Particle-Turbulence Interaction in a Homogeneous, Isotropic Turbulent Suspension

A review is given of numerical, analytical, and experimental research regarding the two-way coupling effect between particles and fluid turbulence in a homogeneous, isotropic turbulent suspension. The emphasis of this review is on the effect of the suspended particles on the spectrum of the carrier fluid, in order to explain the physical mechanisms that are involved. An important result of numerical simulations and analytical models (neglecting the effect of gravity) is that, for a homogeneous and isotropic suspension with particles with a response time much larger than the Kolmogorov time scale, the main effect of the particles is suppression of the energy of eddies of all sizes. However, for a suspension with particles with a response time comparable to or smaller than the Kolmogorov time, the Kolmogorov length scale will decrease and the turbulence energy of (nearly) all eddy sizes increases. For a suspension with particles with a response time in between the two limiting cases mentioned above the energy of the larger eddies is suppressed, whereas the energy of the smaller ones is enhanced. Attention is paid to several physical mechanisms that were suggested in the literature to explain this influence of the particles on the turbulence. In some of the experimental studies, certain results from simulations and models have, indeed, been confirmed. However, in other experiments these results were not found. This is attributed to the role of gravity, which leads to turbulence production by the particles. Additional research effort is needed to fully understand the physical mechanisms causing the two-way coupling effect in a homogeneous, isotropic, and turbulently flowing suspension. This review contains 47 references. [DOI: 10.1115/1.2130361]

1 Introduction

The occurrence of dispersed two-phase flows in nature and industrial applications is abundant. Despite a significant research interest, there are still several open questions in this topic, limiting a good quantitative prediction of these flows. In this publication, a review is given of recent progress relating to one of the more fundamental problems: the so-called two-way coupling between the dispersed phase and turbulence. Two-way coupling refers to the effects of the fluid on the particles and vice versa. The review is limited to rigid particles in homogeneous and isotropic turbulence, in order to avoid further complications. For the same reason, no work on shear flows is incorporated. Even though inclusion of these publications would greatly increase the amount of available data, it would also significantly complicate the analysis, since, among other phenomena, shear-induced turbulence production and particle migration might obscure other effects.

Because of the growth of computer power, detailed direct numerical simulations (DNS) of the behavior of particles in the turbulent fluid velocity field and of the two-way coupling effect became possible. Also, theoretical models were developed that try to capture the main physical mechanisms occurring in turbulent suspensions. Moreover, because of the progress in experimental techniques, new and accurate measurement results became available.

We will give a review of publications about the two-way coupling effect in turbulent suspensions that appeared in the literature during the last decade. It is, of course, impossible to discuss all important publications. However, we hope that the review will give a clear picture of the progress in understanding of turbulent suspensions. Attention will be paid to numerical simulations, theoretical models, and experiments. Emphasis will be placed on the influence of the particles on the turbulent kinetic energy spectrum of the carrier fluid. We know that turbulence spectra are not sufficient to characterize turbulence completely. However, in the literature particular attention was given to the influence of particles on the turbulence spectrum in order to derive a physical understanding of the two-way coupling effect.

In the first part of this review we will integrate the knowledge from numerical simulations with respect to the dependence of the turbulence spectrum of the carrier fluid on the presence of the particles in the fluid. In the second part such an integration will be given with respect to theoretical explanations given in the literature on the two-way coupling effect, in general, and the dependence of the turbulence spectrum on the particles, in particular. The third part is devoted to a comparison between experimental data and results from numerical simulations and theoretical models.

Several good reviews about particle-laden turbulent flows were published during the past decade, see for instance Hetsonri [1], Elghobashi [2], Crowe et al. [3], and Mashayek and Pandya [4]. Our review is different, in our opinion, in the sense that we pay particular attention to the physical mechanisms that play an important role in the interaction between particles and fluid turbulence in a turbulently flowing suspension. In recent years some interesting publications have been written in which detailed information is given about these mechanisms.

2 Relevant Parameters

We define a number of parameters that are of importance for turbulently flowing suspensions and that will be used in this review. The volume fraction of the dispersed phase (the particles) is defined as...
The particle mass loading is given by

\[ \phi = \frac{\delta V_d}{\delta V} \]  

(1)

where \( \delta V_d \) is the volume of the dispersed phase in the volume \( \delta V \) of the suspension (assumed large enough to ensure averaging). The ratio of the average particle spacing (\( d_{\text{spacing}} \)) and the particle diameter (\( d_p \)) is related to the volume fraction by

\[ \frac{d_{\text{spacing}}}{d_p} = \left( \frac{\pi}{6\phi} \right)^{1/3} \]  

(2)

The particle mass loading is given by

\[ \phi = \frac{\rho_p}{\rho_f} \]  

(3)

in which \( \rho_p \) and \( \rho_f \) are the densities of the particles and the carrier fluid, respectively. The particle response time to changes in the surrounding fluid is expressed by the Stokes time

\[ \tau_p = \frac{2\rho_p d_p^2}{9\rho_f \nu} \]  

(4)

where \( \nu \) is fluid kinematic viscosity. For the fluid phase the Kolmogorov time is defined by

\[ \tau_k = \frac{\eta}{\nu} \]  

(5)

with \( \eta \) the Kolmogorov length scale. The integral time scale is given by

\[ \tau_i = A\nu' \]  

(6)

in which \( A \) is the integral length scale of turbulence and \( u' \) the root-mean-square value of the turbulent velocity fluctuations. The Stokes number is defined in this review as the ratio of the particle time scale and the Kolmogorov time scale

\[ St = \frac{\tau_p}{\tau_k} \]  

(7)

For \( St \to 0 \), the particle behaves as a fluid tracer. For \( St \to \infty \), the particle is unresponsive to the fluctuations of the flow. Obviously, the physically most interesting situation occurs when it approaches unity: particles follow the large scale fluid motions.

Finally, the flow regime around the particles can be characterized by means of a Reynolds number

\[ Re_p = \frac{u_{TV} d_p}{\nu} \]  

(8)

In this equation, \( u_{TV} \) represents the terminal velocity (the velocity a particle attains falling in a quiescent medium). Alternatively, it can be defined using, e.g., the root-mean-square value of the free-stream turbulence. In has been postulated by Hetnroni [1] that \( Re_p \) can be used to determine whether particles attenuate (\( Re_p < 100 \)) or enhance (\( Re_p > 400 \)) the fluid turbulence level.

3 Direct Numerical Simulations

3.1 Effect of Particles on Turbulence Spectrum. An early indication about the influence of the particles on the turbulence spectrum was given by Squires and Eaton [5,6]. They used direct numerical simulation to study statistically stationary, homogeneous, isotropic turbulence. They considered particle motion in the Stokes regime. Gravitational settling was neglected. Computations were performed using both 32^2 and 64^2 grid points. The particles were treated as point particles. To achieve the stationary flow, a steady nonuniform body force was added to the governing equations. Particle sample sizes up to 10^6 were used in the simulations. Mass loadings of 0.1, 0.5, and 1.0 were considered. They used the following values for the ratio of the particle response time (\( \tau_p \)) and the Kolmogorov time scale of turbulence (\( \tau_k \)): \( \tau_p/\tau_k = 0.75, 1.4, 1.5, 5.2, 7.5, \) and 15.0. Squires and Eaton calculated the effect of the mass loading on the spatial turbulent kinetic energy spectrum of the carrier fluid. The (dimensionless) spatial spectrum for \( \tau_p/\tau_k = 1.5 \) as a function of the (dimensionless) wave number for different mass loadings is shown in Fig. 1. \( E(k) \) is the turbulent energy spectrum as a function of wave number. As mentioned earlier \( \eta \) is the Kolmogorov length and \( \phi \) the mass loading. The spectra are normalized using \( q^* \), the total turbulent kinetic energy for each particular case. It can be seen that with increasing mass loading, the energy at large wave numbers increases relative to the energy at small wave numbers. As Squires and Eaton found that the total turbulent energy decreases with increasing mass loading, it can be concluded that at small wave numbers (where most of the energy is located) the energy decreases with increasing mass loading compared to the particle-free case. Whether the energy at large wave numbers decreases or increases with respect to the particle-free case cannot directly be concluded from the results of Squires and Eaton. For that it would be necessary to multiply the spectra of Fig. 1 with the total energy \( q^* \). The relative increase of the distribution of energy at large wave numbers with respect to the energy at small wave numbers was found for all particle response times used in the simulations.

More details about the influence of particles on the spatial turbulence spectrum of the fluid became available via the work of Elghobashi and Truesdell [7]. In contrast to Squires and Eaton, they examined turbulence modulation by particles in decaying isotropic turbulence. A point-particle approximation was again made. They used the particle equation of motion derived by Maxey and Riley [8]. Like Squires and Eaton they found that the coupling between the particles and fluid results in an increase in the turbulent energy at the large wave numbers relative to the energy at small wave numbers. Moreover, they concluded from their calculations that the large wave number energy for a flow with particles (with a sufficient small response time) is even larger than the large wave number energy for the particle-free case at the same time in the decay process.

Like Squires and Eaton, also Boivin et al. [9] made a detailed DNS study of the modulation of statistically stationary, homogeneous, and isotropic turbulence by particles. Gravitational settling was neglected and the particle motion was assumed to be governed by drag. The ratio of the particle response time to the Kolmogorov time scale had the following values: 1.26, 4.49, and 11.38, and the particle mass loading was equal to 0.2, 0.5, and
The velocity field was made statistically stationary by forcing the small wave numbers of the flow. Again the effect of particles on the turbulence was included by using a point-force approximation. Fluid turbulence spatial energy spectra, derived by Boivin et al. [9] for different mass loadings are shown in Fig. 2 for $\tau_p/\tau_k = 1.26$ and in Fig. 3 for $\tau_p/\tau_k = 11.38$. Note that the figures as they are represented here are replotted with double-logarithmic axes, to facilitate comparison to the other figures. In their simulations the dimensionless maximum value of $k$ is about equal to the number of grid points in each direction of their cubic simulation domain. So the region around $k=1$ represents the energy-containing eddies and we can say that the wave number along the horizontal axis is made dimensionless by means of the integral length scale. In general, there is a similar damping effect on the smaller wave numbers of the fluid turbulence by both particles with a large response time and particles with a small response time. At the larger wave numbers the turbulence kinetic energy is attenuated by particles with a large response time, but increased by particles with a small response time. It should be noted that in Figs. 1–3 the highest wave numbers appear to be contaminated with noise, since they show a distinct “plateau” (Fig. 1) or even increase (Figs. 2 and 3) at these wave numbers. Nevertheless, even if this part of the graph is ignored, the trends mentioned above remain.

A next step in achieving information about the dependence of the turbulence spectrum on the presence of particles in a turbulent suspension was provided by Sundaram and Collins [10]. Like Elghobashi and Truesdell they performed DNS simulations of particle-laden isotropic decaying turbulence. The particle response time was in the range $1.6<\tau_p/\tau_k<6.4$. The ratio of the particle density and fluid density was of the order $10^3$. The drag force on the particles was described by Stokes law, and the influence of the gravitational force was neglected. The DNS results showed again that the turbulent energy spectrum of the fluid is reduced at small wave numbers and increased at large wave numbers (compared to the particle-free case) by the two-way coupling effect. They also concluded that the location of the cross-over point (the wave number where the influence of the particles changes from a turbulence-damping effect to a turbulence-enhancing one) is shifted toward larger wave numbers for larger values of the particle response time $\tau_p$.

In their DNS calculations Ferrante and Elghobashi [11] fixed both the volume fraction ($\phi=10^{-3}$) and mass fraction ($\phi=1$) for four different types of particles, classified by their ratio of the particle response time and the Kolmogorov time scale of turbulence. The ratio $\tau_p/\tau_k$ had the values 0.1, 0.25, 1.0, and 5.0. The ratio of the particle density ($\rho_p$) and the fluid density ($\rho_f$) is $10^3$. In Fig. 4 the spatial turbulent energy spectrum $E(t, \kappa)$ for the carrier fluid in the suspension is given (for the case without gravity) at a certain moment during the decay process. $\kappa$ is the wave number made dimensionless by means of the the integral length scale $L$. In the figure the result indicated by case A is for the particle-free flow, the results indicated by cases B, C, D, and E are for the carrier fluid in the suspension with particles of increasing response time ($\tau_p/\tau_k=0.1, 0.25, 1.0$, and 5.0), respectively. Microparticles (case B) increase $E(t, \kappa)$ relative to the particle-free flow (case A) at wave numbers $\kappa>12$ and reduce $E(t, \kappa)$ relative to case A for $\kappa<12$, such that $E(t)=\int E(t, \kappa) d\kappa$ in case B is larger than in case A (the particle-free case). Also for the cases C, D, and E, the particles dampen the turbulence at small wave numbers compared to the particle-free flow and enhance the turbulence at
large wave numbers. However the cross-over wave number increases with increasing particle response time. As can be seen from Fig. 4 large particles (case E) contribute to a faster decay of the turbulent kinetic energy by reducing the energy content at almost all wave numbers, except for $\kappa > 87$, where a slight increase of $E_l(t, \kappa)$ occurs.

### 3.2 Physical Mechanisms

In the publication of Squires and Eaton [6], a first proposal is made to explain the physical mechanism responsible for the nonuniform distortion of the turbulence energy spectrum by particles. In their opinion this nonuniform distortion is due to the preferential concentration of particles in the turbulent flow field. They showed that particles with a small response time ($\tau_p/\tau_H < 1$) exhibit significant effects of preferential concentration in regions of low vorticity and high strain rate. The effect of high concentrations of particles in these regions leads to an increase in small-scale turbulent velocity fluctuations. This production of small-scale fluctuations subsequently causes the viscous dissipation rate in the carrier fluid to be increased (for particles with a small response time). Squires and Eaton also showed that preferential concentration causes a significant disruption of the balance between production and destruction of dissipation, again leading to a selective modification of the turbulence spectrum. More research is, in our opinion, needed to fully understand the contribution of preferential concentration to the two-way coupling effect.

Boivin et al. [9] found that in a turbulent flow suspension the cascade process (energy transport from the large to the small eddies) is influenced by the particles. They calculated the spectrum of the fluid-particle energy exchange rate. In the small wave number part of this spectrum the turbulent fluid motion transfers energy to the particles, i.e., the particles act as a sink of kinetic energy. At larger wave numbers of the spectrum the energy exchange rate is positive, indicating that particles are capable of adding kinetic energy to the turbulence. This energy, "released" by the particles, is not immediately dissipated by viscous effects but is, in fact, responsible for the relative increase of small-scale energy compared to the particle-free case observed in the energy spectra for particles with a small response time.

A different type of physical mechanism for the two-way coupling effect was proposed in the publication by Ferrante and Elghobashi [11]. They provided explanations for the behavior of microparticles and large particles. Because of their fast response to the turbulent velocity fluctuations of the carrier fluid, the microparticles are not ejected from the vortical structures of their initial surrounding fluid. The inertia of the microparticles causes their velocity autocorrelation to be larger than that of the surrounding fluid. Since the microparticles’ trajectories are almost aligned with fluid points’ trajectories, and their kinetic energy is larger than that of the surrounding fluid, the particles will transfer part of their own energy to the fluid. The idea is that the microparticles accelerate quickly in an eddy to the velocity of the surrounding fluid. After that acceleration period the small but finite inertia of the particles causes, on average, a larger kinetic energy for the particles than the surrounding fluid, as the particles tend to retain their velocity for a longer time. Much more quantitative details, based on their DNS calculations, are given in the publication by Ferrante and Elghobashi.) On the other hand the microparticles increase the viscous dissipation rate relative to that of the particle-free flow. The reason is that the microparticles remain in their initially surrounding vortices, causing these vortical structures to retain their initial vorticity and strain rates longer than for the particle-free flow. (Again, it is the small but finite inertia of the particles that causes this effect.) The net effect is positive for the turbulent kinetic energy of the carrier fluid, as the gain in energy due to the transfer of energy from the particles is larger than the increase in viscous dissipation. The DNS calculations also show that the microparticles directly interact with the small scales of motion, augmenting their energy content. The triadic interaction of wave numbers then alters the energy content of the other scales of motion, such that after few integral time scales the energy spectrum is modified at all the wave numbers as compared to the particle-free case.

For large particles the explanation is different: because of their significant response time, large particles do not respond to the velocity fluctuations of the surrounding fluid as quickly as microparticles do, but rather escape from their initial surrounding fluid (crossing the trajectories of fluid points). Large particles retain their kinetic energy longer than the surrounding fluid. However, because of the “crossing trajectories” effect, the fluid velocity autocorrelation is larger than the correlation between the particle velocity and the fluid velocity, causing a transfer of energy from the fluid to the particles. On the other hand, large particles reduce the viscous dissipation rate (which is smaller than for the particle-free flow). (It is shown that large particles interacting with a clockwise vortex create a counter-clockwise torque on the fluid, which, in turn, reduces the vorticity.) The net result of the two opposing effects is a reduction of turbulent kinetic energy for a suspension with large particles at nearly all wave numbers relative to the kinetic energy for the particle-free turbulent flow. Again for more quantitative details the publication of Ferrante and Elghobashi should be consulted. We think that their analysis is a very interesting and important step in the direction of a physical understanding of the two-way coupling effect.

### 3.3 Effect of Finite Particle Size

Numerical work in which the particles are fully resolved is slowly becoming available in the literature. An example of this type is the work by ten Cate [12,13], who carried out numerical simulations of a (homogeneous and isotropic) turbulent suspension taking into account the finite size of the particles (by satisfying the no-slip boundary condition at the particle-fluid interface). Nevertheless, the short-range interactions between the particles had to be added explicitly, since they could not be resolved on the grid. For the generation of sustained turbulent conditions a spectral forcing scheme was implemented using the lattice-Boltzmann technique. In these simulations the particle volume concentration is varied between 2% and 10% (which is probably no longer in the two-way coupling regime) and the particle to fluid density ratio was between 1.15 and 1.73. The Taylor-scale Reynolds number was 61. Results were presented concerning the influence of the particle phase on the turbulent energy spectrum. Fluid motion was generated at length scales in the range of the particle size, which resulted in a strong increase in the rate of energy dissipation at the small length scales. With respect to the turbulent energy spectrum, little difference was found between the spectra with and without particles at the lowest wave numbers. At the intermediate wave numbers the particles reduced the fluid kinetic energy (see Fig. 5). At the larger wave numbers the spectra crossed at a clear cross-over or pivot point, and the particles increased the kinetic energy with respect to the particle-free case.

In contrast to suspensions studies, an alternative is the very fundamental approach of studying a single particle. Examples of this type of work, in which a fully resolved particle in a turbulent flow is studied, can be found in, e.g., publications by Mittal [14] and Bagchi and Balachandar [15]. In the former work, the production of turbulence due to vortex shedding is studied. It is found that this can contribute to turbulence production when $Re_p > 300$, yet only when the free-stream turbulence level is sufficiently low. In the work by Bagchi and Balachandar, various forces (inertial, viscous, history) are studied, in detail, in homogeneous and stratifying flow. This type of work may also clarify to what level the point-source approximation, that is used in most numerical and theoretical work, is valid.

### 3.4 Discussion of DNS Results

Some general conclusions can be drawn from the literature on numerical simulations of turbulently flowing suspensions. In the numerical simulations, the
4 Theoretical Models

4.1 Introduction. The starting point for analytical models described in the literature is often the Navier-Stokes (NS) equation for the velocity of the carrier fluid \( u(t, r) \) with external forces

\[
\rho_f \left[ \frac{\partial}{\partial t} + (u \cdot \nabla) u \right] + \nabla p = f_p + f
\]

\( f(t, r) \) is the pressure and \( \rho_f \) is the fluid density. The random vector field \( f(t, r) \) represents the stirring force responsible for the maintenance of the turbulent flow. The equation includes also the effect of the turbulence generation by the particle wakes and by the vortices shed by the particles was not taken into account. It would also have been difficult to include this effect of turbulence generation, as the particles in these publications were treated as point-particles (apart from the work by ten Cate). This is a significant simplification, and the results should thus be interpreted with care. From the simulations it can be concluded that for a suspension with particles with a response time much larger than the Kolmogorov time scale, the main effect of the particles is suppression of the energy of eddies of all sizes (at the same energy input into the suspension as for the particle-free case). So for such a suspension the total turbulent energy of the carrier fluid will be smaller than the total turbulent energy of the fluid for the particle-free case (at the same energy input). However, for a suspension with particles with a response time comparable to or smaller than the Kolmogorov time, the Kolmogorov length scale will decrease and the turbulence energy of (nearly) all sizes increases. In that case the total turbulent energy of the carrier fluid can be larger than the total turbulent energy of the fluid for the particle-free case. For a suspension with particles with a response time in between the two limiting cases mentioned above, the energy of the larger eddies is suppressed, whereas the energy of the smaller ones is enhanced. Several physical mechanisms have been proposed to explain these effects. It is not possible, at the moment, to decide which mechanism is the most important one, or whether they all contribute to explain the influence of particles on the turbulence of the carrier fluid in a suspension. More research is needed on this subject. It is also desirable to extend the DNS work with finite-size particles to investigate, in detail, the important influence of turbulence generation by particle wakes and vortices.

4.2 Physical Mechanisms.

4.2.1 Two-Fluid Models. The treatment mentioned above of the particle phase as a continuum, i.e., the assumption of two interpenetrating fluids, is the basis for the so-called two-fluid models. Many publications have been written about the two-way coupling effect using a version of the two-fluid model, and good reviews about this type of research are available (see, for instance, [4]). As mentioned before, we will concentrate on publications in which special attention is given to the influence of the particles on the turbulence in a homogeneous, isotropic suspension and in which an attempt is made to understand the underlying physical mechanism.

The equations given above were used by Baw and Peskin [17] to derive a set of “energy-balance” equations for the following functions:

- \( E_p(k) \)—energy spectrum of the fluid turbulence (\( E(k) \) in the nomenclature used in other publications)
- \( E_{fp}(k) \)—energy spectrum of the fluid turbulence along a particle trajectory
- \( E_{pp}(k) \)—fluid-particle covariance spectrum
- \( E_{fp}(k) \)—particle energy spectrum

In the balance equations, the following energy transfer functions occur:

- \( T_{fp}(k) \)—energy transfer in fluid turbulence
- \( T_{pp}(k) \)—transfer of fluid-particle correlated motion by the fluid turbulence along the particle path
- \( T_{fp}(k) \)—transfer of fluid-particle correlated motion by the particles
- \( \Pi_{pf}(k) \)—fluid-particle energy exchange rate.

Baw and Peskin made a set of simplifying assumptions in order to be able to analyze the balance equations. First, they assumed that the particles do not respond to the fluid velocity fluctuations due to their (very large) inertia. Therefore

\[
E_{fp}(k) = E_{fp}(k)
\]

Here \( v(t, r) \) is the velocity field of the particles, considered as a continuous medium with density \( m_f / \rho_f = \rho_f \phi \), where \( m_f \) is the mass of a particle, \( f^3 \) suspension volume per particle, and \( \phi \) the mass loading parameter

\[
\phi = m_f / \rho_f f^3
\]

The validity to represent \( f_p(t, r) \) in the form of Eqs. (10) and (11) is based on the assumption of space homogeneity of the particle distribution. If the particles are not homogeneously distributed, one can add additional equations, e.g., the number density. It is assumed that the particles are small enough for the Stokes drag law to be valid. For the simple case of monosize particles moving under the influence of the Stokes drag, the equation of motion for the particles (considered as a continuous phase) has the following form (see, for instance, [16])

\[
\frac{m_p}{f^3} \left[ \frac{\partial}{\partial t} + (v \cdot \nabla) \right] v = -f_p
\]
This assumption is, of course, not realistic for particles satisfying the Stokes’ approximation. Their next assumption
\[ \Pi_{s,f} = \frac{d(E_f(k) - E_{ff,k}(k))}{\tau_p} \]  
may be understood as a statement that the fluid-particle exchange rate is statistically the same for all scales characterized by a
\( k \)-independent frequency \( \gamma_f = \phi / \tau_p \). This is reasonable for particles with very large inertia, but then Stokes law is not valid. For
particles satisfying Stokes law, assumption Eq. (15) has to be replaced with a more realistic, \( k \)-dependent frequency \( \gamma_p(k) \).

A serious difficulty in the derivation of the energy-balance equations is how to find a closure expression for third-order velocity correlation functions, responsible for the various energy transfer functions. Baw and Peskin assumed that
\[ T_{ff,f}(k) \]  
can be expressed similarly as in the case of a pure (single phase) flow
\[ T_{ff,f}(k) = \frac{d}{dk} \left( \epsilon_f^{1/3} k^{5/3} E_f(k) \right) \]  
where \( \epsilon_f \) is the viscous dissipation in the pure fluid (without particles) and \( \alpha \) is the so-called Kolmogorov constant. This assumption is questionable. According to the spirit of the Richardson-Kolmogorov cascade picture of turbulence, one may express inertial range objects, like \( T_{ff,f}(k) \) in terms of again inertial range quantities, like \( k, E_f(k) \), and \( \epsilon(k) \) (the energy flux in \( k \) space). In a single-phase flow, indeed \( \epsilon(k) = \epsilon_f \). However, this is not the case for a turbulent suspension due to the fluid-particle energy exchange, given by Eq. (15). With this simplified model, Baw and Peskin predicted the following influences on the energy spectrum of the fluid turbulence due to the particles:

- a decrease of the energy in the energy-containing range of the spectrum
- an increase in the inertial range of the spectrum
- a decrease in the viscous dissipation range.

Boivin et al. [9] used the same model as Baw and Peskin [17]. They also applied assumptions similar to Eqs. (15) and (16). Fortunately, they took into account the response of the particles to the turbulent velocity fluctuations by relaxing assumptions of Eqs. (13) and (14) and also accounted for the very important physical effect of the energy dissipation due to the drag around the particles. For that reason they approximated \( T_{ff,f}(k) \) and \( T_{ff,p}(k) \) as follows:
\[ T_{ff,f}(k) = \frac{d}{dk} \left( \epsilon_f^{1/3} k^{5/3} E_f(k) \right) \]
\[ T_{ff,p}(k) = \frac{d}{dk} \left( \epsilon_p^{1/3} k^{5/3} E_p(k) \right) \]  
Note that this closure has the same weakness as Eq. (16), involving the dissipation range value \( \epsilon_f \). With the above-described changes with respect to the model as developed by Baw and Peskin, Boivin et al. found an increase in the viscous dissipation range of the fluid turbulence spectrum for small values of the particle response time \( \tau_p \).

4.2.2 Single-Fluid Models. Some analytical models were developed, in which the turbulent suspension was treated as a single fluid with effective (frequency- and wave-number-dependent) physical properties. Felderhof and Ooms [18] (see also the follow-up publications Ooms and Jansen [19] and Ooms et al. [20]) developed an analytical model for the dynamics of a suspension of solid spherical particles in an incompressible fluid based on the linearized version of the Navier-Stokes equation. In particular, the effect of the particles-fluid interaction on the effective transport coefficients and on the turbulent energy spectrum of the suspension was studied. Also the hydrodynamic interaction between the particles and the influence of the finite size of the particles were incorporated. However, it is needless to say that the nonlinearity of the Navier-Stokes equation is of crucial importance in the problem of turbulence. The authors were well aware of this problem, but (as mentioned) wanted to study, in particular, the influences of the particle-particle hydrodynamic interaction and of the finite particle size at a relatively high particle volume concentration. In order to improve the turbulence modeling, they included in one of their publications a wave-number-dependent turbulence viscosity. However, as the turbulence cascade process was not properly accounted for, they never found an increase of the turbulent kinetic energy at large wave numbers for particles with a small response time (as found by numerical simulations and some experiments). The importance of this work lies in the description of the particle-particle hydrodynamic interaction at high particle volume fractions and of the finite particle size.

L’vov et al. [21] develop a one-fluid theoretical model for a stochastically stationary, homogeneous, isotropic turbulently flowing suspension. It is based on a modified Navier-Stokes equation with a wave-number-dependent effective density of suspension and an additional damping term representing the fluid-particle friction (described by Stokes’ law). It can be considered as an improvement of the work of Felderhof and Ooms because in their model, L’vov et al. incorporated a description of the cascade process of turbulence. Ooms and Poelma [22] extended the theoretical model in such a way that it can be applied to a decaying, homogeneous, and isotropic turbulent suspension and can be compared to the DNS data of Ferrante and Elghobashi [11]. They calculated, for instance, the energy spectra \( E(k) \) for the carrier fluid in the suspension for the five cases (A, B, C, D, and E) discussed by Ferrante and Elghobashi and compared the predictions with their DNS results. Here only the results are shown for the particle-free flow (case A), the microparticles (case B), and the large particles (case E). The results for the other particles (cases C and D) are in between those for cases B and E. For a certain moment in the decay process, the results are shown in Fig. 6.

There is a difference between model predictions (Fig. 6) and the DNS results (Fig. 4) at small values of \( \kappa \) (\( \kappa = 1 \)). This is due to a difference in the boundary condition at the small wave-number end between the two methods. It is clear from Fig. 6 that the particles dampen the turbulence for small values of \( \kappa \) (large eddies) and enhance the turbulence for large values of \( \kappa \) (small
eddy eddies). However, there is a difference. The microparticles (case B) enhance the turbulence over a much larger range of $\kappa$ values than the large particles (case E). For microparticles the enhancement is so strong that the total energy over all eddies is larger than for the particle-free flow. That is not the case for the large particles. The cross-over wave number (the wave number where the influence of the particles changes from a turbulence-damping effect to a turbulence-enhancing one) increases with increasing particle response time. This result is the same as found in the DNS calculations.

The following physical mechanism is proposed by L'vov et al. [21] to explain the obtained results. According to them an important effect of the particles is, that they increase the effective density of the suspension. As the dynamic viscosity is not much influenced at low values of the particle volume fraction, the kinematic viscosity of the suspension will decrease compared to the kinematic viscosity for the particle-free case. This will decrease the Kolmogorov length scale and hence elongate the inertial subrange of the energy spectrum. There is a second effect that is, in particular, important in the inertial subrange. There are two competing effects in that subrange: an energy suppression due to the fluid-particle friction and an enhancement due to the acceleration of eddies due to the two-way coupling effect on the decay rate of isotropic turbulence laden with solid spherical microparticles whose response time is much smaller than the Kolmogorov time scale. An increasing particle response time will decrease and the turbulence energy of (nearly) all sizes increases. In that case the total turbulent energy can be larger than the turbulent energy for the particle-free case. For a suspension with particles with a response time much larger than the Kolmogorov time scale, the main effect of the particles is suppression of the energy of eddies of all sizes (at the same energy input into the suspension as for the particle-free case). Thus for such a suspension, the total turbulent energy will be smaller than the total turbulent energy for the particle-free case (at the same energy input). However, for a suspension with particles with a response time comparable to or smaller than the Kolmogorov time, the Kolmogorov length scale will decrease and the turbulence energy of (nearly) all sizes increases. In that case the total turbulent energy can be larger than the turbulent energy for the particle-free case. For a suspension with particles with a response time in between the two limiting cases mentioned above, the energy of the larger eddies is suppressed, whereas the energy of the smaller ones is enhanced. An interesting point is that it seems possible to give different physical explanations for the influence of the particles on a (decaying) homogeneous, isotropic turbulent suspension. One explanation (given by Ferrante and Elghobashi) is based on a microscopic picture about the interaction between individual particles and their local fluid flow environment. The other one (given by [21]) uses a macroscopic picture with eddy-size-dependent suspension properties. Such a physical explanation, not only in words but also mathematically (for details, see the relevant publications).

It is important to point out that only in a few analytical models the turbulence generation due to the particle wakes or vortices shed by the particles is taken into account. In this respect it is interesting to mention briefly the work of Parthasarathy and Faeth [28]. It will also be discussed in the section on experimental work. They investigated theoretically and experimentally the continuous phase properties for the case of nearly monodisperse glass particles falling in a stagnant water bath. This yielded a stationary, homogeneous flow in which all turbulence properties were due to the large eddies of all sizes. The other one (given by [21]) uses a macroscopic picture with eddy-size-dependent suspension properties, such as effective density. Both pictures give a satisfactory explanation, not only in words but also mathematically (for details, see the relevant publications).

4.3 Discussion of Results From Theoretical Models. As a general conclusion from the theoretical work, it can be stated that the more recent analytical models for a homogeneous, isotropic, turbulent suspension predict the same effect of the particles on the turbulent energy spectrum of the carrier fluid as the effect predicted by direct numerical simulations. For a suspension with particles with a response time much larger than the Kolmogorov time scale, the main effect of the particles is suppression of the energy of eddies of all sizes (at the same energy input into the suspension as for the particle-free case). Thus for such a suspension, the total turbulent energy will be smaller than the total turbulent energy for the particle-free case (at the same energy input). However, for a suspension with particles with a response time comparable to or smaller than the Kolmogorov time, the Kolmogorov length scale will decrease and the turbulence energy of (nearly) all sizes increases. In that case the total turbulent energy can be larger than the turbulent energy for the particle-free case. For a suspension with particles with a response time in between the two limiting cases mentioned above, the energy of the larger eddies is suppressed, whereas the energy of the smaller ones is enhanced. An interesting point is that it seems possible to give different physical explanations for the influence of the particles on a (decaying) homogeneous, isotropic turbulent suspension. One explanation is based on a microscopic picture about the interaction between individual particles and their local fluid flow environment. The other one (given by [21]) uses a macroscopic picture with eddy-size-dependent suspension properties, such as effective density. Both pictures give a satisfactory explanation, not only in words but also mathematically (for details, see the relevant publications).

As a final remark we stress the point that more attention may also be given to the theoretical (and numerical) investigation of the influence of preferential concentration (clustering) of particles in the turbulent flow field on the two-way coupling effect. During the last ten years several publications concerning theoretical and numerical studies of particles clustering in a turbulent flow field have appeared in the literature. Some of them are summarized below. We first emphasize, however, that in these publications the effect of turbulence on particle clustering is studied. The influence of this clustering on the turbulence of the fluid velocity field (the two-way coupling effect that is the subject of this review) is not considered. Elperin et al. [29] proposed a theory in which particle clusters are caused by the combined influence of particle inertia (leading to a compressibility of the particle velocity field) and a finite velocity correlation time of the fluid flow field. Particles inside turbulent eddies are carried to the boundary regions between them by inertial forces. This clustering mechanism acts on all scales of turbulence and increases toward small scales. The turbulent diffusion of particles decreases toward smaller scales. Therefore, the clustering instability dominates at the Kolmogorov
An exponential growth of the number of particles in the clusters is inhibited by collisions between the particles. The end result can be a strong clustering whereby a finite fraction of particles is accumulated in the clusters, or a weak clustering when a finite fraction of collisions occurs in the clusters. A crucial parameter for clustering is the particle radius, which has to be larger than a certain critical value. Also Balkovsky et al. [30] considered clustering of inertial particles suspended in a turbulent flow and developed a statistical theory of this phenomenon based on a Lagrangian description of turbulence. The initial growth of concentration fluctuations from a uniform state is studied, as is its saturation due to finite-size effects, imposed either by the Brownian motion or by a finite distance between the particles. The statistics of these fluctuations is independent of the details of the velocity statistics, which allows the authors to predict that the particles cluster at the Kolmogorov scale of turbulence. Also the probability distribution of the concentration fluctuations is calculated. They discuss the possible role of the particle clustering in the physics of atmospheric aerosols, in particular, cloud formation.

5 Experimental Work

5.1 Introduction. In this section, an overview is given of the experimental studies of dispersed turbulent flows found in the literature. Experimental work on the interaction of particles and turbulence in homogeneous, isotropic flows is mostly done in grid-generated turbulence. This is the closest approximation to true homogeneous, isotropic turbulence, while still being experimentally feasible. Most experiments use a static grid through which a fluid moves with a constant mean velocity. Alternatively, an oscillating grid in a enclosed tank can be used [31–33]. The advantage of these is that the turbulence level that can be attained is relatively high. Additionally, the flow does not have a mean flow component. This can be beneficial if Lagrangian measurements are required, such as tracking particles over a longer time to study, e.g., dispersion properties. The biggest drawback of these experiments is the fact that there often is a strong gradient in the flow component. This can be beneficial if Lagrangian description of turbulence is considered to be homogeneous in the context of particle-laden flows. Therefore, these results seem in contradiction to the outcome of the numerical work, which predicts changes in the one-dimensional spectrum at this Stokes number and mass loading.

5.2 Grid-Generated Turbulence. The main concept of grid-generated turbulence is simple: a fluid passes a grid with a certain solidity. Strong gradients in the axial direction are generated (i.e., “jets” emerging from the openings in the grid), which break up to form nearly homogeneous turbulence. The macroscopic length scale of the turbulence is determined by the mesh spacing \( M \). This length scale, as any other length scale of the flow, grows proportional to the square root of the downstream position: \( L \propto x^{1/2} \). Usually, it is found that at a downstream distance of 20 mesh spacings the flow is reasonably isotropic (<10% difference between axial and transversal components). Because of the mixing behavior of a turbulent flow, no influence of the separate mesh bars can be observed from this distance on; the flow is homogeneous in the plane perpendicular to the mean flow direction. Typically, the turbulence level, defined as the ratio of the root-mean-square of the fluid fluctuations \( \langle u' \rangle \) to the mean flow velocity \( U \), is of the order of a few percent. It is mainly determined by the mean fluid velocity and the solidity of the grid. The turbulence obviously decays, therefore, strictly speaking, the flow is not homogeneous in the axial direction. With respect to a typical particle time scale (e.g., the Stokes time), however, this decay is slow. Therefore, the flow can be considered to be homogeneous in the context of particle-turbulence interaction. The decay of the turbulent kinetic energy is usually assumed to decay proportional to the inverse of the distance \( U^2 \propto x^{-1} \). The conventional way of representing the results is therefore by plotting the reciprocal value of the turbulent kinetic energy versus the distance to the grid. For an extensive treatment of grid-generated flow, one is referred to the classic experiments by, e.g., Comte-Bellot and Corrsin [35] or Batchelor [36].

5.3 Overview of Experiments. The first thing that becomes clear when reviewing the available literature is the fact that each of the experiments has a relatively narrow scope. Even though most papers claim to study the two-way interactions between the phases, in general, the authors are often limited to the study of only one or two related phenomena. Two-phase flows are notoriously difficult to study experimentally [37], so each of the experiments has to be more or less tailored to study a certain aspect of the interaction. A broad classification of the experiments can be made:

- changes in carrier-phase properties
- particle-induced turbulence
- clustering, preferential concentrations
- particle-phase properties

The focus of the numerical and theoretical sections was mainly on the first class: the influence of particles on the carrier-phase spectrum. Only a few experiments have reported this because of the difficulties in obtaining good measurements in such flows. Additionally, the decay of the total turbulent kinetic energy (i.e., the integral of the spectrum) is discussed. A full discussion of all related phenomena is clearly unfeasible. For example, the work on the effective settling velocity of particles in a turbulent flow is an important parameter in many engineering models and the topic of numerous publications. The settling velocity of a particle is a direct result of particle-fluid interaction. But since settling obviously indicates a strong contribution from gravitational forces, it is therefore inherently anisotropic. Since most theories and numerical works exclude gravity, this topic is not considered here.

5.4 Influence of the Particles on the Carrier Phase Spectrum. Only three experiments have reported measurements of the influence of particles on the carrier phase turbulence in homogeneous isotropic turbulence: Schreck and Kleis [38], Husainov et al. [39] and Geiss et al. [40]. The first one used solid particles in water, yielding a density ratio of the order of unity. The latter two used solid particles in a vertical wind tunnel (density ratio of order \( 10^3 \)). Work in progress on the topic has recently been reported by Nishino et al. [41] and Poelma et al. [42], which will hopefully contribute to the data available in the near future. Where needed, their preliminary results are discussed. Schreck and Kleis [38] used two types of particles: glass (relative density 2.5) and neutrally buoyant plastic particles. Decaying grid turbulence offers the chance to study the dynamics of turbulent suspensions. In Fig. 7, the (reciprocal value of the) turbulent kinetic energy is plotted for the single-phase and particle-laden case. These data were obtained using laser Doppler anemometry (LDA). As can be seen, the turbulence level is lower for all mass loadings compared to the single-phase flow. This was also the case for the neutrally buoyant particles. The slopes in Fig. 7 corresponding to the particle-laden cases are somewhat steeper than the single-phase case, indicating an increased dissipation rate.

In the longitudinal spectrum a very small decrease in the energy at large scales could be observed, as well as an increase in energy at small scales (Fig. 8). This was most evident for the neutrally buoyant particles. The Stokes number of these particles was 1.9. It should be noted that the Stokes number decreases as the turbulence decays because of the growth of the Kolmogorov scales. For the transversal spectra the reverse effect was seen: the small scales have less energy for the particle-laden flows. The overall effect of these phenomena resulted in almost identical shapes of the one-dimensional spectrum for the particle-laden and particle-free flows. Therefore, these results seem in contradiction to the outcome of the numerical work, which predicts changes in the one-dimensional spectrum at this Stokes number and mass loading.
Obviously, there is a significant difference in volume load (e.g., Ferrante and Elghobashi: $\phi=0.1\%$, Schreck and Kleiss: $\phi=1.5\%$), yet one would expect more of an effect with higher loads.

Hussainov et al. [39] used particles that were similar to those used by Schreck and Kleiss [38], yet instead of a water channel they used a wind tunnel. This led to a mass fraction that was significantly larger ($\phi=10\%$), but more importantly also provided very large Stokes numbers (i.e., of the order $10^3$). Measurements are again done using LDA. Surprisingly, the effects that Hussainov and co-workers measure are less than those obtained by Schreck and Kleiss despite the higher mass load: the decay rate is somewhat larger, but very similar to the single-phase decay rate (see Fig. 9). In the far-downstream region they find that the equilibrium turbulence level (i.e., fully developed pipe/channel flow) is lower than for the particle-free case.

In the reported transversal spectra (see Fig. 10) an increase of energy is observed at higher frequencies (viz. above 1 kHz). Even though this agrees with Schreck and Kleiss, it can be debated that this is well within their measurement uncertainty and there is no difference between the single-phase and particle-laden fluid spectra. Similar results, yet less pronounced, were found in experiments with a grid with mesh spacing twice as large. A possible explanation for the absence of a clear cross-over in the spectrum might be the large Stokes number of the particles. Since they are unresponsive to most fluid fluctuations, true two-way coupling effects cannot be expected; there is only influence of the particle on the fluid and not vice versa.

In a recent publication, Geiss et al. [40] reported very similar experiments as Hussainov’s. The main difference is the used particle size (120, 240, and 480 $\mu$m), which is significantly smaller than the experiments mentioned earlier. Still, the Stokes times of the glass particles are very much larger than unity (the Kolmogorov scales are not reported, only Stokes numbers based on the integral time scale are reported. Obviously these are smaller than the Kolmogorov scale-based values). For their measurements, they used a phase Doppler anemometry. This enabled them to measure both the fluid and the particle velocity simultaneously. At a mass fraction of up to 0.077, they do not find any influence on the normalized carrier phase spectrum within the accuracy of the measurements. On the other hand, there was an influence on the total kinetic energy of the carrier phase and also on the decay rate. One of their findings was the fact that there seems to be a thresh-

Fig. 7 Influence of mass load on decay of turbulent kinetic energy; 0.65 mm glass particles in water. Reproduced from Ref. [38].

Fig. 8 Longitudinal spectrum for unladen and laden flow; 0.65 mm neutrally buoyant particles in water. Reproduced from Ref. [38].

Fig. 9 Decay of turbulent kinetic energy for particle-free and particle-laden flow. Data taken from Ref. [39].

Fig. 10 Smoothened energy spectra for single-phase ($\phi=0$) and particle-laden ($\phi=0.005$) flows. Data taken from Ref. [39].
old in the mass load above which turbulence dampening occurs. However, this effect seems rather weak considering their results given in Figs. 11 and 12, which show the decay of the carrier phase turbulent kinetic energy for various mass loads. A remarkable result of their measurement is the fact that the flow becomes anisotropic while it decays. This was not observed by e.g., Schreck and Kleis, but has been confirmed by recent work of Poelma et al. and Poelma. An example of their decaying axial and transversal kinetic energy components is shown in Fig. 13. Poelma et al. added ceramic particles =0.1%, \( \rho_p/\rho_f = 3.8, Re_p = 18 \) to their decaying grid-generated turbulence in a water channel. It is clear that in the initial stages after the grid, there is less turbulence compared to the single-phase flow at the same centerline velocity. The axial component appears to decay slower than the transversal component, a result very similar to that reported in Figs. 11 and 12. Note that in the work of Poelma, the mass fraction is significantly lower because the experiments were done in a water channel. The reason for the slower decay is probably particle-induced turbulence; the overall decay rate appears lower because the particles generate turbulence, predominantly in the axial (gravitational) direction. This behavior is in contradiction to the often-cited rule of thumb that particles start producing turbulence when \( Re_p > 400 \).

The detailed mechanisms of the generation of turbulence by particles has been studied by an number of authors. Parthasarathy and Faeth performed studies using LDA of turbulence generation due to falling glass particles in stagnant water. An important conclusion was the fact that the turbulence generated by a falling particle is anisotropic; the mean streamwise (i.e., in the direction of gravity) component is roughly a factor 2 higher than the cross-stream component. Furthermore, it was found that the spectrum of the fluid phase showed energy at a large range of frequencies, even though the particle Reynolds numbers were small. This indicates that energy is generated at (or transported to) scales larger than the particle size. Chen et al. and Lee et al. did similar experiments in a counterflow wind tunnel. They found that even at low volume loads (0.003%), the particles can generate a turbulence level of up to 5%.

In a recent study in grid-generated turbulence, Nishino et al. also found strong anisotropic particle-induced turbulence. Again, grid-generated turbulence in a water channel was studied. The particles they used were 1.0 and 1.25 mm glass particles, their size being in between the Kolmogorov and integral length scales (\( Re_p = 138,208 \)). Instead of having a constant mass load they studied a decaying mass load using a innovative idea: the upward mean flow was chosen equal to the mean settling velocity of the particles. The particles were trapped in the test section with only a small hole at the top. This led to a slowly decreasing mass/volume load, which was measured using image processing techniques. The turbulence statistics of the fluid, as measured by a particle image velocimetry (PIV) system, could thus be measured as a function of the volume load. Figure 14 shows the influence of the mass load on the turbulence level. The most important feature...
of this graph is the fact that while the axial component increases significantly (and more or less linearly) with volume load, the transversal component increases only slowly. In total, the turbulence level is roughly three times larger than for the particle-free flow. These results are in contradiction with the experiments of Schreck and Kleiss [38], who found a slight damping (with somewhat smaller particles of the same density). The explanation given by Nishino et al. [41] is the fact that the potential energy of the particles is transferred to kinetic energy. This is the same effect as was studied by Parthasarathy and Faeth [28], apart from the presence of ambient turbulence in Nishino’s work.

In addition to the particle-induced anisotropy, they observed large fluctuations in the concentration of particles. More specific, they observed what they called “columnar particle accumulation,” i.e., vertical bands of high concentration. This could also be observed in the transversal autocorrelation function, which changed drastically. Similar phenomena have also been observed by Poelma et al. [42], also using PIV. These large density fluctuations may also be the cause of the increased turbulence level. Obviously, these effects could only be identified due to the whole-field character of the PIV measurements, in contrast to the earlier single-point LDA work.

The inhomogeneities in particle distribution observed by Nishino et al. [41] and others have been investigated by a number of authors, and the effect is often referred to as “clustering” or “preferential concentration.” Eaton and Fessler [46] collected a significant amount of experiments and simulations done in this field. The main conclusion that can be drawn from this overview is that these effects occur when the Stokes number of the particles is close to unity. Work by Fallon and Rogers [34], based on imaging of particles in microgravity, indicated that the presence of gravity (or any other body force) reduces preferential concentration phenomena. Preferential concentration can have significant effects. For instance, Aliseda et al. [47] studied the effect of preferential concentration on the settling velocity of particles. They observed a quasi-linear relationship between the effective settling velocity and the local concentration. The settling velocity of particles is an important parameter in, e.g., many engineering models, but a discussion of this parameter is beyond the scope of this review.

5.5 Discussion of Experimental Work. No significant changes in the shape of the carrier-phase turbulence spectrum (normalized by the total turbulent kinetic energy) are observed in the experiments. However, the total turbulent kinetic energy of the fluid phase is lower for most experiments, which indicates that there is some way of coupling between the phases. The fact that the Stokes number of the particles used in most experiments is an order of magnitude larger than unity, might explain the absence of bigger changes in the spectrum. It seems to us that a damping effect due to the particles (with large Stokes number) takes place at the largest scales of turbulence, and that because of the cascade process of turbulence all other smaller eddies also receive less energy than in the particle-free case. If energy would be added or taken at any other position in the spectrum, this would become evident in the shape of the spectrum. On the other hand, particles are able to generate turbulence. The particle-induced turbulence is anisotropic, and energy is generated at a large range of scales in the spectrum. The two effects, damping of the fluid motions at large scale and cascade transport to smaller scales and (ii) particle-induced turbulence production, are competing processes in dispersed two-phase flows. A more quantitative description using the presently available experimental data is impossible. The governing parameters such as density ratio, ratio of particle size and fluid length scale, and volume load, are too different to be able to compare the present results directly. More research is therefore needed, preferably varying one single parameter (as was done in, e.g., Nishino’s work with the volume fraction).

6 Conclusion

The numerical work from different researchers for the two-way coupling effect in a homogeneous, isotropic, turbulently flowing suspension agrees reasonably well with respect to the effect of particles on the turbulence spectrum of the carrier phase: low wave numbers are suppressed, while energy is gained at higher wave numbers (dependent on the Stokes number). The cross-over point—the wave number above which the energy is larger compared to the single-phase case—shifts to larger wave numbers for larger Stokes numbers. The overall effect can be either a damping of the turbulence level or an increase, depending on the particle Stokes number and the volume load. Several physical explanations for this phenomenon have been given in the literature.

Analytical theories for the two-way coupling have been developed based on the physical mechanisms that are thought to govern the system. For instance, the pivoting of the carrier-phase spectrum is reasonably well predicted, even though the results are still somewhat qualitative. At the moment, no comprehensive theory that integrates all phenomena exists, however. In particular, preferential concentration effects are not included. This effect can play an important role.

The available experimental data for a homogeneous, isotropic turbulent suspension are scarce. The pivoting of the spectrum was not observed in the obtained spectra, neither in solid/liquid nor solid/gas flows, even though the mass loads were comparable to those used in the numerical simulations. The fact that the Stokes number of the used particles was rather high in most experiments may partly account for the discrepancy. According to the physical explanations mentioned above, a large Stokes number implies that the cross-over (pivoting) point would move to very high wave numbers; thus, effectively damping on all scales occurs. This is in agreement with what is observed in most experiments.

Another important conclusion from the experiments is the effect of gravity, which generates a strongly anisotropic system. This effect is not included in most numerical simulations and analytical theories; therefore, direct comparison is not trivial. It is important to extend the simulations and theories so that the effect of gravity is incorporated.

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References

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