PIV analysis of gas-solid multiphase flow relevant to wind-blown sand:  
Simultaneous measurement of near-wall turbulent motions  
and instantaneous relative velocity

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Abstract The wind-blown sand occurs in the process of the desertification, one of the serious environmental problems in arid areas. To clarify mechanisms of the wind-blown sand and to predict the sand movements, a quantitative understanding of the interaction between gas (air) and solid phases (sand grains) in the multiphase flow. Particle laden flows have been investigated experimentally by several researchers. However, horizontal turbulent flows, i.e. turbulent boundary layer, over sand beds have been less investigated due to difficulties in simultaneous measurement of both the near-wall turbulent motion and the suspending-particle motion. In the present work, a piston-type sand feeding device was applied as particle-supplied method. We measured simultaneously the spatial distributions of the air-flow velocity ($U_g$) and the sand-grains velocity ($U_p$) in the turbulent boundary layer, using the particle image velocimetry (PIV). Then we investigated the relationship between the instantaneous streamwise relative velocity ($U_g - U_p$) and the turbulent characteristics motion. As a result, the local relative velocity ($U_g - U_p$) should be positive instantaneously by the turbulent structures such as the hairpin vortex. The sand particles could drive into the large-scale low-momentum zone from high-momentum zone. In addition, the head of hairpin vortex scale could be reduced by the sand particles, as a result of linear stochastic estimation (LSE) based on swirling strength. Moreover the second invariant II at the multiphase flow was drastically decreased compared to single-phase flow by using the anisotropy invariant map (AIM). It implies that it could be shifted to isotropy condition by feeding sand particles. Therefore the coherent vortex structure in the gas-solid multiphase flow could not develop like single-phase flow. Thus, the head of the hairpin vortex could shrink in the gas-solid multiphase flow.

1. Introduction

Desertification, one of environmental issues becoming serious for us to live with animals and plants, are currently discussed with the significant progress of industry. Desert covers over 1/5 the dimension of land all over the world and extends 6,000,000 hectares per annum. While urgent countermeasures for the issue have been required, the final target of this study is to prevent the desertification area from extending. The wind-blown sand is one of factors in the desertification. This phenomenon is to supply desertification area with a lot of dust and sand carried from a desert area. In this study, we paid an attention to the wind-blown sand in a turbulent boundary layer and investigated experimentally the interaction between the gas phase (air) and the solid phase (sand grains) in the multiphase flow. Various studies were conducted to control the wind-blown sand using a wind-break porous fence (Cornelis & Gabriels, 2005; Tsukahara et al., 2012). Therefore it is important to understand the fundamental relationship between air and sand particles, in order to achieve an advantageous effect of fence for controlling the wind-blown sand.

The gas-solid flow has been investigated by numerical simulations and experiments. For instance, Tashiro et al. (1995) studied the gas-solid two-phase flow in a horizontal pipe by numerical simulations with emphasis on the variation in the air flow by influences of solid particles. Several researchers (e.g., Liljegren et al., 1990; Tsuji et al, 1984; Ljus et al, 2002) have investigated experimentally the gas-solid flow.
and reported that the air velocity and the turbulence intensity have been changed by additive amount of the solid particles and the particle diameter. However the interaction between the solid and gas phases has been not yet discussed based on simultaneous measurement with respect to the two phases. Meanwhile, it is important to discuss compared to particle motion and coherent vortex structures of the turbulent flow. It is well-known that particle dynamics are affected by the coherent structures that induced sweep-ejection cycles in the wall turbulence (e.g., Kinger et al., 2002; van Hout, 2011; Cristian et al., 2002). However, the understanding of the modification of the coherent vortex structures may be less advanced based on the two-way coupling method.

In the present work, we measured simultaneously spatial distributions of the air-flow velocity and the sand-grains velocity in the turbulent boundary layer, using the particle image velocimetry (PIV). We considered the influence of the sand particles by using a horizontal wind tunnel. The obtained raw pictures by PIV were separated into two pictures of either of oil-mist tracers or sand particles based on difference of brightness and the diameter of particles in a shot image. Hence the velocity field of the gas phase and the solid phase were obtained simultaneously. Then we we investigated the relationship between the instantaneous relative velocity of particles and the turbulent characteristics motion.

2. Experimental set-up

The experimental set-up is shown in Fig. 1. In the downstream of the blower and rectification part with the outlet of 250×250 mm², a developing section was installed with 1.0 m length, and a test section was 3.0 m long. Their spanwise width was kept at 250 mm. The upper surface of both sections was movable, so that the pressure gradient was maintained as zero throughout the test section. We used sand
Table 1. Specification of PIV

<table>
<thead>
<tr>
<th>Model</th>
<th>Nano S 65-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Nd:YAG double pulse</td>
</tr>
<tr>
<td>Output (maximum)</td>
<td>40 mJ/pulse</td>
</tr>
<tr>
<td>Wave length</td>
<td>532 nm</td>
</tr>
<tr>
<td>Pulse interval</td>
<td>50 μm</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>5 ns</td>
</tr>
<tr>
<td>Spread angle</td>
<td>20°</td>
</tr>
<tr>
<td>Camera resolution</td>
<td>2048×2048 pixels</td>
</tr>
<tr>
<td>Focal length</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

grains, the nominal mean diameter of which is 50.4 μm. About 80% of sand particles have the diameter ranging from 10 μm to 100 μm. The oil-mist tracer diameter is about 1 μm. The density of the air is 1.21 kg/m³ at the temperature of 20°C and that of the sand particle is 2560 kg/m³. The sand particles were supplied from the upstream of a measurement area by a piston-type sand feeding device, which was located at 250 mm downstream from the entrance of the test section, as shown in Figs. 2 and 3. The cross section of the piston cylinder was 20×250 mm², and the area of sand particles supplied was 10×200 mm². It was installed on the ground so that sand grains sufficiently spread into the measurement area. The sand feeding device was composed of a motor (Panasonic, Co.), pinions, rack gears, a piston, and a cylinder. The piston can be pushed up by using the motor at a constant speed. And the motor was fixed by a frame, for the sake of the motor prevented from turning around by oneself. Then the rack gear was transmitted a torque of the motor by the gear and the pinion, and the sand grains were supplied by the piston pushing up. The piston can move only upward slowly. The sand was continuously supplied at constant amount. It was possible to change the supply quantity by the speed control. The present particle response time is estimated as 0.02 second on the basis of the following equation:

\[ \tau_p = \frac{\rho_p d_p^2}{18 \mu}, \]

where \( \rho_p \) is the particle mass density, \( d_p \) is the particle diameter, and \( \mu \) is the viscosity coefficient.

It is important to understand quantitatively the interaction between the gas phase (air) and the solid phase (sand grains) in the multiphase flow. To discuss this issue, the instantaneous flow field should be analyzed with respect to both sides of the gas phase and the solid phase. In this study, we measured simultaneously the spatial distributions of the air flow velocity and the suspended sand-grain velocity in the turbulent boundary layer, using PIV system. Table 1 summarizes the specification of the PIV, which was composed of a double-pulse laser, laser-sheet optics arrangement, a CCD camera, a synchronizer, and a computer for image processing. The double-pulse laser (Litron Laser, Co.: Nano S 65-15) was a combination of a pair of Nd:YAG lasers, each having an output of 40 mJ/pulse and the wavelength of 532 nm, and pulse interval set 50 μm. The laser sheet thickness and the spread angle can be fixed by the laser-sheet optics arrangement. In this experiment, they were set to be 0.6 mm and 20°. The CCD camera had a resolution of 2048×2048 pixels, the area of a pixel was 7.4×7.4 μm², and the dimension
of the image was 108 × 108 mm². The lens had a 50 mm focal length and aperture of 2.8. The present system enabled us to obtain 5 sets of images per second. Each obtained raw picture was separated into two pictures of either of sand particles or oil-mist tracers based on difference of brightness in a shot image. Then each picture was analyzed with software and obtains velocity vector. In the pictures of oil-mist tracers, incorrect vectors were rejected and replaced through the following process. First, the vectors, which were outside a certain range, were rejected. The range was determined from two components velocities. Next, velocity vectors determined as errors were interpolated from neighboring eight points. The number of particles was counted from the picture. The pictures of oil-mist tracers had 127 × 126 vectors and sand particles had vectors of sand particles number. We calculated the mean velocity from PIV results based on a total of 600 instantaneous velocity fields.

It is known that, when the air streamwise velocity is over 6 m/s, sand storm arises in the desert (Mikami et al., 2006). In this experiment, to measure the wind-blown sand movements, we carried out tests at the main-stream velocity of \( U_0 = 8.7 \) m/s. While the boundary-layer thickness of the single-phase flow (without the sand grains nor sand bed) at \( U_0 = 8.7 \) m/s is \( \delta = 76.3 \) mm, that of the gas-solid multiphase flow is \( \delta_p = 130 \) mm.

3. Result and Discussion

3-1 Instantaneous velocity fields

Figure 4(a) shows an instantaneous field of the relative streamwise velocity, \( U_p \) \( \tilde{I} \) \( U_g \), in an \( x \)-\( y \) plane (\( x \), the streamwise; \( y \), the wall-normal direction), while (b) and (c) indicate the Galilean-decomposed velocity field of \( U_g \) \( \tilde{I} \) 0.8\( U_b \), and the swirling-strength (\( \lambda_{ci} \)) distribution at the same location and instant in the gas-solid multiphase flow. In this paper, \( U_p \) and \( U_g \) represent the velocities of particle and gas (the air) phases, respectively. Galilean decomposition is the technique that visualized uniform momentum zone in instantaneous velocity fields suggested by Adrian et al. (2000). This method deduced arbitrary velocity from the original velocity fields as following equation:

\[
U_c = u - \alpha U_b, \tag{2}
\]

where, \( U_c \), \( u \), \( \alpha \), and \( U_b \) are the processing velocity by Galilean decomposition, the original velocity, the proportional constant, and the main-stream velocity, respectively. The proportional constant is defined arbitrary value in the range from 0.5 to 1. Adrian et al. (2000) suggested that a large \( \alpha \) (close to 1) may enable us to see coherent structures in the outer region: that is, the large-scale structures can be visible by having a larger value of \( \alpha \).

As one of the visualization method of vortices in the flow yield, the vorticity is useful. However, vorticity includes rotation and shear, and it is necessary to extract the vortex deducting shear. Swirling strength is an effective method, which identifies only vortex core. The local velocity-gradient tensor represents the turbulent motion including shear and rotation, and its two-dimensional form can be written as following:

\[
D_{ij} = \frac{\partial u_i}{\partial x_j}, \tag{3}
\]

where \( i, j = 1, 2 \) are the streamwise and wall-normal directions, respectively. In this case, the tensor has a pair complex conjugate eigenvalue. The vortex core can be extracted by plotting iso-surface of \( \lambda_{ci} > 0 \).
Although the statistical relative streamwise velocity of suspending particles with respect to the air flow should be negative in the present measurement area, the relative velocity is found to be positive locally and instantaneously, as shown in Fig. 4(a). The broken line in the figure represents a demarcation between clusters of relatively high and low speed suspending particles. The main flow moves form left to right of the figure. Moreover a uniform momentum zone of low speed fluids can be seen in Fig. 4(b), which shows the Galilean decomposed velocity of the gas phase at the same instance with that of Fig. 4(a). In the similar visualization, but for the single-phase turbulent boundary layer, given by Adrian et al. (2000), a group of hairpin vortices with the same streamwise velocity was referred as the "hairpin vortex packet." They reported that each packet propagated at different velocities and called the demarcation...
between these different-speed packets as the \( \text{shear layer} \). As a proof of this, the spanwise vortices that correspond to heads of the hairpin vortices can be seen on the shear layer: see Fig. 4(c). Here, several vortex heads are denoted with circles of A, B and C. Comparison between Fig. 4(a) and 4(b) reveals that the region, in which the positive value of the relative velocity occurs, coincides well with that of the low momentum fluids. According to the conceptual model of structures in the turbulent boundary layer (Adrian et al., 2000), a large-scale low-momentum fluid region is induced by the hairpin packet. It can be conjectured that the local relative velocity \( (U_p - U_g) \) should be positive instantaneously by the characteristic turbulent structures such as the hairpin packet. This result indicates that the sand particles might be injected into the large-scale low-momentum zone (in the range of \( x/\delta \) from 0.4 to 0.7, \( y/\delta \) from 0 to 0.1) from high-momentum zone (in the range of \( x/\delta \) from 0.4 to 0.7 at \( y/\delta = 0.2 \)) through the shear layer.

According to the Adrian et al. (2000), the Q2 event (ejection), which is the moving-up motions of low-speed fluids from the wall, occurs under the hairpin head. In this respect, we investigated the relation between the present particle response time and the instantaneous wall-normal velocity. Figure 5(a) shows the averaged wall-normal velocity \( V \) and the turbulent intensity \( V_{rms} \) profiles of the sand particles in the gas-solid multiphase flow. It can be clearly found that the wall-normal velocity is almost zero, while the turbulent intensity is 0.25 \( U_0 \) at \( y/\delta = 0.2 \) (corresponding to the lower bound of the high-momentum zone in Fig. 4(b)). Therefore, \( V'/U_0 \) can range from 0.25 to 0.25 in instantaneous velocity distribution. Since the response time of the present particle is estimated as 0.02 second, we may estimate a typical length \( L \) of the traveling particles based on the product of the response time and the velocity magnitude. In this experiment, it can be conjectured that the sand particles near the shear layer (the broken line in the figure) should drive into low-momentum zone, since the length normalized by the boundary layer thickness \( (L/\delta) \) is about 0.33 at \( y/\delta = 0.2 \).

### 3-2 Vortex core

In turbulence, the velocity fluctuation correlates with the scale and structure of underlying vortices. Using this characteristic, Adrian (1994) developed the Linear Stochastic Estimation (LSE) analysis. This
method is effective to extract an arbitrary turbulent structure in the flow. A conditional averaged yield of a certain event \( E \) may be expressed by the following equation:

\[
\langle u(x') \rangle | E \rangle = L_{ij}(x')E_j(x).
\]  

(6)

Here, \( L_{ij} \) is the correlation tensor, which is determined by minimizing the mean square error between the estimate and the conditional average. Adrian (1994) demonstrated an extraction of the hairpin vortex around the Q2 events in isotropic turbulence by the LSE method. There is an arbitrary property for extracting structures, but this method can be applied to clear up hidden structure in turbulence. Moreover, we defined the shape of average swirling strength by the correlation coefficient,

\[
R_{ij} = \frac{\langle \hat{\lambda}_i(x)\hat{\lambda}_j(x') \rangle}{\langle \sigma_i(x)\sigma_j(x') \rangle}.
\]  

(7)

Here, \( \sigma \) represents the root-mean square of the given quantity and the operator \( < \cdot > \) denotes the ensemble average.

Figure 6 indicates contour of the correlation coefficient of swirling strength with respect to the basing point at the vortex center and also shows the velocity vectors, for single-phase and two-phase flows. In these figures, the velocity vector yields represents the conditional averaged velocity around the swirling strength as following:

\[
\langle u'(x') | \hat{\lambda}_i(x) \rangle \approx \frac{\langle \hat{\lambda}_i(x)u'_j(x') \rangle}{\langle \hat{\lambda}_i(x)\hat{\lambda}_j(x) \rangle} \hat{\lambda}_i(x).
\]  

(8)

Note that the rotational direction is clockwise. These velocity vectors are normalized by \( U_0 \). In the single-phase flow, turbulence motions are intense under the swirling strength, that is, the strong Q2 event is observed around the vortex core. This means that the swirling strength which is corresponding to the head of a hairpin vortex in the shear layer. As pointed out by Fig. 6(a), the scale of the head of hairpin vortex is comparable to those observed by Adrian et al (2000). In contrast, for the gas-solid multiphase flow, the vortex-core scale is undoubtedly reduced by the influence with the sand grains, see Fig. 6(b). That is to say, the growth of the hairpin vortex should be suppressed in the particle-laden flow, since its head seems shrink. Theodorsen (1952) proposed a hairpin-vortex model for turbulent
production and dissipation in the boundary layer, that was developed from the vorticity transport form of the Navier-Stokes equations. His model was available for describing an instantaneous field of near-wall turbulence dynamics. In that investigation, it can be conjectured that a hairpin vortex could not occur or develop without the influence of the wall as like in isotropic condition. Therefore we now speculate that the turbulence of the present two-phase flow would be isotropic rather than anisotropic wall turbulence due to the influence of the sand particles. Next section, we will discuss the degree of anisotropy in the turbulence quantitatively.

3-3 Anisotropy characteristic

The state of turbulence can be characterized by the amount of anisotropy that prevails in the flow, as proposed by Lumley & Newman (1997). The anisotropy of a flow can be derived from the Reynolds stresses $\tau_{ij} = -\rho u_i u_j$ by subtracting the isotropic part from $\tau_{ij}$ and normalizing with its trace. This leads to the non-dimensional anisotropy tensor as following:

$$b_{ij} = \left( \frac{u_i u_j - \frac{1}{3} q^2 \delta_{ij}}{q^2} \right) \left( q^2 = u_i u_i, \quad i, j = 1, 2, 3 \right), \quad (9)$$

with the Kronecker delta $\delta_{ij}$. Generally, the turbulence anisotropy is quantified by examining the anisotropy invariant map (AIM), as depicted in Fig. 7. However, we obtained only the two-dimensional...
data due to the limitation of the single-plane PIV. Therefore, we employ the expression as following:

\[ b_{ij} = \left( \frac{u'_iu'_j - \frac{1}{2} q^2 \delta_{ij}}{q^2} \right) \quad (q^2 = u'_iu'_i, \quad i, j = 1, 2) \quad (12) \]

This Reynolds-stress anisotropy tensor satisfies its characteristic polynomial, where its second invariant of \( b_{ij} \) are given by

\[ II = b_{ij}b_{ji}/2. \quad (10) \]

We evaluate only the second invariant II, so that we would investigate the degree of the anisotropy of the turbulent gas-solid multiphase flow. To contrast the single-phase flow with the gas-solid multiphase flow, we plot the profiles of II as a function of the dimensionless wall distance of outer scaling, as shown in Fig. 8. The second invariant II for the multiphase flow was drastically decreased compared to single-phase flow in a limited area of 0.1 \( \delta_0/\delta_0.6 \). It implies that the turbulence shifts to isotropic by feeding sand particles. Therefore, it can be conjectured that the coherent vortex structure in the multiphase flow could not develop as like in the single-phase flow, as illustrated in Fig. 9. Thus, the head of the hairpin vortex shrunk in the gas-solid multiphase flow, see Fig. 6.

4. Conclusion

We investigated the gas-solid multiphase turbulent boundary layer accompanied by wind-blown sand, comparing with the single-phase (air) flow without sand grain. The velocities of the air and sand grains were measured simultaneously using a PIV system:

1. The local relative velocity \((U_\theta, U_\phi)\) can be positive instantaneously by the characteristic turbulent structures such as the hairpin packet. Moreover, the sand particles are injected into the large-scale low-momentum zone from high-momentum zone.
2. The size of the hairpin-vortex head is reduced by the influence with the sand grains, indicating that the growth of the hairpin vortex should be suppressed in the present multiphase flow.
3. The second invariant II on the Reynolds-stress anisotropy tensor for the multiphase flow was drastically decreased compared to that for the single-phase flow. It implies that the turbulence was shifted to isotropic condition by the influence of suspending sand particles. Therefore, the coherent vortex structure in the multiphase flow could not develop as like in the single-phase flow.

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