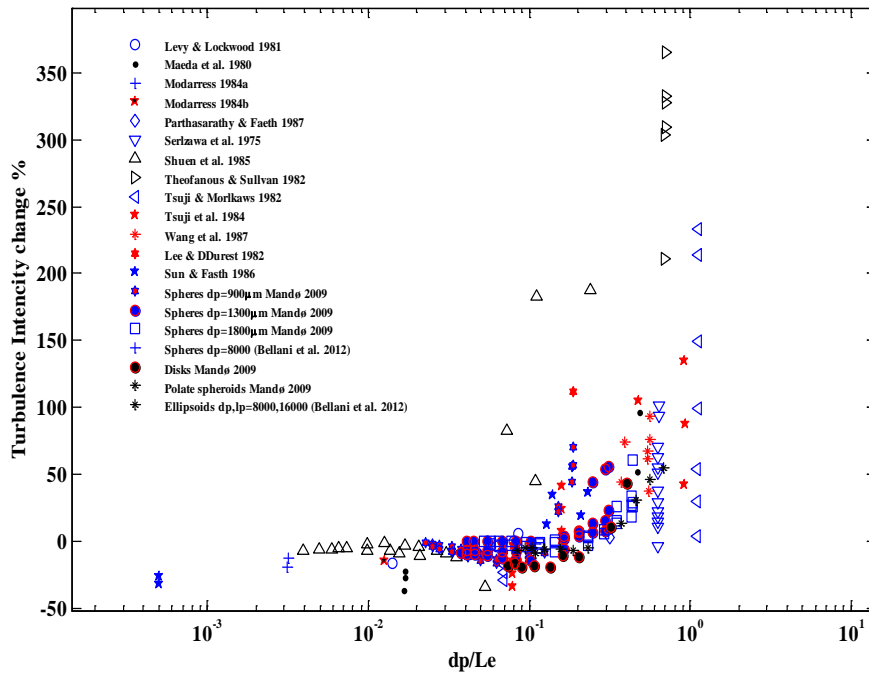


Figure 5. TI as function of dp/Le for spherical and non-spherical particles.

As shown in **Figure 5**, Mandø [17] found attenuation for $dp/Le < 0.1$ and only amplification for $dp/Le > 0.3$ for the range of parameters studied. Mandø [17] and references therein defined 200 μm as the critical diameter above which TI increases for a case with particles compared to one without. Small particles follow the dissipative scale eddies and there is momentum transfer from the carrier phase to the particles increasing energy dissipation and reducing the life time of the eddies. In agreement with the results in **Figure 4**, **Figure 5** results in [18] indicate that a variation in dp/Le has a large effect on the carrier-phase flow.

For non-spherical particles different definitions of the equivalent diameter have been presented and each of them will give different values so the application will decide which one is the most appropriate. To exemplify, [17] used the equivalent volume diameter while [35] used the diameter of the sphere that has the same average Stokesian response time as an ensemble of randomly oriented ellipsoids.

7. Particle Volume Fraction and Mass Loading

The volume fraction Φ_v may be defined as the volume occupied by the dispersed phase to the unit volume of the carrier phase in two phase flow, while, the mass loading Φ_m is defined as the ratio of dispersed to carrier phase mass flow rates. The intermediate volume loading fraction, which is defined by the lower and upper limits for two-way solid-gas interaction, is $10^{-6} < \Phi_v < 10^{-3}$. For cases with $\Phi_v > 10^{-3}$ the particle-particle interaction will be important and the situation is denoted four way-coupling. If $\Phi_v < 10^{-6}$ the particles are few and there is a large distance between the particles which is referred to a one way coupling case, as shown in **Figure 6**. Notice that these limits are restricted to spherical particles and that the limits for respectively coupling is typically lower for non-spherical particles.

Some researchers argued that even with a very low Φ_v (lower than 10^{-6}) there is change in turbulence of the carrier phase (two-way coupling) [36] [37]. Balachandar, Eaton [10], Hwang and Eaton [30] and Wu *et al.* [36] (2006) show that there is generally attenuation of turbulence when adding particles and for small particles $dp < \eta$, the attenuation increased with increased Φ_m . It was concluded that turbulence modulation was observed even for very small Φ_v and Φ_m . For very small particles with very small Φ_v , the turbulence is, however, generated almost as for single-phase flow.

Li [38] investigated a fully develop horizontal channel gas-solid flow with $dp = 60$ and $110 \mu\text{m}$ for small Φ_m . By a simultaneous two-phase PIV measurement technique they found a reduction in the relative mean velocity in the core region and increase of it in the near wall region when adding particles. It was also found an overall

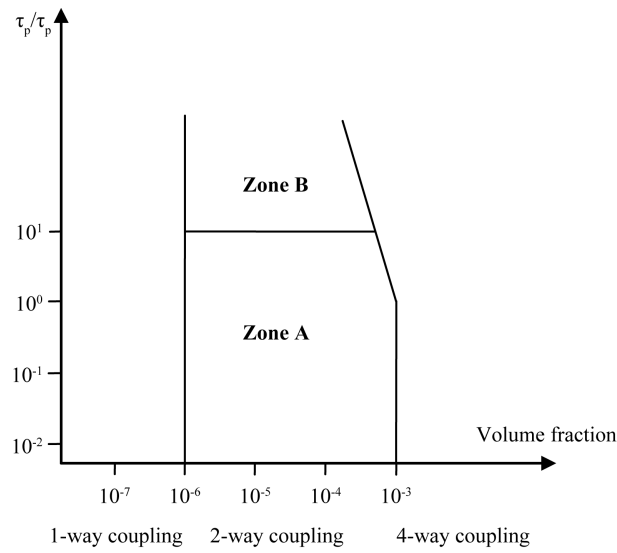


Figure 6. Elgobashi *et al.* [17] classification map.

attenuation of turbulence, in the boundary layer and in the core region. Hence although turbulence is attenuated there is an increase in transport of momentum from the core to the boundaries. Li [39] used the same experimental set-up with simultaneous two-phase PIV high spatial resolution and a small interrogation window to enhance the accuracy. One result was that particle inertia changes the viscous sub-layer of the carrier fluid turbulence another result was a modification in turbulence with a very small Φ_m .

Tanaka [22] studied the microscopic particle-fluid interaction around particles with a high resolution PIV system. In general, there was attenuation of turbulence for the parameters studied with a maximum reduction of 25%. By using the two-point correlation it was found that the dissipation rate was significantly less altered as compared to the TKE. This finding was explained with two mechanisms. First, as the large scale turbulence attenuate there is less energy to be transferred to the smaller scales and less dissipation can be predicted. On the other hand, the particles were heavy, relative to the gas and owing to this, the particles themselves will produce vortices and amplify the rate of dissipation. Measurements near the particles show that the TKE attenuated because of the large density ratio, $\approx 10^{-3}$, so the particles behave like localized dampers for the turbulence, with strong energy dissipation around them. Hence the particles contribute to transport of the momentum as previously discussed.

Other studies show small Φ_v has no influence on the carrier phase turbulence modulation, indicating that a one-way coupling approach is sufficient, [40]. Sad Chemloul [41] studied the effect of glass particles on water pipe flow with LDA and found a reduction in TI as a function of an increase in volume fraction particles. Mandø [17] investigated large particles in the form of spheres, disks, and prolate spheroids, in a vertical jet setup with a standard LDA system. Both attenuation and amplification was found for the St investigated. The author established a clear relation between turbulent modulation and Φ_v . Only amplification was observed for $\Phi_v > 2 \times 10^{-4}$ while only attenuation was observed for $\Phi_v < 2 \times 10^{-5}$. In agreement with [39] it was confirmed that $\Phi_v = 10^{-6}$ is a distinguishing limit between one-way and two-way coupling. Li [39] and Mandø [17] found more attenuation in turbulence when moving from spherical to non-spherical shaped particles (actually in conflict with [35], see Figure 7 showing the relation between TI and volume fraction Φ_v as derived from the literature with spherical and non-spherical particles. Goswami [42] investigated a two-dimensional fully developed vertical solid-gas turbulent flow (1 m developing section, and length to width ratio = 25). At low Φ_v they found no significant effect from the solid phase on the carrier phase.

It has been observed that the fractions Φ_m and/or Φ_v of non-spherical particles influence the flow. It has, for instance, been shown that the turbulence intensity increased in regions with increase in fiber volume concentration [16]. In the cases where qualitative effect was found, [31] for instance, it has been argued that this is a result of interactions with the length scale. This may be an evidence of that the mechanism of the carrier phase turbulent modulation takes place near the particle size scale or at least the important part of it.

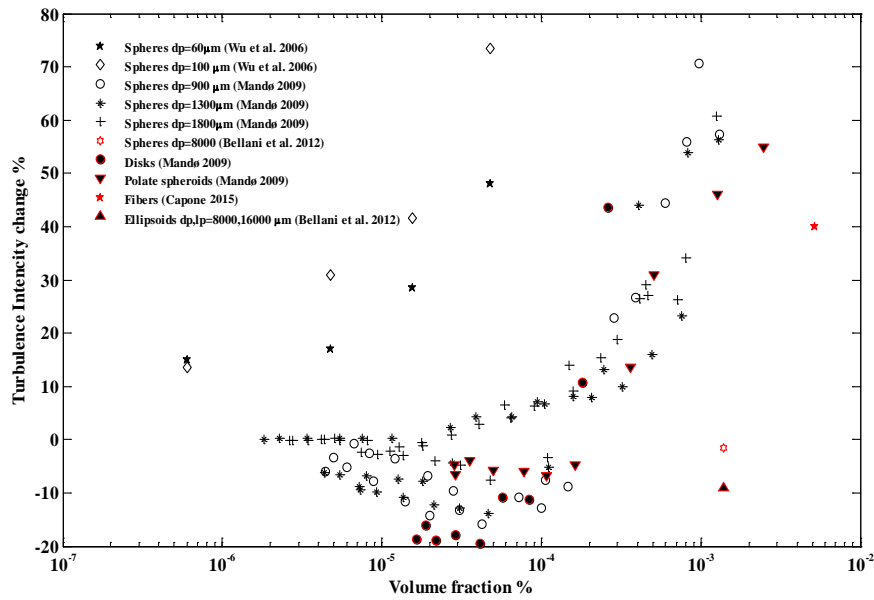


Figure 7. Relationship between TI and volume fraction Φ_v .

8. Particle Momentum Number

A relatively new dimensionless number, the Particle momentum number Pa , was proposed by [18] for the particle laden Navier-Stokes equation in order to classify results from the literatures into TKE amplification and attenuation respectively. The definition is $Pa = St Re^2 (\eta/Le)$ which is equal to $Pa \approx \frac{St}{(ReLe)^{1/4}}$ [43]. By plotting

Pa as function of $ReLe$ Tanaka and Eaton found that there was augmentation in TKE for $Pa < 10^3$ and attenuation for $10^3 < Pa < 10^5$. Another area of augmentation was found after $Pa = 10^5$, as shown in Figure 8. As usually when dealing with St , Tanaka and Eaton derived the particle response time with the assumption of creeping flow which is valid for $Re < 1$. Lohse [43] had two viewpoints related to the non-monotonic behavior of TKE with Pa and the relation of Pa with St and $Re^{1/4}_{Le}$. By usage of data from numerical simulations with two-way-coupled point-particles in Navier-Stokes turbulence and data for lower Re a systematic trend may be found. Also, data for particles lighter than the carrier phase could be a good extension. In general, more data is required before decisive conclusion can be made. At the moment, Pa may be rescaled with the aim to eliminate the effect of using different fluids by multiplying Pa with relevant properties of the fluid like relative density and relative viscosity or both. As shown in Figure 9 a monotonic behavior of TKE with Pa multiplied with fluid to water viscosity $Pa \mu_f/\mu_w$ is then obtained.

9. Conclusions

A critical review of the most important mechanisms and variables for the classification of turbulent modulation in the presence of spherical and non-spherical particles has been presented. At the moment there is no agreement in the scientific community on a single dimensionless number that can safely describe the influence of particles in turbulent flow. Hence, additional evaluations of turbulent modulation are required to estimate the interaction of several mechanisms at the level of single particles.

For non-spherical particles additional levels of freedom are introduced and the dependence on drag and lift from the orientation of the particles as and a function of Re adds to the complexity. Therefore, for non-spherical particles, the most convenient solution presently is to use length scales. Alternatively, Re and the response time describe phenomenon related to rotation, orientation and shape.

We showed that each of the important dimensionless numbers has their advantages and drawbacks and none of them covers all parameters relevant to turbulent modulation. The particle momentum number seems promising but need more analyzing and data especially for attenuation in water. Table 2 gives a summary for the

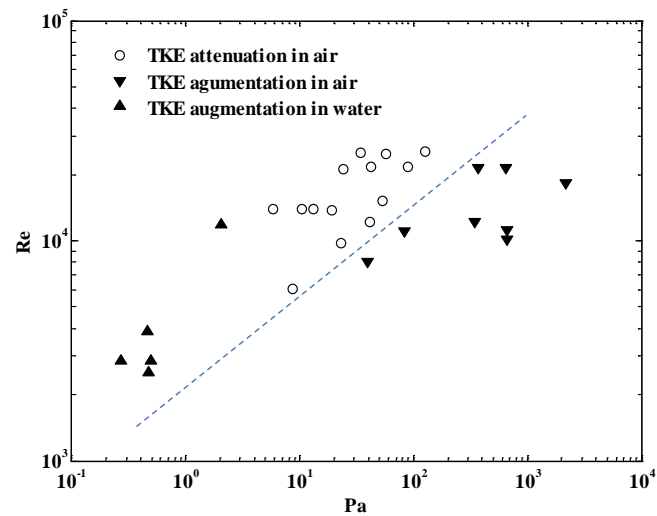


Figure 8. Particle momentum number Pa as function of Reynolds number $ReLe$.

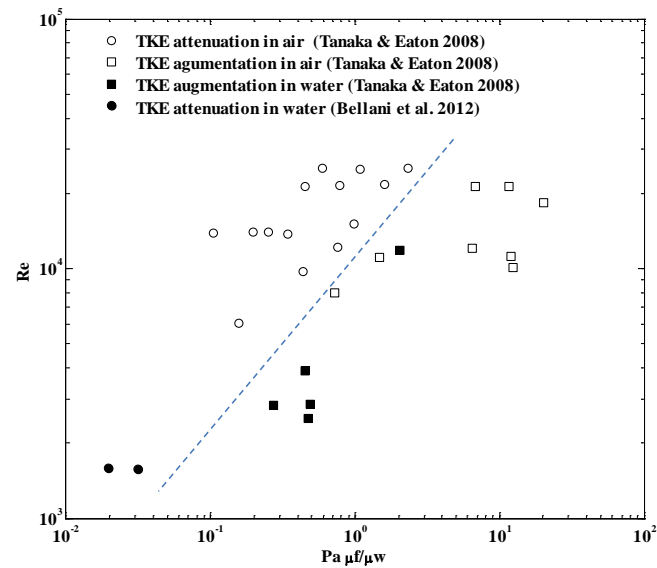


Figure 9. $Pa \mu_f / \mu_w$ as function of Reynolds number $ReLe$.

Table 2. Non-dimensional parameters range for turbulence modulation.

Factor	Dimensionless parameter	Symbol	Description
Response effects	Stokes No.	St	$St < 60$ turbulent attenuation, $60 < St$ both attenuation and augmentation
Inertial effects	Particle Reynolds No.	Re_p	$Re_p < 200$ only attenuation, $400 < Re_p$ only augmentation (spherical particles) $Re_p < 200$ only attenuation, $650 < Re_p$ augmentation (non-spherical particles)
Surface effect	length scale ration	dp/le	$dp/le < 0.1$ only attenuation, $0.25 < dp/le$ only augmentation
Loading effect	Mass loading, article volume fraction	Φ_m, Φ_v	$\Phi_v < 10^{-6}$ one way coupling $10^{-6} < \Phi_v < 10^{-3}$ two way coupling $10^{-3} < \Phi_v$ four way coupling

ranges of the parameters describe qualitatively the turbulent modulation.

Many studies were oriented toward introducing a particle source term based on the Euler/Lagrange approach that can account for the effect of spherical particles on the turbulence equations models regarding both augmentation and attenuation. No such source term has successfully been introduced for non-spherical particles.

The review demonstrates the need for more numerical and experimental work with higher accuracy than presented 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. It is very expensive to use the DNS method to resolve the flow of hundreds of particles and the use of LES with point force coupling is limited for small particles $d \leq \eta$.

An interesting observation overall is that the particles may absorb a lot of turbulent energy at the same time as they themselves transport momentum from areas of high flow rate to areas of low flow rate.

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