MEASUREMENTS AND NUMERICAL PREDICTION OF FLOW AND PARTICLE FIELDS IN TURBULENT PARTICLE-LADEN FLOWS – TURBULENCE MODULATION

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ABSTRACT

The objective of the present study is to analyze the influence of solid particles dispersed in a fluid on the fluid itself. This phenomenon, known as turbulence modulation, is investigated here by experimental as well as numerical methods. The study is restricted to the investigation of the respective turbulent properties. Experiments are performed in a specially designed vertical closed-circuit wind-tunnel. Air is used as continuous phase and solid non-reacting mono-dispersed particles of various diameters in the range from 120 to 480 μm act as dispersed phase. Phase-Doppler Anemometry (PDA) is used to measure fluid and particle velocities, respectively. In order to gain preliminary information in predicting the physical features of modulation with existing models, numerical simulations are performed in a first step using the k-ε model for turbulent flows, modified to allow for Euler-Lagrange gas-particle flow analysis. Experimental and numerical results are compared to each other. The results display very clearly the influence of the particle concentration and diameter. Parameters for generation and attenuation of continuous phase turbulence are identified.

INTRODUCTION

Turbulent two-phase flows are of high interest in the engineering practice, such as spray or pulverized-coal combustion. In particular, gas-particle turbulent suspension flows in vertical configurations are found in a wide variety of chemical processes, such as coal injection into entrained-flow gasifiers, cyclone separators and classifiers, pneumatic conveying of powder in transport lines, sand blasting, and high-velocity fluidization as encountered in circulating fluidized beds.

These systems are often characterized by complex flow phenomena, such as non-uniform spatial distribution of particles, large slip velocities between the gas and the particle phase, and attenuation or enhancement of the gas-phase turbulent intensity.

With regard to power plants, numerous studies which have been carried out to design the network in pulverized coal-fluid power plants, are solely based on empiricism. In the circulating fluidized bed process in power plants, cyclones ensure solid particles (usually coal particles) recycling to the furnace (Minier, 1999). Therefore, an accurate understanding of the turbulent flow behavior of gas-particle mixtures is necessary for scale-up, design and optimization of such processes. In recent years, two-phase turbulent flows in vertical systems were investigated both experimentally as well as numerically (Lee & Durst, 1979, Tsuji et al., 1984, Huber & Sommerfeld, 1994, Louge et al., 1993, Fan et al., 1997 for vertical pipe; Li & Ahmadi, 1992, Cao & Ahmadi, 1995 for vertical channel flows). General information on two-phase flows can be found in (Crowe, 2000, Soo, 1987, Elglobashi, 1994). Due to the complexity of the matter, investigations performed so far resulted, among other things, in the identification of general trends and led to the most representative parameters characterizing turbulent two-phase flows (Crowe et al., 1998).

One of the most important parameters is the particle concentration because it determines the nature of the interaction between continuous and dispersed phase. The particle concentration is expressed by the *particle volumetric fraction.*

For different particle volume fractions the interaction between continuous and dispersed phase can be divided into three classes. According to previous findings (see Sato, 1996, Elglobashi, 1994), for particle volume fractions less than 10^{-6}, particles have practically no influence upon properties of the continuous phase flow. Of course their own motion depends on the flow properties of the continuous phase. This is known as *one-way coupling*. Flows with particle volume fractions between 10^{-6} and approximately $5 \cdot 10^{-4}$ are denoted as dilute, and the mutual influence between particle and continuous phase has to be taken into account. However, the interaction between particles themselves can be neglected. This is known as *two-way coupling*. For particle volume fractions higher than $5 \cdot 10^{-4}$, a flow is denoted as dense (or laden) and in addition inter-particle interactions have to be considered. This is known as *four-way coupling*.

The particle size is another important parameter. Small particles attenuate continuous phase turbulence while particles larger than a certain threshold generate continuous phase turbulence. To compare data of different flow geometries the ratio of particle diameter D_p to integral length scale L_E has to be considered as suggested by Gore & Crowe, 1989. According to their results, for values of D_p / L_E below 0.1 continuous phase turbulence is attenuated. For values exceeding this limit a generation of continuous phase turbulence is observed. The influence of other important parameters (Stokes number St, continuous phase Reynolds number Re, etc.) can also be investigated. Kohnen and Sommerfeld (1997) considered the influence of particle Reynolds number, as well as the influence of the particle turbulence intensity.

To facilitate the development of design methodology in engineering applications, advanced appropriate models need to be formulated and validated from well-conceived experimental configurations. Several models have been proposed to describe turbulence modulation. However, in general no model is available right now that correctly predicts the mutual influence of the dispersed and continuous phase (Crowe et al., 1998). Especially the prediction of turbulence properties of the dispersed phase remains limited (Santiago and Kohnen, 1999). In addition, no complete data-set of dispersed phase turbulence characteristics is available (Mostafa et al., 1989). Therefore, the main objective of the present paper is to supply a complete data-base of a well characterized non-reacting two-phase flow that comprehends flow properties of the dispersed and continuous phase, respectively.

For this purpose experiments are performed in a vertical closed wind-tunnel using air as continuous (carrier) phase and mono-dispersed glass particles with diameters ranging from 120 to 480 μm as dispersed phase and that are seeded to the flow. The carrier phase is represented by small glass particle 3 μm in diameter. In a parametric study the size of the turbulence generating grid, the Reynolds number of the continuous phase, the particle diameter and particle concentration are varied. A modern laser based diagnostic measurement technique (PDA) allows simultaneous measurement of velocity components of the carrier (continuous) and particle phase, particle size and particle-carrier velocity correlation. In order to gain preliminary information on the performance of the existing models predicting turbulence modulation, selected experimental results are compared to numerical investigations carried out by using a modified version of the k-ε model in the framework of the Euler / Lagrange method.

EXPERIMENTAL SET-UP

The experimental set-up is shown in Fig.1. The carrier phase - driven by a radial compressor - circulates in a closed pipe system. Glass particles are dispersed in required doses by a sluice, generating the two phase flow. The flow passes a diffusor with an half-angle of $\alpha/2 = 4.1°$ before reaching the settling chamber where two meshes (first mesh b = 0.37, second mesh b = 0.60; b: open area ratio) and honeycombs are integrated. Subsequently, a nozzle with a contraction ratio of 9:1 homogenises the flow. At the nozzle exit a turbulence grid and the vertical oriented measurement section are placed. In a following section the two phases are separated by use of a cyclone.

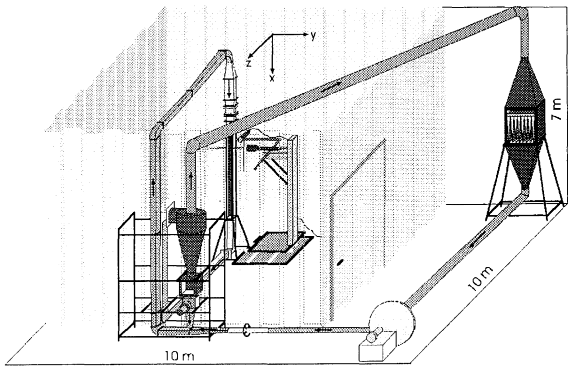

Figure 1 Experimental set-up of the flow system.

The main characteristics of the set-up are: a) The measurement section is designed as a vertical square glass tunnel with inner dimensions of 0.2 m by 0.2 m by 2.0 m suitable for laser-based diagnostics. b) The maximum mean velocity of the measurement section is 12 m/s; the mean velocity of the investigations presented here is set to 5 and 10 m/s, respectively. c) The particle size can be varied between 60 μm and 1500 μm (the maximum of the particle size is limited by the smallest mesh size used); in this study mono-dispersed particles with mean diameters of 120, 240 and 480 μm are employed. d) The particle concentration can be chosen between $\mu = 0 - 2$ (μ: ratio of mass of the particle phase and mass of the carrier phase; the maximum of the particle concentration is limited by the optical transparency of the flow).

For simultaneous measurements of velocity components (mean velocity, higher moments), velocity correlations as well as fluid-particle velocity correlations and particle size a two-dimensional standard PDA system is used. The optical set-up consists of a fibre flow transmitting probe including a beam expansion; the beams are separated on the focusing lens (f_{Tr} = 310 mm) by b_s = 75.24 mm. For this optical configuration the measurement volume results in a diameter of d_{fl} = 46 μm and a length of d_l = 380 μm. As receiving unit a standard PDA optic with a focal length of f_{Re} = 400 mm (fiber PDA probe without beam expansion) is used. Detailed descriptions of the measurement technique can be found in Ruck, 1990. Particle concentrations are measured by conventional probe techniques.

RESULTS

Wind-tunnel characteristics

By use of a grid previous to the vertically oriented test section for a single-phase flow a nearly homogeneous, stationary and isotropic turbulence is generated. For such a flow, the local turbulence energy is a function of the dissipation rate only. In the direction of the mean flow the intensity of the turbulent kinetic energy decreases. The decay of turbulence is characterized by at least two different regions. The first region is defined between 10 and 150 mesh length downstream the grid. The second region is located beyond 500 mesh lengths and is not considered here.

M(square mesh)	[mm]	12	24
square whole	[mm]	10	20
d (wire)	[mm]	2	4
S (solidity)	[ ]	0.31	0.31

Table 1 Characteristics of the two grids used for the study.

In this study two different bi-planar square turbulence grids are employed. The characteristics of the grids are presented in Table 1. The grids are selected for a high level of turbulence but also to maintain locally an isotropic flow field. To obtain the degree of local isotropy, the ratio of the mean square velocity fluctuation in axial direction $\overline{u'^2}$ to that of the vertical $\overline{v'^2}$ and horizontal $\overline{w'^2}$ cross stream direction is computed. With respect to these needs a solidity ratio (projected solid area over total area) of S = 0.31 is chosen. The flow field measurements by use of PDA are performed over a fine point grid covering the core (8cm square area) of the wind-tunnel to avoid the influence of the boundary layer. Gravitational effects are negligible. The measurements span in axial direction from x/M = 10 to x/M = 50. Measurements of decay of the turbulent energy in the axial direction are found to agree well with that expected by the use of such grids as shown in Fig.2. This figure shows the turbulent kinetic energy measured in the center of the test section in dependence of the axial position (stars in Fig.2). In this example the grid with a mesh size of 12 mm and a mean axial velocity of 10 m/s are used. It is obvious that the turbulent kinetic energy decays from an initial value of 0.7 m^2/s^2 to 0.1 m^2/s^2.

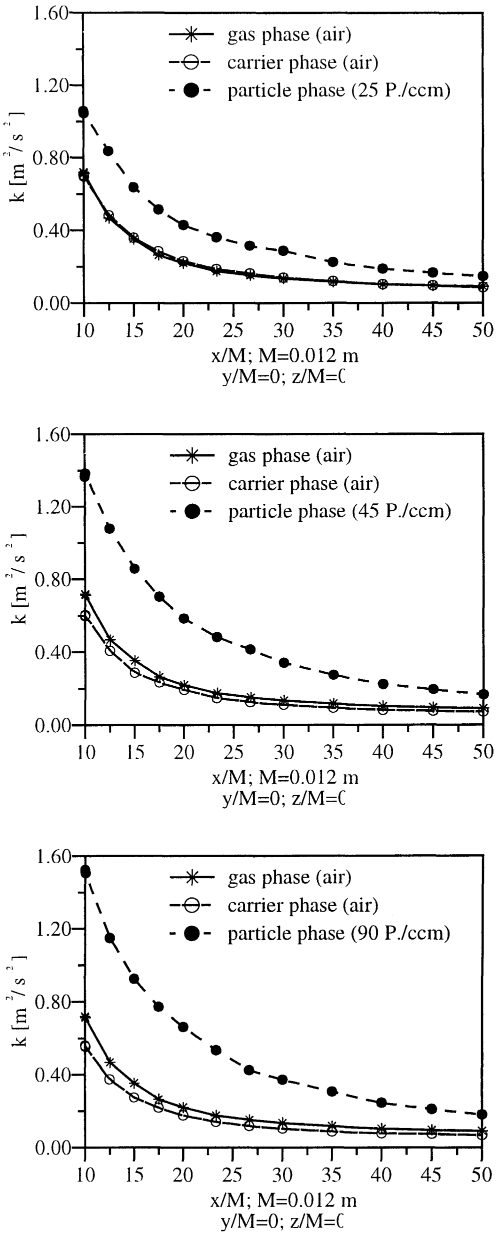

Figure 2 Axial decay of the turbulent kinetic energy for different particle concentrations as measured in the center line of the vertical wind tunnel.

In order to compare the characteristics of the presented wind-tunnel to experiments cited in the literature Fig.3 shows the squared mean axial velocity normalized by the respective squared RMS value. Taking into account the differences in, e.g., geometry it is obvious that the wind-tunnel presented here shows comparable features to those of previous set-ups.

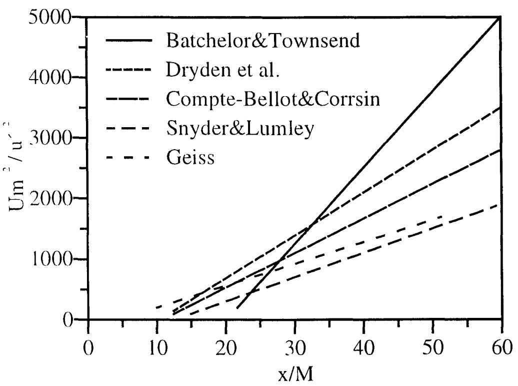

Figure 3 Comparison of normalized RMS values in axial direction. Data are taken from (Wells and Stock, 1983) and expanded by own results.

Results of the two-phase flow

Fig.2 shows the influence of the particle concentration on the turbulent kinetic energy. In this example particles of 120 ± 21 μm in diameter, a mean axial velocity of 10 m/s and a mesh size of 12 mm are employed. Concentrations as measured by a conventional probe technique are varied from 25 to 90 particles per ccm. In comparison between single- (stars) and two-phase flows (open circles) particles of 120 μm attenuate the turbulent kinetic energy of the carrier (gas) phase if the particle concentration exceeds a limit of 30 to 40 particles per ccm.

However, an increase of the turbulent kinetic energy of the dispersed (particle) phase (closed circles in Fig.2) is observed for increasing particle concentration. This effect is attributed to collisions between particles and the grid. For axial positions beyond x/M = 50 the turbulent kinetic energy of the particle phase approaches a value independent of the particle concentration. It is worth to note that the mean axial flow velocity is not influenced by the particle concentration.

For a geometrically similar grid with a mesh size of 24 mm similar observations as for the 12 mm case shown in Fig.2 are made. In this case, however, the influence of collisions between grid and particles is less pronounced. Therefore initial turbulence levels at x/M = 10 are lower.

The influence of the Reynolds number is investigated by changing the axial velocity from 10 (Re=64000) to 5 m/s (Re=32000). Fig.4 shows the turbulent kinetic energy normalized by the squared mean axial velocity in dependence of the center axial position. In this case the grid with 12 mm spacing is used. Similar to Fig.2 the normalized turbulence level of the carrier phase is shown for the single- (stars) and the two-phase flow (open circles). Closed circles represent the turbulence level of the particles in the two-phase flow. It is obvious from this graph that in this normalized representation the respective values correspond very well for the two Reynolds numbers. The small deviations especially in case of the single (gas) phase can be attributed to slightly different particle concentrations in the run of the experiments.

The influence of the particle size is highlighted in Fig.5. For this example a mean axial velocity of 10 m/s and the 12 mm wide grid are employed. The mean particle diameter is varied from 120 to 480 μm. For each particle class the standard deviation for the diameter distribution is close to 10 %. For this comparison the respective maximal particle concentration is chosen. From this figure one can deduce that particles with 120 μm attenuate carrier phase turbulence, 240 μm are close to the transition from turbulence attenuation to turbulence generation. For large particles with mean diameters of 480 μm a strong turbulence generation is observed. Notice, that for the different particle classes it was not yet possible to keep μ constant (ratio of the particle mass to the mass of the carrier phase).

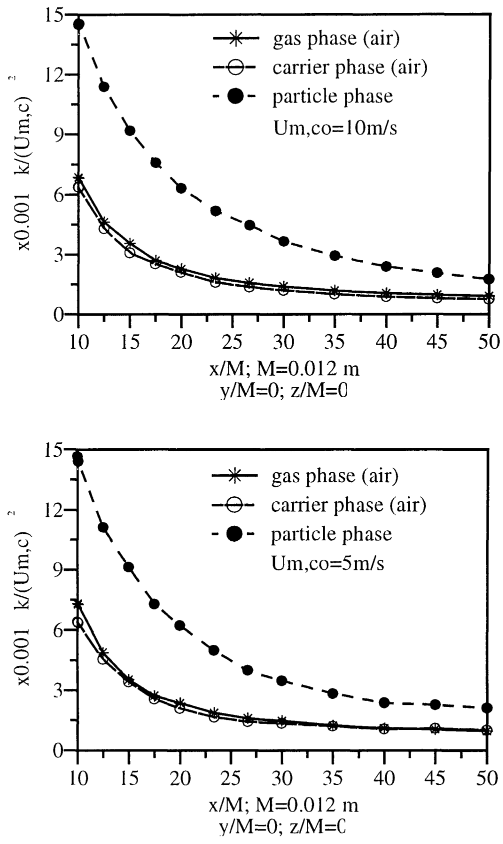

Figure 4 Influence of the Reynolds number on the axial decay of the normalized turbulent kinetic energy.

NUMERICAL SIMULATION

To gain preliminary insight into the performance of the existing models in predicting turbulence modulation, numerical calculations have been carried out. In a first step only the continuous phase flow, without particles, was simulated. Because calculation results can be sensitive to the inlet boundary values, particularly with respect to the dissipation rate during this step, a considerable care was taken to determine the adequate initial dissipation rate for the k-ε model. Initial dissipation rate was determined upon experimental data, considering nature of isotropic turbulence behind the grid.

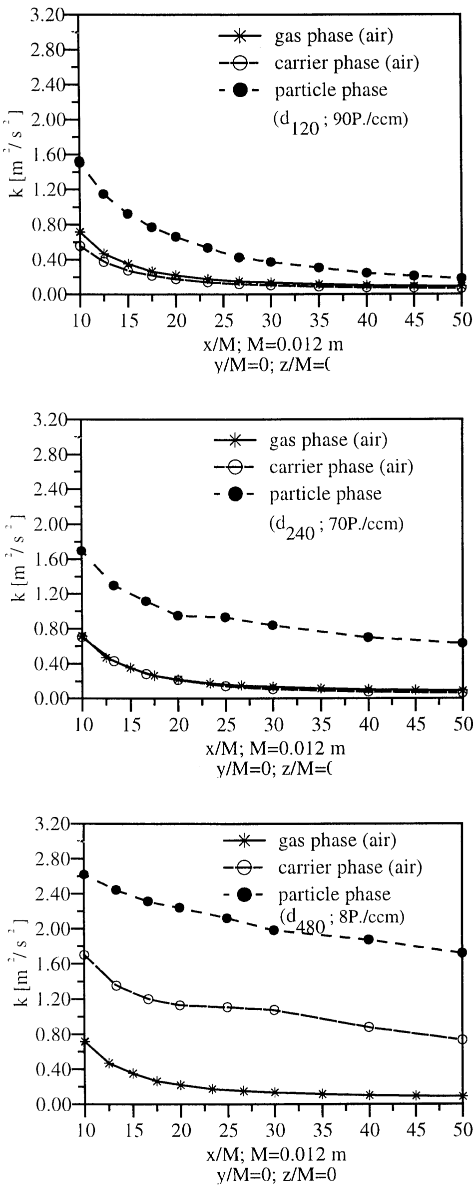

Figure 5 Influence of the particle size.

To numerically illustrate the influence of the dispersed phase on the carrier phase, particles (diameter d_p = 120 μm ± 21 μm) are used. The density of the particles is ρ_p = 2440 kg/m^3 and the particle concentration is set to 90 particles / cm^3.

The approach used follows the method of Eulerian treatment of continuous phase, coupled with Lagrangian particle trajectories prediction, as described in Kohnen and Somerfeld, 1997. In this context it can be used only to predict continuous phase turbulence attenuation, so its applicability is somewhat limited to smaller particle sizes, but is very valuable as the comparison of obtained results with experimental data is satisfactory.

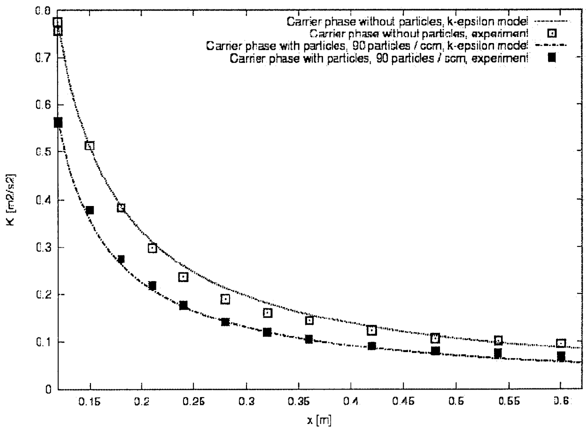

Figure 6 Comparison of numerical and experimental results. Numerical results are shown as lines, experimental data as squares. The upper curve shows the axial decay of the turbulent kinetic energy without a particle phase. Seeding of 120 μm particles leads to an attenuation of turbulence intensity.

As shown in figure 6, this modified version of the k-ε model to account for the gas-particle interaction compares well to measurement data which indicate the attenuation of turbulence by small particles used with particle concentrations exceeding 40 particles per ccm.

CONCLUSIONS

In the present study we experimentally analyze the influence of solid particles dispersed in air flowing in a vertical oriented channel. The results display clearly the effect of the particle concentration and diameter on the generation or attenuation on the turbulence of the carrier phase. Further investigations are necessary to take account of other parameters. We compare numerical results of the turbulence decay based on an Eulerian-Lagrangian strategy (a modified k-ε model for the gas has been used) with experimental results. We demonstrate the applicability of this strategy to predict the attenuation of the carrier phase turbulence. To account for other gas-particle properties and to better describe the complex turbulence modulation, more advanced models have to be used or formulated. This is ongoing research in our laboratory.

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