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Experimental investigation of the particle distribution of gas-solid turbulent flow in the boundary layer

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ABSTRACT

By the three-dimensional and no-contact optical technique digital holography, the particle distributions of a turbulent gas-solid boundary layer were studied in a fully developed horizontal channel, and the velocity field of the gas phase was obtained by particle image velocimetry (PIV) with main upstream speeds of $U_h = 2.1\ \mathrm{m\ s^{-1}}$, $5.2\ \mathrm{m\ s^{-1}}$, and $8.74\ \mathrm{m\ s^{-1}}$. Carborundum powders with diameters of 38 μm and 60 μm were used as the particle phase and titanium dioxide nanoparticles were used as ghost particles. It was found that the peak of the particle distribution occurs in a logarithmic region. With an increase of particle size, the peak shifts toward the wall. As the velocity increases, the peak shifts toward the channel center. The gravity and sweeps have influence on the particle motion toward the wall; particle–wall collisions, ejections and the Magnus lift force have influence on the particle motion toward the channel center. Through analysis of the velocity field and shear strain distribution in the gas boundary layer, the existence of sweeps and ejections caused by quasi-flow vortices has been confirmed. Meanwhile, it was found that the peak of shear strain occurred near the wall and that wall-normal fluctuation and shear strain under high flow rate were significantly higher than at low flow rate; these characteristics were consistent with the distribution of particles in the boundary layer.

1. Introduction

Turbulent gas-solid flow is an important phenomenon in a number of relevant engineering and environmental applications, for instance, the pneumatic conveying of powder particles [1], solid fuel combustion [2,3], particle deposition in material processing and the dispersion of pollutants in the atmospheric boundary layer. The distribution and motion of the solid particles in the boundary layer directly affect the flow resistance and the wear of the particles on the wall. In order to develop clean and efficient use of energy and optimized design of industrial production facilities, it is necessary to research the particle distribution and its movement in turbulent boundary layers. Due to the complexity of coherent structures (e.g. hairpin vortex, streamwise vortex, lateral vortex, burst) and interaction between particles and turbulent structures, the topic of turbulent boundary layer theory is a difficult and important topic in the research of hydrodynamics [4,5].

A large number of theoretical and experimental studies have been dedicated to the motion, deposition, and entrainment of solid particles, and the influence of solid particles on turbulent structures in boundary layers. In a challenging study of the liquid-solid flow in a horizontal channel, Rashidi [6] found that near walls, particles accumulate in low-speed streaks, and particle transport depends on "burst" events. Kaftori [7,8], Tanière [9], and Vyhnalikova et al. [10] studied the interaction between the particle motion and the turbulence in a horizontal boundary layer and observed that particle positions tend to correlate with the instantaneous location of the lower values of the streamwise velocity – low-speed streaks; this phenomenon may be caused by quasi-streamwise vortices in the wall region. Huber et al. [11] analyzed the particle-wall collision process in a particle-laden horizontal channel flow. The results showed that wall roughness and non-sphericity of particles have a considerable influence on the wall collision process, the rebound properties of particles, the momentum exchange of particles and fluid, and particle distributions with height. For a range of solid loadings and particle sizes, the particle behavior in a turbulent boundary layer of a dilute gas-solid flow was studied experimentally by Wang et al. [12,13]. The results showed a non-uniform distribution of particle concentrations with the peak concentration occurring inside the turbulent boundary layer. Concentrations of larger particles were also higher with the peak value closer to the wall. Li et al. [14,15] studied the mechanism of turbulence modifications in a horizontal channel flow at low mass loadings. Both experimental and simulation results showed that the presence of particles inhibits the coherent structures and the influence of particles on the near-wall quasi-streamwise vortices was an important mechanism of turbulence modification at low mass loading. Fan et al. [16,17] studied the interaction of particles and vortices in a flat-plate boundary layer. Simulated results showed that heavy particles with small inertia concentrate in the upper fringes of the low-pressure zone behind the hemisphere and hinder the process of vorticity

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concentration. They also found that ejection and sweep events dominate the transport of particles in the boundary layer, and in the near-wall region sweeps show stronger ability of transporting particles than ejections.

In recent years, in the study of gas-solid boundary layers, scholars are devoted to examining the influence of particle loading on coherent structure, particle motion and particle–wall interactions, and the beneficial effect of the particles on the enhancement of heat transfer [18–21]. However, there is less research on particle motion and distribution with height and span across a turbulent boundary layer. In this paper, digital holography in combination with a particle tracing algorithm and PIV, are used to study the characteristics of particle distribution and motion and clean air flow field in the boundary layer of a horizontal channel flow.

2. Principles of digital holography

Digital holography contains two steps: digital recording and numerical reconstruction [22]. Fig. 1 illustrates the principles of digital in-line holography with a plane wave. Based on the principle of interference of light, the object light (scattered light), which carries the object information, and the reference light interfere with each other. The charge coupled device (CCD) records the amplitude and phase of the object light by recording the interference fringe patterns. The numerical reconstruction of digital holography is based on the scalar diffraction theory. It uses the reference light to illuminate the hologram, so as to reproduce the object light to obtain the particle field information. In the following section, the detailed process of particle imaging using digital holography is presented.

2.1. Holographic recording

Fig. 1(a) depicts the digital holographic recording process. Assuming that the light intensity is a function of particles on the object plane, $O(x,y)$, the light intensity function in the recording plane (α,β) can be written as $I_{z0}(\alpha,\beta)$:

$$I_{z_0}(\alpha,\beta) = 1 - \frac{2}{\lambda z_0} O(x,y) \otimes \sin\left[\frac{\pi}{\lambda z_0}\left(x^2+y^2\right)\right] \quad (1)$$

where $\otimes$ is the two-dimensional convolution operation, λ is the laser wavelength, and z_0 is the distance between the particle-field plane and the holographic recording plane.

2.2. Holographic reconstruction

The numerical reconstruction of digital holography is based on scalar diffraction theory. To date, many holographic reconstruction algorithms have been developed such as Fresnel approximation, convolution algorithm, wavelet transform and fractional Fourier transform [22]. The holographic reconstruction algorithm based on wavelet transform has advantages of high signal-noise ratio of the reconstructed image and background uniformity. Therefore, the wavelet transform algorithm was adopted hereinafter.

With a wavelet based function $\psi(x,y) = \sin(x^2 + y^2)$ and scalar parameter $k = (\lambda z_0 / \pi)^{1/2}$, the wavelet function can be constructed as [23]:

$$\psi_\alpha(x,y) = \frac{1}{\alpha^2}\left[\sin\left(\frac{x^2+y^2}{\alpha^2} - M_\psi\right)\right] \bullet \exp\left(-\frac{x^2+y^2}{\alpha^2\sigma^2}\right) \quad (2)$$

where the σ-band width factor, which depends on the sampling characteristics of hologram, can be expressed as:

$$\sigma = \min\left[\frac{N\delta_{ccd}}{2}\sqrt{\frac{\pi}{\lambda z}\ln\left(\varepsilon^{-1}\right)} \bullet \frac{1}{2}\sqrt{\frac{\pi\lambda z}{\ln\left(\varepsilon^{-1}\right)}}\right] \quad (3)$$

M_Ψ is a zero-adjustment parameter to ensure a zero mean of $\psi_\alpha(x,y)$, and can be constructed as:

$$M_\psi = \frac{\sigma^2}{1+\sigma^4} \quad (4)$$

Eq. (1) can then be expressed as [23,24]:

$$I_{z_0}(x,y) = 1 - \frac{2}{\pi} O(x,y) \otimes \psi_\alpha(x,y) \quad (5)$$

The light intensity distribution function of the hologram can be described as a function of wavelet transform. The reconstruction of the hologram is equivalent to the inverse of the holographic recording. After the particle field hologram is recorded by a digital camera, space planes of the image are selected to generate the wavelet function for reconstruction. Then the convolution operation is conducted on the hologram and the wavelet function, and the reconstructed images are obtained.

3. Materials and methods

3.1. Experimental device

To study the gas-solid turbulent boundary layer based on the LaVision PIV system, the experimental system of digital holography and PIV were built, as shown in Fig. 2. The system composition is: the laser system, the beam adjustment section, the CCD and experimental section. There are two lasers (5 and 8) illuminating the flow field. The hologram is to reconstruct the "solid phase" and the PIV signal is to obtain gas velocity.

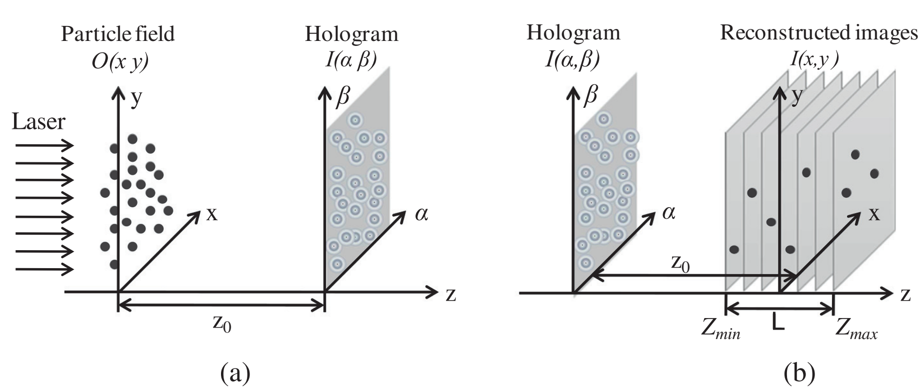

Fig. 1. Schematic of holographic recording and reconstruction of particle field illuminated by plane wave: (a) Hologram recording using plane wave illumination. (b) Numerical reconstruction process of holographic images.