Experimental Study on Hydrodynamics Characters of Flow Laden with Micro-bubbles

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ABSTRACT

The effect of micro-bubbles on the hydrodynamics characters in the turbulent boundary layer is quite complex. In order to clarify the influence of micro-bubbles on coherent structure, turbulence channel flows laden with and without micro-bubbles were experimentally studied by using particle image velocimetry (PIV) technique at a Reynolds number of \( Re = 8.9 \times 10^4 \). Micro-bubbles were produced by the electrolysis of water in a low speed circulating water tunnel. Proper orthogonal decomposition (POD) method was used to analyze the coherent structures of the flow fields. The results show that the micro-bubble decreases the large scale structure and suppresses the intensity of wall-normal vorticity in the near wall region. The longitudinal speed streaks numbers decrease and the energy cumulative growth rate becomes moderate due to the micro-bubbles injection.

INTRODUCTION

The drag reduction technology by micro-bubbles has received widespread attention during the past few decades due to its obvious advantages such as environmental friendships, easy operations, low costs and high saving of energy.\(^1\) The technique adds the micro-bubbles into the fluid of boundary layer and produces a gas-liquid mixed fluid that affects the characteristics of the boundary layer and consequently reduces the skin friction drag of the boundary layer.

McCormick et al. firstly employed electrolysis water to produce micro-bubbles on the hull of a submersible body and obtained a 30\% of drag reduction.\(^2\) Subsequently, great deal of experimental researches and numerical simulation studies were carried out to investigated hydrodynamics characters of flow laden with bubbles. There are usually several methods for micro-bubbles production such as electrolysis of water, injection through porous plate, a Venturi type bubble generator, ultrasonic forcing, generation air bubble using a hydrofoil et al. The key parameters of the micro-bubbles drag reduction include the bubble size effect, the bubble concentration effect, the location of the injection position and the optimal air

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flow rate. The flow laden with bubble is quite complex and it is significant to clarify the liquid turbulence modulation by bubbles and the mechanism of drag reduction. Murai et al. studied the relationship between the local skin friction and the local void fraction. Jacob et al. performed an experimental investigation of a flow laden with a small amount of bubbles having sizes comparable with the local Kolmogorov lengthscale. Mazzitelli et al. simulated the effect of micro-bubbles on the homogeneous and isotropic turbulence. Ferrante and Elghobashi investigated the liquid turbulence modulation by bubbles. Shen et al. also pointed that the presence of bubbles changes the average density and viscosity of the liquid, thus the shear stress decreases accordingly. Pang and Wei showed the liquid-phase turbulence modulation is related to the bubble location.

The effect of micro-bubbles on the coherent structures in wall boundary turbulence is important to understand the interaction between the bubble and the liquid. As the key elements of coherent structure, longitudinal low-speed streaks and vortices play important roles in the development of near-wall turbulent boundary. However, few investigations have been conducted on the streaks in bubbly flow, so this paper focuses on the dominate flow behavior of the single-phase fluid (without micro-bubbles) and the mixed fluid (with micro-bubbles) by using the Proper Orthogonal Decomposition technique. Micro-bubbles were generated by the electrolysis of water. The velocity profiles of turbulent layer were obtained by using PIV measurements. The variation of the main energy contents structure were discussed.

EXPERIMENTAL METHODS

Experimental Setup

The experiments are carried out in a low speed circulating water tunnel. The tunnel is composed of contraction section, test section, downstream section, and other components. The test section is a two-dimensional rectangular horizontal channel made of transparent acrylic resin, which measures 200 mm (W) × 250 mm (H) × 1300 mm (L). The turbulent boundary layer flow is developing along a flat acrylic glass plate which is mounted horizontally in the test section. A nearly zero-pressure gradient in the streamwise direction is achieved by adjusting the pitch angle of the plate. The PIV illuminant consisted of a double-pulsed Nd: YAG laser. Polyamide seeding particle is selected to be the tracer particles. The resolution of the CCD camera was 2048 × 2048 pix². The schematic diagram of PIV system is shown in Fig. 1. The measuring plane (xoz plane) corresponding to 110 × 110 mm² is parallel to the bottom of the test section. The micro-bubbles are produced by electrolysis of water, the platinum wires with the diameter of 100µm are used as the electrolysis electrodes that are located at the upstream of the testing area, as shown in Fig.1. The power of the electrolysis is provided by DC regulated power. The method we used to discriminate the micro-bubbles and the tracer particles in the mixed fluid is explained by Pang and Wei.10

![Figure 1. Schematic diagram of PIV system (xoz plane).](image-url)
In our experiment, velocity fields of single-phase fluid and mixed fluid in the streamwise-spanwise plane ($xoz$ plane) are measured. The velocity of the center line in the channel in the experiments is $U_c = 0.10 \text{ m/s}$ and the corresponding Reynolds number ($Re = U_cL/\nu$) is about $8.9 \times 10^4$, where $\nu$ is the water kinematic viscosity at working conditions whose value is $1.006 \times 10^{-6} \text{ m}^2/\text{s}$ and $L$ is the distance from the leading edge of the flat plate to the centre of the testing area. We measured three different heights which were $y^+ = 16, 26$ and 37 respectively along the wall normal direction. The background turbulence intensity level is approximately 2%.

**Snapshot method POD technique**

The POD snapshot is very appropriate to analyze the velocity field. The mean velocity field that is considered to be the 0th mode of the POD is calculated from all the snapshots. And the matrix of fluctuating parts components $u = (u', v')$ can be expressed as $U = [u^1 u^2 \ldots u^N]$. The auto-covariance matrix $C$ can then be determined by $C = U^TU$. And the eigenvalue problem $C\phi_i = \lambda_i\phi_i$ can be solved, where $\lambda_i$ and $\phi_i$ are corresponding eigen-values and -vectors. Solutions are ordered according to the size of their eigenvalues: $\lambda_1 > \lambda_2 > \ldots > \lambda_N = 0$. The eigenvector corresponding to each eigenvalue is combined with the $U$-matrix to calculate the eigenfunction, and thus the POD modes can be obtained when the eigenfunctions are further normalized:

$$\phi_i = \frac{U\phi_i}{||U\phi_i||}, \quad i = 1, 2, \ldots, N$$

Each of the snapshots from which the POD modes were determined can be expanded in a series of the POD modes with expansion coefficients $a_n$ for each POD mode $n$. The POD coefficients are determined through projecting the fluctuating velocity field on the POD modes: $a_n = \Psi^T u_n, \ (n = 1, 2, \ldots, N_n)$ where $\Psi$ is the mode matrix and each of the POD modes is a column of it: $\Psi = [\phi_1^T \phi_2^T \ldots \phi_N^T]$. The velocity vectors can be reconstructed by the following expansion with the POD coefficients $a_n$:

$$u_n = \Psi a_n.$$

The total energy of the fluctuating flow can be obtained directly by the sum of all eigenvalues: $E = \lambda_1 + \lambda_2 + \ldots + \lambda_N$. And the percentage of energy distribution corresponded to each eigenmode based on its eigenvalue can be calculated as:

$$E_i = \frac{\lambda_i}{E}$$

**RESULTS AND DISCUSSION**

**Flow Energy Content Distribution**

As is known to all, high energy content fluid corresponds to large scale structure and low energy content fluid is associated with small scale structure in the wall turbulent flow. The energy of large scale structure is transported to small scale structure while the energy of small scale structure is dissipated to thermal. Fig. 2 (a) denotes the energy fraction, and (b) denotes the energy cumulative. We measured three different heights of the wall normal which were $y^+ = 16, 26, 37$ at $Re = 8.9 \times 10^4$ for single-phase and mixed fluids. As shown in Fig. 2 (a), We can clearly distinguish the different scale structures with POD mode number. The energy fraction of small POD mode number is high, and it means the most significant mode is the first mode, and it usually denotes the largest scale structure in turbulent flow. With the increasing of the mode number, the energy fraction is rapidly reduced for the first several eigenmodes and then decreases gradually. Fig. 2 (a) demonstrates that the presence
of micro-bubbles decreases the large scale structures in turbulent flow which is agreed well with Jacob’s researches.\(^4\) As we can see from Fig. 2 (b), the cumulative of the energy in the mixed fluids are more gentle than that of the single-phase fluids. The decrease of the energy cumulative growth rate reveal the suppression on the turbulence. With the increasing of \(y^+\), the energy cumulative growth rate decreasing in sequence can be seen clearly. Though the energy cumulative growth rate of mixed fluids are lower than those of single-phase fluids at these three heights of the wall normal, the decreasing is more obvious at \(y^+ = 16\) than at \(y^+ = 37\). It demonstrates that the micro-bubbles mainly work at the near wall region.

![Figure 2](image1.png)

**Figure 2.** The energy fraction (a) and cumulative (b) of POD modes for single-phase and mixed fluids (solid symbol with lines – single-phase fluids; hollow symbol without lines – mixed fluids).

**Longitudinal Low-speed Streaks of Single-phase and Mixed Fluids**

Figure 3 shows the longitudinal streaks results obtained for single-phase fluids (a, b, c) and mixed fluids (d, e, f) at \(y^+ = 16\) of the first three POD modes. The red color denotes the high-speed streaks and the blue color denotes the low-speed streaks in the flow. As we can see from Fig. 3 (a) and (d) (POD modes 1 for single-phase and mixed fluids), the streaks are longitudinal and the high- and low-speed streaks occur by turns. It also shows that the streaks number of mixed fluid are less than those of single-phase fluid and the distance between the streaks becomes larger. It means that the streaks are greatly influenced by the micro-bubbles. The POD modes 2 (Fig. 3 b and e) show nearly the same variation. However, the change is not such obvious at POD modes 3. The streaks denote very important structures in the turbulent boundary. The presence of micro-bubbles decreases the number of the speed streaks at modes 1 and 2, thus the large scale structures, i.e. high energy content fluid, decrease in turbulent flow. For further analyzing the main structures in the turbulence, spanwise vorticity \(\omega_y\) corresponding to Fig. 3 is shown in Fig. 4. For the first three modes of single-phase and mixed fluids, the presence of micro-bubbles suppressed the intensity of vorticity, and the flow fields seem to be more clean. The decreases of the streaks number and the lower spanwise vorticity intensity of the first 3 modes demonstrate that the energy transportation is suppressed, i.e. the fluid in the turbulent boundary layer become quietly, and the energy transportation intensity is decreased.
CONCLUSION

In the present study, the effects of micro-bubbles on the hydrodynamics characters in the turbulent boundary layer have been experimentally studied. POD technique is employed to analysis PIV velocity field measurements obtained through a low speed circulating water tunnel testing at Reynolds number of $8.9 \times 10^4$. The micro-bubbles are produced by electrolysis of water. Flow energy content of different POD modes for single-phase fluid and mixed fluid are investigated. Vorticity fields and speed streaks are discussed. For the present investigation, some important conclusions can be summarized as follows:

1. The POD analyses show that the presence of micro-bubbles has an important influence
of the large scale turbulence structures, i.e. high energy content fluid. The energy contribution of the large scale structures to the total energy becomes smaller, and the energy cumulative growth rate is more moderate due to the micro-bubbles injection.

(2) The micro-bubbles mainly work at the near wall region and the accumulation of the micro-bubbles suppress the intensity of wall normal vorticity. It also decreases the longitudinal speed streaks number and increases the distance between the streaks in the $xoz$ plane.

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REFERENCES

1. Hashim A., Yaakob O. B., Koh K. K., Ismail N., Ahmed Y. M., Review of Micro-bubble Ship Resistance Reduction Methods and the Mechanisms that Affect the Skin Friction on Drag Reduction from 1999 to 2015. Jurnal Teknologi 2015 74(5): p105-114.
2. McCormick M. E., Bhattacharyya R., Drag Reduction of a Submersible Hull by Electrolysis. Nav. Eng. J. 1973 85: p11-16.
3. Murai Yuichi, Fukuda Hiroshi, Oishi Yoshihiko, et al. Skin Friction Reduction by Large Air Bubbles in a Horizontal Channel Flow[J]. International Journal of Multiphase Flow, 2007, 33(2): p147–163.
4. Jacob Boris, Olivieri Angelo, Miozzi Massimo, Campana Emilio F., Piva Renzo., Drag Reduction by Microbubbles in a Turbulent Boundary Layer. Phys. Fluids, 2010 22 p115104.
5. Mazzitelli I. M., Lohse D., Toschi F., The effect of microbubble on developed turbulence. Phys. Fluids, 2003, 15p:685-697.
6. Ferrante A., Elghobashi S., On the physical mechanisms of drag reduction in a spatially developing turbulent boundary layer laden with microbubbles, J. Flud Mech. 2004, 503p:345-355.
7. Shen Xiaochun, Ceccio Steven L., Perlin Mare. Influence of bubble size on micro-bubble drag reduction. Experiments in Fluids 2006, 41:p415-424.
8. Pang M J, Wei JJ, Yu B. Investigation on influences of bubble location and momentum transfer direction on liquid turbulence modification for the dilute bubbly flow. Int. J. Fluid Mech. Research 2016 43(2) p161.
9. Li Jian, Dong Gang, Zhang Jianlei. Numerical study on evolution of subharmonic varicose low-speed streaks in turbulent channel flow. Appl. Math. Mech.2016 37(3):p325-340.
10. Pang Mingjun, Wei Jinjia. Experimental investigation on the turbulence channel flow laden with small bubbles by PIV. Chemical Engineering Science, 2013 94:p302-315.
11. Sirovich L. Turbulence and the dynamics of coherent structures. Part I: Coherent structures. Quart. Appl. Math. 1987 45(3):p561-571.