Movement of Small Spheres in a Plane Mixing Layer*

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Experiments were performed in a two-phase, two free-stream plane mixing layer to study the behavior of heavy spheres in an intermittent shear flow. Particles with three different diameters were employed in these experiments. Comparisons between data on streamwise and transverse components of particle and gas velocities are presented. These data, as well as flow visualization images, suggest that the ratio of the particle time constant τ_p and the large-scale eddy turnover time plays an important role in the cross-stream transport of a heavy dispersed phase. When the τ_p/τ was approximately on the order of 1, heavy particles began to move with gas flow. There exists movement of heavy spheres back toward the particle feed stream. The transverse component of large-particle turbulent velocity, v_p' , in the interior of the layer was observed to be significantly smaller than the corresponding streamwise component, $u_p' \langle v'^2 \rangle / \langle u'^2 \rangle$ of the particle reaches an asymptotic value, 0.2, around the high-speed side of the mixing layer.

Key Words: Turbulence, Multiphase Flow, Plane Mixing Layer, Large-Scale Vortex, Coherent Structures, Flow Visualization, Particle Dispersion, LDV

1. Introduction

Analyses of the behavior of many multiphase commercial and geophysical flows of current interest may be facilitated by information on particle transport in turbulent shear regions. While the number density of this second phase is a scalar, as are temperature and chemical species concentrations, its dispersion in space may be complicated further by non-negligible inertial effects or forces arising from interactions between particles, with external fields or local fluid velocity gradients, or due to particle rotation.

In many commercial combustor designs, pulverized coal and preheated combustion air are injected into the furnace in separate streams. In these multi-

phase diffusion flames, mixing of the fuel and oxidizer, and ignition of the fuel particles, take place in a free shear layer. In the present investigation, the two-feed stream, plane mixing layer configuration was selected to simulate the conditions in the ignition zones of the combustor. This paper reports the results from the first phase of the experimental program, in which particle transport in a nonreacting plane mixing layer was investigated.

Over the past decade, with the improvement of the measurement technique of laser Doppler velocimetry (LDV), a number of studies of particle transport in turbulent flow have been conducted in the two-feedstream plane mixing layer^{(1)~(5)}. Yuu, et al.⁽⁶⁾ measured and calculated number densities of particles in a round jet mixing layer, and they concluded that the Stokes number plays an important role in the transport mechanism of particles. The critical role played by large vortices in multiphase mixing phenomena has been elucidated by the computer simulations of Chen and Chung⁽⁷⁾ and Chung and Troutt⁽⁸⁾. They concluded that the Stokes number estimated from a large-scale turnover time described particle motion better than did the integral scale. Modarres et

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al.⁽¹⁾ and Hishida et al.⁽²⁾ measured interaction between particles and gas phase in the share flow, and found that the presence of particles reduced the velocity fluctuations of the gas phase as the particle mass loading increased.

Before investigating particle movement in share flow, the present authors measured velocity statistics of a plane mixing layer with a streamwise pressure gradient^{(9),(10)}. The pressure gradient influenced vortex interactions through induced changes in the local values of the free-stream velocities. Also the relationship between the transverse velocity component of heavy spheres and the scale of the spanwise vortices in the mixing layer⁽³⁾ was demonstrated.

The main purpose of this paper is to present a comprehensive set of data for plane mixing layer with dilute suspension.

2. Nomenclature

- a_i : curve-fit coefficient of similarity velocity profile
 C : particle mass flow rate/gas mass flow rate
 d_p : particle diameter
 r : free-stream inlet velocity ratio: $\langle U_l \rangle / \langle U_h \rangle$
 St : Stokes number: τ_p / τ
 u' : r.m.s. fluctuating component of streamwise velocity

- $\langle U \rangle$: mean streamwise velocity
 v' : r.m.s. fluctuating component of transverse velocity
 $\langle V \rangle$: mean transverse velocity
 X : streamwise coordinate; $X=0$ at the trailing edge of the splitter plate
 Y : transverse coordinate
 Y_0 : center of the mixing layer; location where $\langle U \rangle = \langle U_2 \rangle + \Delta U / 2$

Greek letters

- δ : 1% thickness (layer thickness defined as the distance between points where $\langle U \rangle = \langle U_2 \rangle + 0.01 \Delta U$ and $\langle U \rangle = \langle U_2 \rangle + 0.99 \Delta U$)

- ΔU : difference of mean velocities of the two free streams

- η : similarity variable $= (Y - Y_0) / \theta$

- θ : momentum thickness

$$= \Delta U^{-2} \int_{-\infty}^{+\infty} [(\langle U_1 \rangle - \langle U \rangle)(\langle U \rangle - \langle U_2 \rangle)] dY$$

- ρ : density

- σ : solid volume fraction $= C(\rho_a / \rho_p)$

- τ : large-scale vortex turnover time $= \delta / \Delta U$

- τ_p : particle relaxation time constant $= \rho_p d_p^2 / 18 \nu$

- ν : kinetic viscosity

Subscripts

- h : high-speed free-stream inlet

- l : low-speed free-stream inlet

- p : particle

- 1: high-speed free stream

- 2: low-speed free stream

3. Experimental Details

3.1 Experimental facility

A schematic diagram of the facility is shown in Fig. 1. Experiments were conducted in a vertically oriented, continuous flow, induced-draft wind tunnel. Filtered room air is drawn into two separate, constant-area, flow-quieting plenum sections and is accelerated through a pair of two-dimensional nozzles. Contraction ratios of 6:1 (high-speed side) and 3:1 (low-speed side) were used in this study. The exit to the contractions measured 90 mm × 90 mm (30 mm × 90 mm, and 60 mm × 90 mm for the high-speed and low-speed nozzles, respectively). Nozzle contours were matched a cubic equation determined by the method outlined by Morel⁽¹¹⁾.

The two initially separate gas streams meet at the trailing knife edge (3.5 deg enclosed angle) of the splitter plate. A mixing layer develops in a test section comprising a rectangular channel formed between two parallel windows (separated by 90 mm) and a pair of pivoting, straight interior sidewalls. The test section extends 500 mm beyond the edge of the splitter plate.

The pitch of the sidewalls, i.e., the separation between them as a function of distance downstream, can be adjusted to vary the mean streamwise pressure gradient. Optical access is provided from all four sides of the test section. Gases exiting the test section are decelerated in a low-divergence-angle diffuser section. Rows of pressure taps along the centerline of the side walls connected to an air scanner valve and piezoelectric pressure transducer unit provide information on the streamwise variation of static pressure in the test section. Pressure taps with 0.4 mm diameter were designed following the recommendations of

Fig. 1 Schematic diagram of the test section

Franklin and Wallace⁽¹²⁾. Gas temperatures were monitored using copper-constantan thermocouples mounted in the inlet of the facility.

3.2 Measurement techniques

Velocity measurements were performed using single (Model 0251, Kanomax) and crossed hot-wire (Model 0252, Kanomax) anemometry and LDV. The gold-plated hot-wire probes had tungsten sensing elements approximately 5 μm in diameter with 1 mm active lengths. Analog output signals from the constant-temperature anemometer units (Model 1011, Kanomax) were amplified and low-pass filtered before being interfaced into a personal computer via a 12-bit A/D converter board (ADX-98 E, Canopus Electronics). The cutoff frequency of the low-pass filter was 4 kHz with 24 dB/Oct., and sampling frequency was 10 kHz. Gas velocity data were generated from time histories comprising continuous strings of 8192 data points. A custom-built, one-dimensional (Y) traversing unit based on an optical translation stage was used to move the hot-wire probes in the test section. Using both L-shape (90°) and straight hot-wire probe supports, data could be obtained at 8 streamwise locations in the flow between the trailing edge of the splitter plate and $X=370$ mm.

A dual-beam, differential scatter (real fringe) LDV system was employed to perform measurements of particle (and gas) velocities. Near-forward scattered light (20 degrees off-axis) from a 15-mW He-Ne laser was focused on a photomultiplier. Output from this detector was analyzed using a counter processor unit (Model 1071, Kanomax) coupled to a personal computer for data storage and reduction. Frequency shifting eliminated the velocity ambiguity and reduced fringe biasing effects. The typical shift frequency was 2 MHz. The optical-grade windows of the facility test section provided visual access to most of the flow field for LDV measurements of particle velocities. Since the entire wind tunnel was mounted on a two-dimensional (X-Y) traverse, the mixing region could be moved relative to the fixed LDV optical sample volume. Alternative measurement by rotating LDV optics provided streamwise velocity, U , and transverse velocity, V . The difference between the measurement direction of LDV and the axis of the test section was less than ± 0.1 degree, and hence the measurement accuracy of velocity fluctuation was less than $\pm 1\%$.

3.3 Measurement conditions

Velocities in the test section were controlled by means of a bypass valve located upstream of the induction fan, and by varying the flow resistance at the inlet to the two quieting plenums. For the present experiments, gas velocities were set at the conditions

of $r=0.377$ with $\langle U_h \rangle = 10.87$ m/s. Velocity ratios in all tests fell within $\pm 1.5\%$ of the values stated above.

At the inlet to the test section, profiles of streamwise mean velocity, $\langle U \rangle$, outside the wall boundary layer were uniform to within 1%, and streamwise turbulence intensities were less than 0.5%. Mean velocity data taken in both high- and low-speed side boundary layers of the splitter plate were in good agreement with the Blasius laminar boundary layer profile. Momentum thicknesses on the high- and low-speed sides of the splitter plate were calculated to be 0.202 mm and 0.267 mm, respectively.

Characteristics of the particles studied in these experiments are given in Table 2. Water mist and two nonoverlapping size distributions of glass spheres were used to seed the low-speed fluid. Water mist was generated by dry ice and temperature-controlled distilled water. A laser Fraunhofer diffraction technique was used to obtain in situ estimates of the water droplet size distribution. This instrument (Malvern Model 2600 particle sizer) also was employed to check estimates of the glass sphere size distribution obtained by means of a projection microscope technique. The ensemble mean diameters of these spheres were 2.6, 31.6 and 50.8 μm , with standard deviations of 0.99, 2.48 and 1.89 μm , respectively. Particle relaxation time constants, τ_p , were 3.7×10^{-2} ms for the 2 μm particle, and 7.31 ms and 18.8 ms for the 30- and 50- μm particles, respectively. Speed-controlled turntable particle feeders (MFEV-1, Sangyo-dengyo) were employed to provide a relatively constant supply of glass spheres. Compressed nitrogen from a bank of cylinders was fed into the particle feeder, where mixed with the falling stream of particles. This mixture was introduced to the low-speed side of the plenum section. Particle carrier gas flow rate was set at approximately

Table 1 Particle Information

	2 μm mist	30 μm glass	50 μm glass
ρ_p (kg/m ³)	996	2490	2490
d_p (mm)	2.6	31.6	50.8
σ (mm)	0.99	2.48	1.89
τ_p (ms)	3.7×10^{-2}	7.31	18.8
v_p (cm/s)	3.6×10^{-2}	6.29	19.1

Table 2 Curve-fit coefficients

	124 < X < 130 mm	244 < X < 370 mm
a_0	-1.32337×10^{-2}	6.63603×10^{-3}
a_1	-4.02046×10^{-1}	-3.04364×10^{-1}
a_2	2.67801×10^{-2}	-2.53705×10^{-2}
a_3	-1.77779×10^{-2}	-3.02889×10^{-2}
a_4	-1.22660×10^{-3}	1.71827×10^{-3}
a_5	3.57165×10^{-4}	-4.07382×10^{-4}
a_6	1.49398×10^{-5}	-5.73097×10^{-5}

$1.1 \times 10^{-3} \text{ Nm}^3/\text{s}$, which represents about 5.3 % of the total gas flow rate at the exit to low-speed contraction.

In the flow visualization experiments, the solid density ratio, C , did not exceed 0.028; during the velocity measurements, C was always less than one-half of this value. Shih and Lumley⁽¹³⁾ have suggested that the effect of the dispersed phase on the motion of the fluid can be neglected if the solid density ratio is small, and that the particles are noninteracting if the solid volume fraction, σ , is less than 0.003. For $C = 0.028$, σ is approximately 10^{-5} . It was assumed, therefore, that particle interaction effects were not significant and that gas velocities in the multiphase mixing layer remained unchanged from those measured in the single-phase experiments with the hot-wire anemometer. As the relaxation time constant of $2 \mu\text{m}$ particles is small enough to trace the turbulent velocity of the gas phase, $2 \mu\text{m}$ particles were also used as the tracer of flow visualization and seed particle of LDV measurement at $X = 60 \text{ mm}$.

4. Results and Discussion

4.1 Flow visualization

Typical flow visualization images of the $30\text{-}\mu\text{m}$ -particle mixing layer are presented in Fig. 2. The time period of the stroboscope was less than $10 \mu\text{s}$. In the picture on the left side of Fig. 2, water mist of $2 \mu\text{m}$ particles was injected into the high-speed stream.

Fig. 2 Flow visualization images of the two-phase mixing layer. Flow proceeds from top to bottom with high-speed stream on the left

Since the timeconstant of the liquid droplets was short ($37 \mu\text{s}$) relative to the estimated time scale of the flow, it is assumed that the droplets faithfully track the motion of the gas phase. The two photographs, taken sequentially under identical flow conditions and depicting the same region in space, provide a comparison of the instantaneous spatial distributions of the gas and condensed phases. We observe that, in the near field (e.g., $X < 50 \text{ mm}$), the heavy, solid particles appear to slip against the flow, their vertical trajectories slicing through the row of developing Kelvin-Helmholtz vortices. Further downstream, as the scale of the mixing layer increases and vortex interactions commence, the organized motion of particle-laden fluid forms, stretching across the layer. Flow visualization images suggest that motion induced by the large vortex structures play an important role in the spatial dispersion of solid particles. Similar results were obtained with the $50 \mu\text{m}$ particles.

4.2 Velocity profile of gas

In Fig. 3, normalized streamwise mean velocity, $[\langle U \rangle - \langle U_2 \rangle] / \Delta U$, is plotted against the similarity variable, η , defined as

$$\eta = (Y - Y_0) / \theta, \quad (2)$$

where Y_0 is the location where $\langle U \rangle = \langle U_2 \rangle + \Delta U / 2$, and θ is the momentum thickness of the mixing layer defined as⁽¹⁴⁾

$$\theta = \Delta U^{-2} \int_{-\infty}^{\infty} (\langle U_1 \rangle - \langle U \rangle)(\langle U \rangle - \langle U_2 \rangle) dy. \quad (3)$$

Applying these normalizations to the plane mixing layer with a streamwise pressure gradient yielded a similarity velocity profile⁽¹⁰⁾, which suggests that a moderate streamwise pressure gradient does not alter normalized $\langle U \rangle$ velocity distributions if the length and velocity scales are chosen to be θ and ΔU .

The profiles of streamwise velocity in the upstream region ($124 < X < 130 \text{ mm}$) are slightly different from the profiles of downstream region (244

Fig. 3 Normalized mean streamwise velocity profiles of the gas phase at $X = 124 \text{ mm}$ and 370 mm

$\langle X \rangle < 377$ mm). The hyperbolic tangent velocity profile of the typical mixing layer was recognized in the upstream region. The velocity profile of the downstream mixing layer displays double inflection points with small width of the normalized mixing layer. Double inflection point distributions of mean concentrations of conserved scalars in the plane mixing layers have been observed previously⁽¹⁵⁾.

Due to the ease of using the momentum thickness and gas velocity, least-squares-curve fits of the function

$$(\langle U \rangle - \langle U_2 \rangle) / \Delta U = 0.5(1 - \tanh(a_0 + a_1\eta + a_2\eta^2 + a_3\eta^3 + \dots + a_n\eta^n)) \quad (4)$$

were applied to the two velocity profiles in Fig. 3. Coefficients of these curve fits are listed in Table 2. The estimated error of Eq. (4) to the data in Fig. 3 was less than 0.7 %, which is less than the measurement accuracy. The relative velocities of particles and gas were obtained from measured values of $\langle U_p \rangle$ and calculated values of gas velocity.

Streamwise and transverse r.m.s. turbulent veloc-

Fig. 4 Nondimensionalized streamwise r.m.s. turbulent velocity fluctuations of the gas at $X=124$ mm and 370 mm

Fig. 5 Nondimensionalized transverse r.m.s. turbulent velocity fluctuations of the gas at $X=130$ mm and 370 mm

ity fluctuations, u' and v' , are shown in Figs. 4 and 5. The u' profiles of six locations of the X axis were determined by single- and X-wire anemometry, and v' was measured by X-wire anemometry. The data of u' and v' were nondimensionalized using ΔU and plotted as functions of η . From $\langle U \rangle$ profiles shown in Fig. 3, the turbulence structure of the mixing layer attains a self-preserving condition beyond $X=130$ mm. The maximum values of u' profiles were almost the same under these measurement conditions; the turbulent intensity of the border of the mixing layer was decreased downstream. Transverse turbulent intensity was decreased in the mixing layer and free stream. The maximum value of v' decreased to 60 % of the peak value at $X=130$ mm.

Mehta et al.⁽¹⁶⁾ have proposed that a decrease of v' may be related to the development of three-dimensionality in the mixing layer. By forcing the flow, they claimed to be able to maintain a high degree of two-dimensionality and to have observed values of v' approximately two times larger than those existing in the unforced mixing layer. Strong intensity of v' was also recognized in these experiments. A fully developed mixing layer was recognized between 130 and 250 mm. The transition of turbulence structure is related closely to the change of streamwise velocity profiles at $X=130$ mm.

4.3 Particle streamwise velocity

Ensemble mean streamwise velocity profiles of 30 μ m-diameter spheres are shown in Fig. 6. Particles were fed into the low-speed fluid. These data were acquired with the LDV at $X=60$, 130, 250, and 300 mm. Values of $\langle U_p \rangle$ were normalized using values of the low-speed free-stream gas mean velocity, $\langle U_2 \rangle$, and the velocity difference, ΔU , and plotted against the similarity variable η . The dashed lines are curve fits to gas velocity data taken at $X=250$ and 370 mm (Fig. 3).

Fig. 6 Normalized particle mean streamwise velocity profiles at $X=60$ mm and 300 mm for $d_p=30 \mu$ m

The η -locations of the data points on the extreme left of the four curves correspond to the effective detection limits; beyond these locations, the LDV data were prohibitively slow. Particles were dispersed from low-speed fluid to the high-speed side of the mixing layer. Full dispersion of particles was obtained at $X=250$ mm. Particle mean streamwise velocity in the mixing region lags behind gas velocities. This effect is particularly noticeable near the low-speed edge of the layer. At $X=60$ mm, $\langle U_p \rangle$ deviates only slightly from the low-speed free-stream velocity for values of η greater than about 1.5.

The difference in mean velocities of two phases, ΔU^* , defined as

$$\Delta U^* = [\langle U \rangle - \langle U_p \rangle], \quad (5)$$

is nondimensionalized using ΔU and presented in Fig. 7. Gas mean velocities were estimated using least-squares-curve-fitted velocity profiles of Eq. (4). Negative values of $\Delta U^*/\Delta U$ observed near the low-speed border of the mixing layer and in the free stream result from the finite terminal velocity of the solid spheres relative to the gas phase. With the growth of the mixing layer, decrease of ΔU^* was well recognized on the high-speed side of the mixing layer. At $X=300$ mm, good agreement between particle and gas mean velocities are observed near the high-speed edge of the layer. On the other hand, distributions of ΔU^* show almost the same values for η greater than about 1. Particles do not follow the gas flow in these regions. It would be informative to conduct measurements at larger values of X to determine whether any asymptotic profile of $\Delta U^*/\Delta U$ exists; however, interactions between sidewall boundary layers and the mixing region in the present facility may complicate interpretation of such results. Differences between mean velocities of the gas and solid phases were consistently larger in the case of the 50- μ m-diameter beads.

Fig. 7 Difference of particle and gas streamwise velocities at $X=60$ mm and 300 mm for $d_p=30 \mu\text{m}$

R.m.s. fluctuations of particle streamwise velocity, u'_p , are shown in Fig. 8. These data were obtained at $X=60, 130, 250$ mm, with 30- μ m-diameter particles in the low-speed feed stream. While the r.m.s. profiles of gas velocity attain an equilibrium distribution, there are differences in the u'_p data obtained at the three values of X . At $X=130$ and 250 mm, the magnitudes of peak values of u'_p agree well with the gas turbulence data.

As shown in flow visualization images, the mixing layer consists of coherent vortices. When particles pass through an organized vortex, gas velocities change from low speed to high-speed. However, particle inertia limits the response to high-frequency velocity fluctuations. For scalars such as chemical species, the late-limiting step in the mixing process is characterized by large-scale eddy turnover time, $\tau = \delta/\Delta U^{(15),(17)}$. From such a viewpoint, the Stokes number, defined as the ratio of the particle relaxation time constant to the large vortex turnover time, is a key parameter of particle response in the mixing layer. The critical role played by large vortices in multiphase mixing phenomena has been elucidated by the computer simulations of Chen and Chung⁽⁷⁾ and Chung and Trout⁽⁸⁾. They concluded that particle dispersion in the shear layer depends strongly on the value of the Stokes number. Transverse dispersion of particles increases as the Stokes number decreases to 1. Particles are flung outside by the centrifugal force of the vortices in the mixing layer and therefore are dispersed at a higher rate than the fluid.

Stokes numbers, $\tau_p/\tau = 3.7, 2.1, 1.2$ and 1.02 at $X=60, 130, 250$ and 300 mm, respectively, were employed for 30 μ m glass particles. Particles were not accelerated on the low-speed side of the mixing layer at $X=60$ mm (Fig. 6), and the magnitude peak value of u'_p became the same as maximum value of u' at $X=130$

Fig. 8 Nondimensionalized particle streamwise turbulent velocities at $X=60$ mm and 250 mm for $d_p=30 \mu\text{m}$

mm (Fig. 8). It can be argued that, as τ_p/τ approached to 1, the dispersed phase began to follow the motion of the surrounding gas between $X=60$ and 130 mm.

4.4 Particle transverse velocity

In multiphase combustion applications, we are concerned with cross-stream transport of the dispersed phase, since the relative transverse motion of gas and particles determines the extent of interpenetration of fuel and heated oxidizer and, hence, strongly influences ignition and combustion characteristics of a burner. In Fig. 9, probability density functions of V_p are presented for $d_p=30\text{ }\mu\text{m}$ at $X=130\text{ mm}$. Proceed-

Fig. 9 Probability density functions (pdfs) of the transverse velocity component, V_p , for $30\text{ }\mu\text{m}$ glass spheres at $X=130\text{ mm}$

Fig. 10 Contour map of the probability density functions of the transverse velocity component at $X=130\text{ mm}$ for gas and $30\text{ }\mu\text{m}$ particles

ing across the layer from the low-speed free stream ($\eta>0$), we note that probability densities of positive V_p (movement toward the low-speed free stream) first increase, then decay to near zero from the center of the mixing layer.

Figure 10 presents a contour map of probability density functions of the V component of gas and $30\text{ }\mu\text{m}$ particles at $X=130\text{ mm}$. Measured results are divided into three groups: free stream ($\eta>6$), border of low-speed free stream ($4<\eta<6$), and the mixing layer ($-4<\eta<4$). Those regions are labeled as III, II, and I, respectively. The probability density functions of gas and particles are equal in region III. Particles follow the gas fluid. In region II, gas fluid receives potential fluctuations through pressure fluctuation of the mixing layer. If particles follow the gas phase, the probability density function of particles should spread to equally positive and negative values of V . The probability density function of particles that have large positive value of V only increases. It is considered that particles entering the low speed fluid did not originally remain in region II. Those particles were flung outside of the mixing layer from region I by centrifugal force of the organized vortex. Large negative V , particle dispersion toward the high-speed flow, was obtained in region I.

Figure 11 shows the relationship between $\langle V_p \rangle$ and particle size at $X=130\text{ mm}$. The diameters of particles were $2, 30, 50\text{ }\mu\text{m}$, and the dashed line indicates transverse mean velocity of gas phase. Positive values of $\langle V \rangle$ show momentum transfer from the high-speed fluid to the low-speed fluid. The $2\text{-}\mu\text{m}$ -diameter droplets seeded into the low-speed stream followed the flow well, and the values of $\langle V_p \rangle$ decreased continuously across the layer. For the 30- and $50\text{-}\mu\text{m}$ -diameter glass spheres, profiles of $\langle V_p \rangle$ typically rise to a maximum value before decreasing sharply. For $\eta<-0.7$, i.e., on the slightly high-speed side of the

Fig. 11 Nondimensionalized mean transverse velocity profiles at $X=130\text{ mm}$ for three particle sizes

layer, good agreement was observed between data obtained for the two particle sizes.

Figure 12 presents a comparison of $\langle V_p \rangle / \Delta U$ of 30- and 50- μm glass spheres at $X=130\text{ mm}$ and 250 mm. The dashed line and dot-dashed line represent $\langle V_p \rangle$ of 30- and 50- μm particles at $X=130\text{ mm}$, respectively. The peak values of $\langle V_p \rangle$ for 30 μm particles occur in the same level between $X=130\text{ mm}$ and 250 mm. In the case of 50 μm particles, the maximum of $\langle V_p \rangle$ increases downstream. Similar profiles of $\langle V_p \rangle$ were recognized on the high-speed side of the mixing layer where $\eta < -0.7$. And the range of the particle size in these experiments does not affect the transverse velocity profiles. In the previous work⁽³⁾, similar velocity could not be obtained profile by the accuracy of measurement technique. Because the order of $\langle V \rangle$ is approximately 2% of $\langle U \rangle$, minimization of error requires good agreement between measurement direction and facility axis. The coordinate error of about ± 0.1 degree gave $\pm 5\%$ accuracy of the $\langle V \rangle$ measurement in the present work.

Fig. 12 Streamwise evolution of nondimensionalized transverse velocity profiles of glass spheres

Fig. 13 Nondimensionalized r.m.s. transverse velocity fluctuations for three particle sizes at $X=130\text{ mm}$. Dashed line is a curve fit to data obtained from hot-wire anemometry

Influences of particle diameter distinctly appear on the distribution of fluctuation velocity, u'_p . Figure 13 shows the v'_p profiles at $X=130\text{ mm}$. Particle diameters were 2, 30, and 50 μm . The dashed line is the distribution of u' . Profiles of $v'_p / \Delta U$ for the heavy solid spheres quickly approach asymptotic values near the outer edge of the particle mixing region. The magnitudes of the v'_p of the two sizes of glass beads are comparable in the free stream, and, at this value of X , are still smaller than those recorded for 2 μm particles. The peak values of v'_p decrease with increasing particle mass in the mixing layer.

In Fig. 14, $u'_p / \Delta U$ and $v'_p / \Delta U$ are presented for the two size distributions of glass beads at $X=130\text{ mm}$. Also included is a curve fit to the streamwise turbulence values of the gas phase at this location. Peak values of u'_p are more than twice the corresponding values of v'_p , implying that the streamwise component of turbulent kinetic energy of heavy spheres can be more than four times the transverse component. Maximum values of u'_p are comparable to those of the gas: particle mass here again appears to exercise some effect on measured u' . At the border of the low-speed side of the mixing layer, $4 < \eta < 6$, the magnitude of v'_p is higher than that of u'_p . Comparable values of u'_p and v'_p are recognized in the free-stream region.

In order to elucidate the relationship between the turbulence structure and velocity fluctuation of particles, the ratio of the squared value of transverse velocity fluctuation and streamwise velocity fluctuation, $\langle v'^2 \rangle / \langle u'^2 \rangle$ is examined. The distributions of $\langle v'^2 \rangle / \langle u'^2 \rangle$ of two streamwise locations, $X=130$ and 50 mm, are shown in Figs. 15 and 16, respectively. Three types of particles were fed into the low-speed stream. The $\langle v'^2 \rangle / \langle u'^2 \rangle$ values of the gas phase were calculated from u' and v' data. In the case of 2 μm

Fig. 14 Comparison of glass particle streamwise and transverse velocity fluctuations at $X=130\text{ mm}$. Dashed curve is fit to gas streamwise velocity fluctuations

particles, proceeding across the layer from the low-speed free stream, we note that the minimum value of $\langle v'^2 \rangle / \langle u'^2 \rangle$ is in the center of the mixing layer. The differences between 2 μm particles and the gas phase indicate a bias error caused by noncontainment of particles in high-speed streams. At $X=130\text{ mm}$, $\langle v'^2 \rangle / \langle u'^2 \rangle$ has the minimum value of about 1. As

Fig. 15 Turbulence structure parameter $\langle v'^2 \rangle / \langle u'^2 \rangle$ at $X=130\text{ mm}$ for three particle sizes

Fig. 16 Turbulence structure parameter $\langle v'^2 \rangle / \langle u'^2 \rangle$ at $X=250\text{ mm}$ for three particle sizes

Fig. 17 Streamwise evolution of turbulence parameter $\langle v'^2 \rangle / \langle u'^2 \rangle$ for $d_p=50\text{ }\mu\text{m}$

three-dimensionality in the mixing layer develops, this ratio becomes 0.5. Nonisotropic turbulence structure of the plane mixing layer is evident in the minimum value of $\langle v'^2 \rangle / \langle u'^2 \rangle$. For the case of 30- and 50- μm particles, $\langle v'^2 \rangle / \langle u'^2 \rangle$ has an asymptotic value of 0.2 on the high-speed side of the mixing layer. At the low-speed side of the mixing layer, $\langle v'^2 \rangle / \langle u'^2 \rangle$ of two large heavy particles is comparable to the $\langle v'^2 \rangle / \langle u'^2 \rangle$ of the gas phase.

Figure 17 shows the $\langle v'^2 \rangle / \langle u'^2 \rangle$ profiles of 50 μm particles at three streamwise locations, $X=60, 130, 250\text{ mm}$. The asymptotic value of $\langle v'^2 \rangle / \langle u'^2 \rangle=0.2$ is independent of streamwise location in the flow for η less than about 0. As shown in Fig. 12, at $\eta < 0$, the transverse velocity of $\langle V_p \rangle$ exhibits a similar profile. Maximum values of $\langle v'^2 \rangle / \langle u'^2 \rangle$ occur presented in the low-speed side of the layer. At $X=60\text{ mm}$, the peak is located in the mixing layer, and going downstream, peak location is shifted to the low-speed free stream.

The maximum value of gas $\langle v'^2 \rangle / \langle u'^2 \rangle$ suggests that the isotropic turbulence is produced by the potential fluctuation translated from the mixing layer. At the low-speed side of the mixing layer, $\langle v'^2 \rangle / \langle u'^2 \rangle$ of large particles has a maximum value (Fig. 17), and particles were dispersed into the low-speed free stream (Fig. 10). The peak value of $\langle v'^2 \rangle / \langle u'^2 \rangle$ of particles suggests the existence of particles that are flung into the low-speed free stream by the centrifugal force of the organized vortices.

Particle velocity fluctuation is strongly dependent on the response ability to the gas flow. It is considered that $\langle u'^2 \rangle$ and $\langle v'^2 \rangle$ of particles are closely related to the frequency distribution of turbulence energy. Particle response to the gas flow is well described by Stokes' law. Particle inertia limits the frequency response of the 30- and 50- μm glass spheres to fluctuations below about 200 Hz. According to the spectra of U and $V^{(10)}$, near the middle of the mixing layer, the energy of the transverse velocity fluctuations is well below that calculated for the streamwise fluctuations in the band below, e.g., 300 Hz. The nonisotropic turbulence agrees well with the value of $\langle v'^2 \rangle / \langle u'^2 \rangle$ of about 0.2 on the high-speed side of the measurement points.

5. Conclusions

Experiments were performed in a two-phase, plane mixing layer. Gas and particle velocity data and flow visualization images suggest the following.

(1) The Stokes number, a ratio of the characteristic time constant of large scale vortices and the particle relaxation time constant, is a key parameter describing the particle movement in the mixing layer. As the Stokes number decreases to 1, particle orga-

nized motion induced by large vortex structures are recognized and particles follow the gas velocity.

(2) When particles begin to move with gas velocity, particles are moved back into the particle feed stream by the centrifugal force of the large-scale vortex.

(3) Transverse mean velocity of large heavy particles presents a similarity velocity profile on the high-speed side of the mixing layer. The range of the particle size under these experimental conditions does not affect the transverse velocity profiles.

(4) The ratio of the squared value of the transverse component of 30- and 50- μm particle turbulent velocity and the streamwise component of turbulent velocity, $\langle v'^2 \rangle / \langle u'^2 \rangle$, was insensitive to particle size and measurement location on the high-speed side of the mixing layer. The asymptotic value of $\langle v'^2 \rangle / \langle u'^2 \rangle$ of particles was 0.2 in these experiments, which is approximately 1/2 the value of the gas phase.

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