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ScienceDirect
International Journal of Multiphase Flow 32 (2006) 1386–1396
International Journal of Multiphase Flow
www.elsevier.com/locate/ijmulflow

Brief communication

Turbulence attenuation by small particles in the absence of gravity

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Received 16 May 2005; received in revised form 20 June 2006

Keywords: Turbulence attenuation; Homogeneous isotropic turbulence; Micro-gravity

1. Introduction

Some examples of particle-laden turbulent flows that can be found in nature and industry include dust storms, chemical reactors, and pollutant abatement systems. In these type of flows particles are not only dispersed by the turbulence but they may also affect it in such a way that the carrier-phase turbulence level may be modified. Depending on the flow conditions and particle characteristics, augmentation and attenuation of turbulence levels have both been observed. Turbulence attenuation can become a problem if high turbulence levels are required, in areas such as heat transfer and mixing. Kulick et al. (1994) and Paris and Eaton (2001) have shown that the carrier-phase turbulence level can be attenuated up to 80% by a dilute dispersion of particles that has negligible volume fraction. The addition of an extra phase to a turbulent flow poses a very complex problem, however, and it is still not clear what causes this phenomenon of turbulence attenuation.

Previous researchers have attempted to use optical measurements in simple flows to study this problem. Parthasarathy and Faeth (1990), Mizukami et al. (1992) and Chen et al. (2000) created stationary homogeneous turbulence by dropping particles through stagnant water, air, and a counterflowing upward wind tunnel, respectively. The carrier-phase velocity fluctuations depended only on the viscous dissipation rate, which was obtained from the potential energy loss of particles and particle drag. Grid-generated turbulence has also been investigated. Schreck and Kleis (1993), Geiss et al. (2004) and Poelma et al. (2006) observed turbulence modification using laser Doppler velocimetry (LDV), phase Doppler anemometry (PDA), and particle image velocimetry/particle tracking velocimetry (PIV/PTV), respectively. Nishino et al. (2004) created a nearly stationary dispersion of particles using an upward water flow and eliminated the transfer of potential to kinetic energy of settling particles.

The ideal environment to study turbulence attenuation by particles would be in stationary homogeneous and isotropic turbulence without mean flow, in the absence of gravity so a stationary dispersion of particles

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0301-9322/$ - see front matter
doi:10.1016/j.ijmultiphaseflow.2006.06.008

can be created. Since this is very difficult to realize in a laboratory setting, several researchers have relied on numerical simulations. Squires and Eaton (1990) and Boivin et al. (1998) used direct numerical simulations (DNS) and Boivin et al. (2000) used large eddy simulations (LES) to examine such flows, and found that the turbulence kinetic energy and dissipation rate decreased with increasing particle loadings, while the energy spectra increased at high wavenumbers relative to low wavenumbers. Fallon and Rogers (2002) were recently able to experimentally create such a flow on NASA's KC-135 parabolic aircraft using fans mounted in a chamber. However, their focus was on particulate-phase measurements of particle dispersion and not carrier-phase measurements of turbulence attenuation.

The goal of this study was to experimentally investigate the ideal case of attenuation of stationary homogeneous and isotropic air turbulence without mean flow (fluid velocity $u = u'$) by a uniformly dispersed stationary array of heavy particles (particle velocity $v = v'$). More specifically, the following conditions were considered. The particulate phase was small spherical monodisperse glass beads, where the ratio between particle diameter and fluid Kolmogorov length scale $d_p/\eta \sim 1$, particle-to-fluid density ratio $\rho_p/\rho_f \sim 2000$, particle Stokes number (based on the fluid Kolmogorov time scale) $St_k \sim 140$, and particle Reynolds number $Re_p \sim 10$. The flow was dilute and had a negligible particle volume fraction $\alpha_p \sim 10^{-4}$, but non-negligible particle-to-fluid mass loading ratio $\phi \sim 0.1$, which corresponded to total number of particles $N_p \sim 10^6$ and inter-particle spacing $l_p \sim 20d_p$.

A parallel experiment was performed in ordinary terrestrial gravity. That work has already been reported in Hwang and Eaton (2006). The purpose of this brief communication is to specifically describe the different experimental procedures and data analysis techniques required for the microgravity experiments, and to present and discuss the differences in the experimental results. Only a short description of the main apparatus is given, and the reader is referred to Hwang and Eaton (2004a, 2006) for more details.

2. Experimental setup

The turbulence was created in a sealed chamber, which has been described in detail by Hwang and Eaton (2004a). The experiments were conducted in a free-floating environment aboard NASA's KC-135 parabolic flight aircraft to eliminate the effects of gravity. The turbulence chamber and particle image velocimetry (PIV) system were housed in a sturdy free-floating rack, while the computer and other electronics had to be housed in a stationary rack. Details of the experimental setup can be found in Hwang and Eaton (2004b).

2.1. Experimental facility and procedures

The KC-135 experiences fluctuations in g-levels, up to 0.1 g (Groszmann, 2001), due to vibrations of the body of the plane as it free falls. This "g-jitter" can mask the particle motion produced by the fluid turbulence in our experiments, so the main apparatus was free-floated. Although the duration of micro-gravity in each parabola was reduced, as the rig tended to float into the walls and ceiling of the cabin, the g-levels were greatly reduced to the order of milli-g and smaller.

The free-floating apparatus, depicted in Fig. 1(a), housed the turbulence chamber, camera, laser, optics rail, flow seeder, and accelerometer. The turbulence chamber is a sealed symmetric Plexiglas box with each side being 410 mm and the corners cut off to make it nearly internally spherical. Homogeneous and isotropic turbulence with small mean flow was created by eight synthetic jet actuators mounted on the corners, which used loudspeakers that had random frequency (centered at 100 Hz) and phase sine waves sent to them. The PIV system consisted of a Continuum Minilite PIV dual-head Nd:YAG laser (25 mJ/pulse at 532 nm), sheet-creating optics mounted on an optical rail, Kodak ES1.0 10 bit CCD (1018×1008 resolution) camera, and fluidized bed seeder. A Crossbow CXL01LF3 accelerometer that had a range of ± 1 g measured the vertical acceleration. The accelerometer measurements determined the validity of the data, as spikes would appear when the rack bumped into a wall or ceiling, or when the NASA flight crew touched it. The rack was made from aluminum 80/20 components and covered with aluminum panels to prevent laser light from escaping. It is shown free-floating in Fig. 1(b).

A second rack was bolted securely to the cabin floor and housed the laser power supplies, Phast PLB-Amp8 power amplifier, computer, monitor, keyboard, computer interface box, and the random frequency sine wave