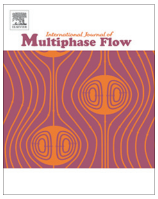
International Journal of Multiphase Flow 75 (2015) 12–25

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



Drag reduction promoted by repetitive bubble injection in turbulent channel flows

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form 1 April 2015
Accepted 6 May 2015
Available online 15 May 2015

Keywords:
Drag reduction
Gas-liquid two-phase flow
Boundary layer control
Turbulent flow

ABSTRACT

To promote the efficiency of frictional drag reduction using bubbles, we designed a novel bubble control method that involves repetitive injection of bubbles rather than the conventional continuous bubble injection approach. Even if the mean void fraction of bubbles to be injected into the turbulent boundary layer is set to be low, repetitive bubble injection (RBI) maintains the frictional drag reduction by generating bubble swarms. The enhanced drag reduction mechanism and the effectiveness of the RBI approach are investigated by studying wall shear stress and the velocity vector field in the liquid phase when measured in a turbulent horizontal channel flow. The bubble swarms generated by RBI consist of bubbles of various sizes with leading large air films, which have high reproducibility. The leading air films, which are a result of the concentrated void fraction, maintain a high drag reduction effect by air lubrication and by suppression of Reynolds shear stress events in the turbulent vortical structures beneath the bubble swarm. The latter effect of RBI in particular plays a significant role at higher Reynolds numbers. Based on the combination of these effects, we confirmed that RBI provides an extra drag reduction effect when compared with continuous bubble injection.

Introduction

Turbulent boundary layer control by injection of bubbles into the boundary layer is expected to enhance the energy efficiency of vessels by reducing the frictional drag that constitutes nearly 80% of the total drag acting on large class vessels. This is also attractive to engineers because it offers installation simplicity and is pollution-free. This technique has been studied in a number of institutes to clarify the drag reduction mechanism and to enable practical use on actual vessels since McCormick and Bhattacharyya (1973) first introduced the technique. Some studies indicate the importance of modifications to the vortical flow structures in turbulent boundary layers caused by the fragmentation and deformation of bubbles; these structures create Reynolds shear stress that dominates the skin friction drag in turbulent flows (Meng and Uhlman, 1989; Kawamura and Kodama, 2002; Xu et al., 2002; Kitagawa et al., 2005; Jacob et al., 2010). As a practical demonstration, Kodama et al. (2005 and 2008) evaluated the performance of this technique on a real vessel, a cement carrier named the Pacific Seagull, and a net power saving of approximately 5%, calculated based on the fuel consumption and the energy consumption required to inject bubbles, was reported. Other groups experimenting on the same vessel also reported that the maximum average drag reduction reached approximately 11% in their experiments (Hoang et al., 2009). These experimental results using a real vessel posed two problems, which must be addressed for practical applications: (i) high energy consumption occurs when injecting bubbles at the bottom of deep draft ships against hydrostatic pressure; (ii) only a small bulk drag reduction effect is obtained, whereas sufficient local drag reduction can be realized. Adoption of huge vessels with shallow draft can avoid the first problem but restricts general use of the technique for various other types of vessel. In fact, to cause relatively low or negative drag reduction effects, researchers have indicated that two-phase flow structures in the case of low void fractions (i.e., the volume fraction of the bubbles) should be studied (Kato et al., 1999; van den Berg et al., 2007). Fatter bubbles that are comparable in size to the boundary layer thickness also increase the wall shear stress (Murai et al., 2007). Fig. 1 summarizes these known facts schematically. Fig. 1(a) represents the existence of a critical void fraction, α_c, at which the wall shear stress becomes smaller than the original value without the bubbles. The value at which α_c appears depends on the Reynolds, Froude, and Weber numbers. Typically, α_c has a

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.05.003
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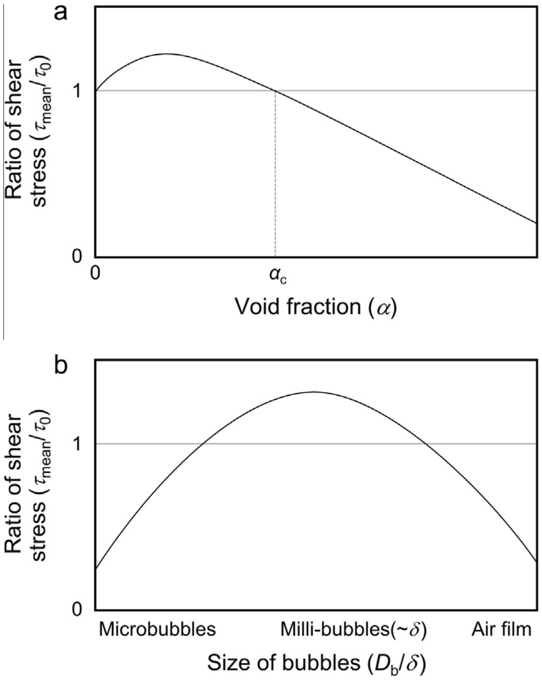

Fig. 1. Schematic representations of wall shear stress modified by bubble injection parameterized in terms of (a) mean void fraction and (b) bubble size, where the flat lines represent the time-mean shear stress in the single-phase flow (τ_0), α_c is the critical void fraction required to obtain drag reduction, and δ is the turbulent boundary layer thickness.

value of more than 0.1 in the case of low Reynolds number turbulent flows, and tends to infinity for laminar boundary layers containing spherical bubbles. Fig. 1(b) illustrates the bubble size (D_b) dependency: microbubbles and air films achieve drag reduction by different mechanisms (Elbing et al., 2008), but very often intermediate-sized bubbles conversely increase the wall shear stress. The bubble-to-liquid interactions of these intermediate bubbles were measured by Oishi and Murai (2014), and their results indicate that inclusion of such fat bubbles should be avoided to obtain stable drag reduction performance. Also, the size of the bubbles generated by the most commonly used types of bubble generators, such as blowers, changes with the void fraction. The bubbles are naturally small in size at low void fractions and become larger with increasing void fraction. This means that conventional bubble generators cannot control the bubble size and the void fraction independently, which means that the drag reduction performance could not be maximized using these generators.

To improve the efficiency of drag reduction produced by bubble injection, we propose a novel bubble injection control method that enables the historically accumulated knowledge of the parametric dependency to be applied effectively. The method involves control of repetitive bubble injection (RBI). This control is realized by simple open-close iteration of a valve for the bubble supply, but provides complex variability in the bubbly two-phase turbulent boundary layers to lead to new phenomenological discussions. A preliminary experiment on the effects of RBI was reported by our group (Park et al., 2009), and we confirmed the feasibility of this method for improvement of the drag reduction performance. This RBI scheme is expected to produce (i) concentration of the air resource to increase the local void fraction so that the system avoids a drag-increasing regime at low void fractions, (ii) reduction of the air volume flow rate required to introduce bubbles at deep locations where the hydrostatic pressure is high, and (iii) repetitive renewal of the vortical flow structures that develop inside the turbulent boundary layers. The first and second expectations are obvious, as we mentioned in the previous paragraph. Our recent work on flow visualization (Park et al., 2014) indicated that the RBI system provides reproducible bubble swarms in the downstream region with leading air films that insulate the vortical structures present in the turbulent boundary layer from the wall. Interestingly, we found that the most of the vortical structures survive underneath the bubble swarms and their capability to create frictional drag on the wall, as in the single-phase condition, may be restored after the passage of the leading air films, although with a considerable delay. This series of visualizations has indicated to us that the renewal time of the vortical flow structures promotes drag reduction as a third effect of RBI, and this effect can be added to the previously mentioned purposes of RBI.

The RBI method that is adopted in this paper injects bubble swarms with locally high void fractions into a turbulent boundary layer at controlled intervals. Even if the mean void fraction is set to be low, these bubble swarms produce strong void fraction fluctuations within the boundary layer to maintain the two-way interaction between the bubbles and the liquid flows. As we will show later in the paper, individual bubble swarms are always led by local air films that refresh the turbulent boundary layer that is developing spatially in the streamwise direction. In this paper, we report a new series of experimental data that were obtained by multiple diagnoses, including the ultrasound Doppler method, which leads to an in-depth discussion of the improved performance of RBI-based drag reduction. As a platform for these investigations, we use a turbulent channel flow at relatively low Reynolds numbers, where $Re \sim 10^3$. In this regime, bubbly drag reduction hardly occurs in the case of continuous bubble injection (Oishi and Murai, 2014), and, contrastingly, the effects of RBI can be clearly distinguished. Since viscous modification by bubbles remains significant in this low Reynolds number turbulent flow regime, we can discuss the reason why the drag reduction is promoted by RBI, based on comparing the wall shear stress and the Reynolds shear stress profiles.

Experimental setup

Setup and measurement equipment

A schematic diagram of the experimental apparatus is shown in Fig. 2. The test section is a horizontal rectangular channel made from transparent acrylic resin, and is 40 mm high ($H = 2h$), 160 mm wide (W) and 6000 mm long. Silicone oil (KF-96-10cs, Shin-Etsu Chemical Co., Ltd.) is used rather than water as the working fluid to ensure the reproducibility of the experimental results by avoiding any uncontrollable influences of contamination of the bubble interfaces by tracer particles and other impurities, because the oil is a non-polar liquid. The kinematic viscosity (ν), density (ρ_0) and the surface tension of the silicone oil at 25 °C are 10×10^{-6} m^2/s, 930 kg/m^3 and 20.1 mN/m, respectively. Spherical polyolefin fine powders called FLO BEADS (CL-2507, Sumitomo Seika Chemical Co., Ltd.) are adopted as tracer particles to measure the velocity vector fields. The average diameter of these particles (D_p) is 180 μm and the particle density (ρ_p) is 920 kg/m^3. Concerning the traceability in turbulence, relaxation time of the particles in the liquid phase (t_p) is estimated to be 0.27 ms as defined by $t_p = ((2\rho_p + \rho_0)D_p^2)/(36\nu\rho_0)$. In the case of fully developed turbulent flow at the maximum bulk velocity at $U_{bulk} = 2.0$ m/s, Stokes number (St) of the particle, $St = t_p/t_\eta$, being estimated from the equivalent Kolmogorov time scale (t_η) is smaller than 0.07, thus sufficiently smaller than unity. A bubble injector plate, which has a single open slit with 10 mm in the streamwise side and 120 mm in the spanwise length, is mounted on the upper wall of the channel without step at $x/H = 43.75$ from the channel inlet, where the x, y, and z coordinates are defined as the streamwise distance from the channel inlet, the vertical downward coordinate from the upper