Turbulence Modification and Interface Deformation in Turbulent Liquid Plane Couette Flow with an Immiscible Droplet*

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Experiments have been conducted for turbulent liquid plane Couette flow with an immiscible droplet in order to understand interfacial deformation and the modification of the structure of shear-dominant turbulence due to immiscible droplets in turbulent dispersed liquid-liquid two-phase flows. Flow visualisation, an image-capturing method and image processing have been used for the measurement of the fluctuating velocity field. Mean velocity, turbulence intensities, turbulent kinetic energy and mean vorticity have been estimated from the velocity field. The present work clarifies that the turbulence energy and the vorticity increase at the confluence of the axial flow and the flow along the interface in the direction perpendicular to the moving wall, and that they decrease in the stagnation region of the main flow near the interface.

Key Words : Multiphase Flow, Turbulence, Vorticity, Liquid Couette Flow, Particle-tracking-velocimetry Method, Immiscible Droplet

1. Introduction

Interest has been growing recently in the turbulence modification due to the dispersed-phase in dispersed multiphase turbulent flows. Various models have been proposed to explain the turbulence modification^{(1),(2)} for the case where the dispersed phase consists of fine solid particles smaller than Kolmogorov micro scale, η_K , in particular. None of them, however, is directly available for the understanding of turbulent liquid flows with immiscible droplets. This is partly because the interaction between the deforming droplets and continuous-phase turbulence has not yet been made clear and partly because the dimension of the droplets is much larger than η_K in many practi-

cal applications of the dispersed two-phase flows such as direct-contact heat exchangers, chemical or biochemical reactors, oil separators and so on.

We demonstrated in our recent direct numerical simulations for turbulent liquid channel flow with similar immiscible droplets that the droplet deformation depends on the structure of the near interface turbulence⁽³⁾. In Ref.(3), the instantaneous turbulence field was classified into eddy-dominant zone, shear-dominant zone, convergence-dominant zone and streaming zone. However, it is not easy to understand the phase interaction because the size and the location of each zone change with time in actual turbulent flow field. Therefore, we have focused on an immiscible droplet and the near-droplet velocity fluctuation in a turbulent flow in which a specific structure of turbulence is always predominant.

In the present experimental study, we select a turbulent plane Couette flow as the flow having a shear-dominant structure of turbulence. In a plane Couette single-phase flow, the bulk velocity can be zero and the linear shear is obtained in the central core region. According to the results of direct numerical simulations (DNSs) by Lee and Kim⁽⁴⁾, Bech et

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al.⁽⁵⁾, and Hagiwara et al.⁽⁶⁾, their uniform distributions of turbulence intensity are realised in the core region. These features are very useful for examining obtained results. Flow visualization and image processing are well-accepted methods for the measurements of droplet deformation and near-interface velocity fluctuation. Therefore, we carry out flow visualisation and image processing for the turbulent Couette flow with an immiscible droplet.

2. Nomenclature

- f : lens aperture
 h : half of the distance between moving walls
 k : turbulent kinetic energy ($=1/2[\overline{u^2} + \overline{v^2} + \overline{w^2}]$)
 Re : Reynolds number ($=U_w h/\nu$)
 r : ratio of two turbulence intensities
 U : axial velocity
 U_w : speed of moving wall
 $\overline{U}$: axial mean velocity
 u : fluctuating component of axial velocity
 $\sqrt{\overline{u^2}}$: turbulence intensity in the x direction
 V : velocity in the y direction
 $\overline{V}$: mean velocity in the y direction
 v : fluctuating component of velocity in the y direction
 $\sqrt{\overline{v^2}}$: turbulence intensity in the y direction
 w : fluctuating component of velocity in the transverse vertical direction
 $\sqrt{\overline{w^2}}$: turbulence intensity in the transverse vertical direction
 x : axial distance
 y : normal distance from the plane of symmetry
 η_K : Kolmogorov micro scale
 ν : kinematic viscosity
 Ω : mean vorticity ($=\frac{1}{2}[\partial \overline{V}/\partial x - \partial \overline{U}/\partial y]$)

3. Experimental Method

3.1 Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. The apparatus is similar to that of Tillmark and Alfredsson⁽⁷⁾. Water was stored in a rectangular tank of 1 800 mm in length and 240 mm in width. The depth of water was 180 mm. The main roller and sub roller were 80 mm in diameter and 180 mm in length. Both were submerged. The main roller was driven directly by a DC motor. A transparent belt made of a polypropylene film of 3 m in length, 180 mm in width and 0.1 mm in thickness was driven by the main roller and used for the moving walls. To stabilise the motion of the belt, two transparent plates were arranged in parallel as belt guides. The tension of the belt was adjusted by changing the positions of

(a) sketch

(b) top view

Fig. 1 Experimental apparatus

Table 1 Physical properties of silicon oil

density [g/cm ³]	viscosity [cP]	interfacial tension [dyn/cm]
1.01	20	6.0

four guide rods and the sub roller. The speed of the belt was controlled by adjusting a servo-controller of the motor. Thus, the plane Couette flow with zero bulk velocity was realised between the counter-moving belt with a constant speed of U_w keeping the distance of $2h$. This distance was set equal to 30 mm in the present study. The Reynolds number based on U_w and h was 1 500.

The test section was given at the centre between the two rollers where a developed turbulence field is formed by the propagation of roller-generated turbulence. The axial length of the test section was 45 mm. The origin of coordinates was allocated at the centre of the test section. The, x , y and z axes were positioned in the axial direction of the apparatus, perpendicular to the moving wall and in the transverse vertical direction of the flow, respectively.

3.2 Immiscible droplet

Silicon oil (Shin-etsu Chemical Inc., KF-99) was used as immiscible fluid. The catalog data for the density and viscosity of the oil are detailed in Table 1. The interfacial tensions were measured by the capillary method and are also tabulated. The oil was injected into the water from a fine needle using a syringe to form an immiscible droplet. The droplet was kept at the centre of the test section by a fine rod

of 1 mm in diameter throughout the measurement to prevent the droplet from approaching the wall as a result of fluctuating velocity in the y direction. The diameter of the droplet was 8.0 mm, which was about 70 times larger than η_K near the plane of symmetry estimated from DNS result⁽⁶⁾.

3.3 Flow visualisation

The tracer particle method was adopted for the visualisation of the Couette flow. Fine particles made of Nylon 12 of diameter less than 0.3 mm were adopted for the tracer particles. The upper limit of the frequency beyond which the particles in this size range cease to respond to fluid sinusoidal fluctuation was estimated to be 33 Hz⁽⁸⁾. This was higher than the highest frequency of 30 Hz whose statistical reliability was guaranteed by the frame-grabbing rate mentioned below and the sampling theorem.

A halogen lamp was utilized for the light source of the visualisation (see Fig. 2). The light was expanded by a flat light guide made of 320 aligned optical-fibres and a cylindrical lens. The expanded light illuminated the droplet and the particles horizontally from outside the tank through the transparent belt and the transparent belt-guide plate.

3.4 Image-capturing method

Reflected light from the surfaces of the particles and the droplet was captured by a progressive-scanning video camera (Photron Co., Photocam 120) set above the tank (see Fig. 2). The lens aperture and the shutter speed were $f=1.6$ and 1/60 second, respectively. The shutter speed was appropriate for capturing the motion of particles in the core region. The image capturing rate was 60 frames per second. Each frame consists of 640×480 pixels. A value in the 256-gray-level depending on the intensity of the reflected light was assigned to each pixel. One pixel covered a square 0.07 mm by 0.07 mm in the observing field.

The output from the camera was directly recorded on random access memories as digital images without image compression through the frame grabber board (Photron Co., FDM-PCI) using a personal computer. A total of 360 frames were recorded successively over six seconds ($=44h/U_w$) for one series

of image capturing; this being the limit of the 110-MByte memories managed by the computer. The digital images on the memories were then stored in a hard disk of the computer.

3.5 Pre-processing of images

Before the image processing, improvement of the digital images was carried out. First, the nonuniformity of the shading for the background of the digital images was compensated by using a reference frame. The reference frame was the median of 17 frames extracted every 0.33 second from the series of captured images. It was confirmed that the reference image did not include any particle image. Secondly, the neighbourhood averaging technique⁽⁹⁾ was applied for the smoothing of the images. Finally, binarisation was done for the smoothed images to enhance the particle images. The location of the centre of each particle was thus determined with an error of less than two pixels.

3.6 Image processing

A particle-tracking-velocimetry (PTV) method was adopted for obtaining the local velocity vectors on the horizontal plane. Seven successive images were used to obtain the trajectory of the particles. The fluid velocity was obtained from these trajectories.

The velocities were redistributed to the grid points allocated uniformly on the images in the following manner: (i) for a certain grid point, three neighbouring tracer particles were detected, (ii) if the grid point was located inside the triangle formed by the particles, the velocity components were obtained by the interpolation of those of particles (see Fig. 3(a)), (iii) if the grid point was on a side of the triangle, the interpolation was done along the side (see Fig. 3(b)), (iv) if the grid point was located outside the triangle, one of the particles was replaced by the next closest particle so that the grid point was inside the new triangle and the procedure mentioned in (ii) was done. The error of velocity vectors was estimated to be 2 percent. The occurrence of the error vectors was reduced to less than 0.2 percent by the present procedure.

Fig. 2 Flow visualisation and image capturing

Fig. 3 Velocity interpolation

4. Results and Discussion

4.1 Deformation of droplet

The deformation of the droplet was observed to be less than 3 percent of the droplet diameter over the whole frames processed. The DNS result done by Takashina⁽¹⁰⁾ showed that the droplet deformation is noticeable for the case where the viscosity is identical

(a) without droplet

(b) with droplet

(c) with droplet

Fig. 4 Distribution of mean velocity

but in that study the interfacial tension is much lower than the present case. Comparing these results, we considered that the interfacial tension plays an important role in the droplet deformation. In the present study, we assume that the droplet keeps its spherical shape.

4.2 Mean velocity field

Figure 4 illustrates the mean velocity field. Figure 4(a) shows the profile of the axial mean velocity, $\bar{U}$, obtained by summing the time-averaged local velocities at the positions where the absolute values of y are identical for the case without the droplet. The experimental result of the profile for $Re = 1262$ by Bech et al.⁽⁶⁾ is also shown in the figure. The uniform shear was obtained in two profiles in the core region. Both profiles show good agreement with each other.

Figure 4(b) indicates the contour map of the axial mean velocity in the case with the droplet. The circle in the figure expresses the interface. Since the velocity redistribution process aforementioned was applied to the grid points even inside the droplet, the velocities were allocated and, consequently, the contour lines were drawn inside the droplet. Therefore, these velocities and these contour lines have no meaning. Apart from this fact, a noticeable distortion of contour line was found outside the interface.

The mean velocity field in Fig. 4(c) illustrates the distortion of the axial flow more clearly. In the upper-right and the lower-left regions near the interface, the main flow is observed to be bifurcated into the axial flows over the interface and the flows along the interface in the y direction, and the main flow is also found to stagnate close to the interface. The flows in the y direction and the axial flows over the interface along the opposite wall join in the upper-left and the lower-right regions for the interface. Similar secondary flow was predicted for the liquid laminar Couette flow with an immiscible droplet by Tanaka et al.⁽¹¹⁾.

4.3 Turbulence intensities

Figure 5 shows the turbulence intensity in the x direction, $\sqrt{u^2}$, normalised by U_w . The profile corresponding to that in Fig. 4(a) is shown in Fig. 5(a) with the experimental result by Bech et al.⁽⁹⁾. The value of the intensity in our result does not depend on the position in the y direction in the core region. This tendency is similar to that obtained by the DNS⁽⁶⁾.

Figure 5(b) indicates the contour map of $\sqrt{u^2}/U_w$ in the case with the droplet. The contour is found not to be point-symmetrical. This is mainly because the period of the image-capturing is shorter than that of the regeneration process of the largest turbulence

Fig. 5 Turbulence intensity in the x direction

structure of Couette flow estimated by DNS result of Hamilton et al.⁽¹²⁾. Apart from this, the higher and the lower intensity regions are found near the upper-left and the lower-left for the droplet, respectively. These regions correspond to the confluence and the stagnation, respectively.

Figure 6 shows the turbulence intensity in the y direction, $\sqrt{v^2}$, normalised by U_w . Figures 6(a) and 6(b) are the counterparts of Fig. 5(a) and 5(b), respectively. The nearly uniform distribution in this intensity in the core region in Fig. 6(a) shows qualitative agreement with that obtained by DNSs⁽⁴⁾⁻⁽⁶⁾.

In the contour map of $\sqrt{v^2}$ shown in Fig. 6(b), the higher intensity regions are found near the upper-left and the lower-right for the droplet, while the lower intensity region is found near the upper-right for the droplet. These regions correspond to the confluence and the stagnation region, respectively.

4.4 Turbulent kinetic energy

We considered that the ratio, r , of $\sqrt{w^2}$ to $\sqrt{v^2}$ takes the nearly-constant value of 1.2 in the core region based on the results of DNSs by Lee and Kim⁽⁴⁾ and Bech et al.⁽⁵⁾ By assuming the r is valid for the turbulence near the droplet, the turbulent kinetic

Fig. 6 Turbulence intensity in the y direction

energy, $k (=1/2[\overline{u^2} + \overline{v^2} + \overline{w^2}])$, can be calculated. Figure 7 shows the distribution of the turbulent kinetic energy thus estimated. For the case without the droplet shown in Fig. 7(a), the nearly uniform distribution is obtained in the core region, which is similar to that predicted by DNS by Lee and Kim⁽⁴⁾.

Figure 7(b) indicates the contour map of k with shading for the case with the droplet. The darker the shade is, the higher the energy is. The high energy regions are clearly found near the upper-left and the lower-right for the droplet where the flow in the y direction and the axial flow join. Also the low energy regions are seen near the upper-right and the lower-left for the droplet where the stagnation of the main flow occurs at the interface.

None⁽¹³⁾ obtained a similar tendency of the turbulence energy in his experiment for the Couette flow in which the immiscible droplet was replaced by a solid sphere. His result showed that the region for the turbulent-kinetic-energy modification was wider than the counterpart of the droplet.

4.5 Vorticity

Figure 8 shows the contour map of the mean vorticity, $\Omega (=1/2[\partial \bar{V}/\partial x - \partial \bar{U}/\partial y])$, with shading for the case with the droplet. The darker the shade is, the

Fig. 7 Distribution of turbulent kinetic energy

Fig. 8 Vorticity contour

higher the vorticity is. The derivative coefficients were obtained by applying the second-order central differencing to the velocities at the grid points. The regions of high vorticity and low vorticity almost match with those of high turbulent kinetic energy and the low turbulent kinetic energy, respectively.

5. Conclusion

The experiments were carried out for a turbulent liquid plane Couette flow with an immiscible droplet.

The main conclusions obtained are as follows:

(1) The flow visualisation, the image-capturing method and the image processing used in the present study are effective for the examination of the modification of near-droplet turbulence dealt with in the present study.

(2) It is found that the turbulence intensities, turbulent kinetic energy and the vorticity take higher values in the confluence region of the axial flow and the flow in the direction perpendicular to the moving wall, and that those quantities take lower values in the stagnation region of main flow.

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