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Numerical investigation on turbulence drag reduction by small bubbles in horizontal channel with mixture model combined with population balance model

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ABSTRACT

The drag reduction by small bubbles is investigated with mixture multiphase flow model combined with population balance model for the horizontal channel turbulence. The influence of liquid-phase Reynolds number and global void fraction on the drag reduction is fully analyzed. The present results show that the addition of small bubbles cause the drag reduction, and the liquid-phase Reynolds number and the global void fraction have the great influence on the drag reduction rate. For the same global void fraction, the larger the liquid-phase Reynolds number is, the sharper the bubble breakup phenomenon is, which leads to that the bubble diameter is smaller and the drag reduction rate is higher. The influence of the global void fraction on the drag reduction rate is related to the liquid-phase Reynolds number. For the low liquid-phase Reynolds number, the case with the lower global void fraction has the higher drag-reducing rate. However, for the high liquid-phase Reynolds number, the higher void fraction corresponds to the larger drag reduction rate. It is very important for investigating the drag reduction by bubbles to consider the bubble coalescence and breakup phenomena. And the present results show that the drag reduction rate strongly depends on the bubble size.

1. Introduction

Drag reduction in the turbulent flow has been a very important issue in engineering and academic circles. As is well known, many ways have been proposed to reduce turbulence frictional drag in liquid (such oil and water) transport process in the past. Of all drag-reducing methods, in view of the environmental friendly characteristic and the high drag-reducing rate, the drag reduction by bubbles with different sizes has recently been paid more and more attention by researchers and engineers to expect that it can be applied to reduce the frictional drag for ships in water and liquid transport in pipelines in the near future. Presently, a large number of investigations on the drag reduction by bubbles have been performed so as to understand the drag-reducing mechanism and to promote its engineering application. Some early investigations have shown that the drag reduction effect by bubbles is tightly related to the bubble size, and it is found that the drag reduction by bubbles is very effective only when the bubble size is very small. For this reason, the early investigations on the drag reduction by bubbles mainly focus on microbubbles whose diameter is less than 1 mm. Some researchers (such as Mccormick and Bhattacharyya, 1973; Bogdevich et al., 1977; Merkle and Deutsch, 1989; Madavan et al., 1984 and 1985a; Guin et al., 1996; Kim and Cleaver, 1995; Kato et al., 1999; Kodama et al., 2000; Gabillet et al., 2002; Moriguchi and Kato, 2002; Nagaya et al., 2002; Latorre et al., 2003; Deutsch et al., 2004; Hassan et al., 2005; Van den Berg et al., 2005; Akoi et al., 2006; Murai et al., 2006, 2007; Sanders et al., 2006; Shen et al., 2006; Elbing et al., 2008; Jacob et al., 2010; Kumagai et al., 2015; Paik et al., 2016; Qin et al., 2017; etc) carried out studies on the drag reduction by microbubbles by means of experimental methods, and other researchers (such as Legner, 1984; Madavan et al., 1985b; Marie, 1987; Meng and Uhlman, 1989; Kanai and Miyata, 2001; Kawamura and Kodama, 2002; Xu et al., 2002; Kunz et al., 2003; Ferrante and Elghobashi, 2004, 2005; Lu et al., 2005; Skudarnov and Lin, 2006; Xu et al., 2007; Kunz et al., 2007; Mohanarangam et al., 2009; Pang et al., 2014; Asiagbe et al., 2017; Qin et al., 2017; etc) performed theoretical and numerical studies on the drag reduction by microbubbles.

With the deep investigation on the drag reduction by bubbles in the turbulent flow, it is found that the bubbles with a diameter greater than 1 mm can also cause the drag reduction (Van Gils et al., 2013; Maryami et al., 2015; Verschoof et al., 2016). Thus, the importance of the bubble size for the drag reduction becomes a controversial focus. It was even pointed out by Shen et al. (2006) and Ceccio (2010) that the drag

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reduction is independent of the bubble size. Therefore, the mechanism on the drag reduction by bubbles becomes more and more bewildered. The present mechanism on the drag reduction by bubbles can be summarized as follows. The first explanation is the density and viscosity effect (Legner, 1984; Marie, 1987; Chanson, 1994; Lvov et al., 2005; Shen et al., 2006; Skudarnov and Lin, 2006; etc); namely, the injection of bubbles changes local viscosity and density of the mixture phase to cause the drag reduction. The second explanation is based on interactions between bubbles and liquid-phase turbulence (Kanai and Miyata, 2001; Xu et al., 2002; Ferrante and Elghobashi, 2004; Mohanarangam et al., 2009; Jacob et al., 2010; Pang et al., 2014; etc); namely, the addition of bubbles influences the liquid-phase turbulence structure and reduces Reynolds shear stress of the liquid phase to cause the drag reduction. The third explanation is based on the bubble fluctuations; namely, the bubbles in the turbulence flow happens to shape change and volume compression to lead to the drag reduction (Lu et al., 2005; Van den Berg et al., 2005; Lo et al., 2006; Van Gils et al., 2013; Verschoof et al., 2016; etc).

As a matter of fact, the bubble deformation depends on the Weber number. If the thermos-physical parameters of bubble and liquid phases and the liquid-phase velocity field are fixed, the bubble deformation is only related the bubble size according to the definition of the Weber number. For the definite liquid-phase velocity field laden with bubbles, the bubble size strongly depends on the coalescence and breakup processes. Even if the initial diameter of bubbles (corresponding to the small Weber number) is very small, it can also become relatively big due to the coalescence effect (corresponding to the big Weber number). With the increase of the bubble size, the bubble deformation happens, and the drag reduction will also change (Vershoof et al., 2016). Accordingly, it is very important for the drag reduction by bubbles to consider the bubble coalescence and breakup processes.

To further explore the physical phenomena and to understand the mechanism of the drag reduction by bubbles, in this paper, the influence of the bubble coalescence and breakup on the drag reduction is numerically investigated with mixture multiphase flow model combined with population balance model (PBM) in the horizontal channel. The Reynolds stress model (RSM) is applied to solve the turbulence velocity field. The diameter range of the bubble coalescence and breakup is 0.001–8 mm, the global void fraction is 1%–5% and the liquid-phase Reynolds number is 10^4-10^5. The paper structure is arranged as follows: Section 1 is introduction, Section 2 introduces physical model and computational method, Section 3 presents result analyses and discussion, and Section 4 summarizes conclusions.

2. Physical model and computational method

2.1. Geometric model and boundary conditions

Here, the two-dimensional channel is chosen as the computational region to investigate the drag reduction by bubbles, as shown in Fig. 1. The coordinate system can be seen in Fig. 1. The coordinate origin is set at the center of cross section in the channel inlet. The x direction denotes the flow direction, the y direction is the spanwise one and the z direction is the wall-normal one. The gravity acceleration acts on the negative direction of the z axis. Dean (1978) pointed out that the secondary flow occurring in the spanwise wall can be ignored when the aspect ratio of the channel is greater than 7. For the present computation, the channel width and height are 150 mm and 10 mm, respectively, and thus the aspect ratio of the channel is 15 greater than 7, which can ignore the influence of the secondary flow. The channel length should be long enough to make the turbulence develop fully. For the Newtonian fluid, the channel length, which the full development of turbulence needs, can be computed by the equation of $L = 8.14Re^{1/6}H$. For the present computation, the largest liquid-phase Reynolds number is 10^5, and thus the channel length L should be larger than 550 mm. To eliminate the influence of the back flow in the channel outlet, the final length of the channel is set as 2000 mm. Thus, the channel sizes $L \times W \times H$ correspond to $2000 \times 150 \times 10$ mm in the x, y and z directions. In the computational process, the inlet section of the channel is the velocity inlet condition, and the outlet is the free flow condition. The top and bottom walls of the channel are set as no-slip boundary conditions, and the periodic boundary condition is applied to the spanwise direction in order to reduce the computational cost.

2.2. Calculation conditions

In this paper, the influence of the liquid-phase Reynolds number on the drag reduction is investigated under the same void fraction. The global void fraction of bubbles is 1% and 5%, each global void fraction corresponds to 10 liquid-phase Reynolds numbers, and thus there are 20 computational cases in all. Thermo-physical parameters of bubble and liquid phases are ones of air and water at the temperature of 20 °C. The initial diameter of bubbles is given to a constant value $d_{\mathrm{b,first}} = 4$ mm, and the breakup and coalescence range of the bubble diameter is 0.001–8 mm. As a matter of fact, Murai (2014) presented a detailed reviewer on the drag reduction by bubbles, and it is found that the bubble diameter is in the range of 0.001–8 mm for the published cases with the liquid-phase velocity in the range of 1–10 m/s and the bubble void fraction in the range of 0–20%. It can be seen from the above fact show that the range of the bubble diameter is reasonable. According to the calculation need of PBM, the bubble diameter is classified into 40 groups, and the volume ratio between two adjacent bubbles (v_{i+1}/v_i) is equal to 2. The related computational parameters are listed in Table 1. In addition, according to the current calculation parameter, the number of bubbles is $\sim 10^8$, and thus the calculation cost is very large if the discrete phase model is used as the multiphase flow model.

2.3. Governing equations

2.3.1. Continuity equation

The mixture model is one kind of the models based on the Eulerian coordinate system, for which both gas and liquid phases are regarded as the continuous media. Only one set of the gas-liquid two-phase mixture equations are solved. Here, the continuity equation is presented as follows:

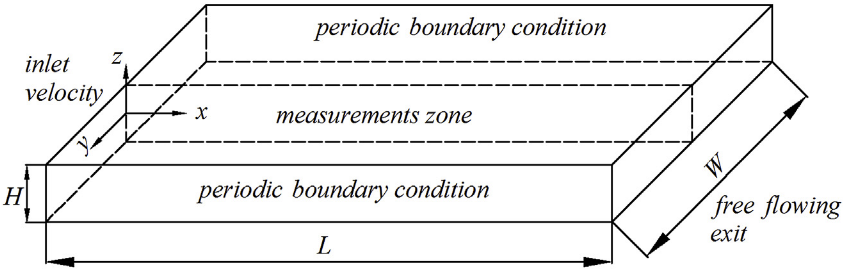

Fig. 1. The geometry size and coordinate system.