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Robust design of microbubble drag reduction in a channel flow using the Taguchi method

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Abstract

This study attempts to obtain optimum parametric levels for robust design of the microbubble drag reduction in a turbulent channel flow. This work was carried out experimentally by measuring the frictional resistance on the upper wall of the channel to analyze the efficiency of drag reduction. Considering the mean flow speed as an indicative factor, several controllable factors that influence the effect of microbubble drag reduction were investigated in this work by using the Taguchi method. The controllable factors in this study were the amount of air injected, area of air injection, and microbubble size. For the condition of optimum parametric levels, the effect of drag reduced could reach up to 21.6%.

Keywords: Robust design; Taguchi method; Microbubble; Drag reduction

1. Introduction

Vehicles consume large quantities of energy and fuel, and most of the consumption is due to the drag forces of the vehicle. Among these drag forces, form drag and frictional resistance are the two principal forces affecting energy consumption. As vehicles have been streamlined to their limit, further decreasing form drag is difficult. However, there may still be opportunities to reduce frictional drag. Vehicles moving in water are more resistant to frictional drag than vehicles on land or in the air, because the viscosity of water is higher than that of air. Consequently, decreasing the frictional drag of submerged vehicles has become a very important area of research.

Numerous technologies, such as surface coatings, microblowing, riblet equipment, and microbubbles have been utilized to reduce the frictional resistance of a surface. Among these, the use of microbubbles seems to be the best choice based on their ability to significantly reduce frictional resistance and cause minimal environmental impact. Madavan et al. (1984, 1985a), Kodama et al. (2000), and Takahashi et al. (1995, 2000) found promising results using microbubbles for drag reduction. It is well known that the presence of microbubbles in a turbulent liquid flow leads to drag reduction for two reasons: first, by lowering the average viscosity and density of the gas–liquid mixture flow, due to the low viscosity and density of the gas; second, the diminution of the Reynolds stress through the interaction of microbubbles with the liquid. Skudarnov and Lin (2006) simulated a two-dimensional microbubble flow over a flat plate to assess the affect of mixture density variation on drag reduction. The results of their simulation indicated that variation of mixture density played a significant role in microbubble drag reduction; they also found that a gradual increase in drag reduction along with a decreasing mixture density resulted from a flow rate of high gas injection. Kitagawa et al. (2003) studied the turbulence modification in boundary layers; they found an

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increase in turbulence intensities, and a decrease in the Reynolds stress, with a void fraction increase.

McCormick and Bhattacharyya (1973) made the most significant contribution regarding microbubble drag reduction by demonstrating that hydrogen bubbles generated by electrolysis reduce drag on a fully submerged body of revolution. Since then, a large number of studies have investigated on microbubble drag reduction. Using a laser Doppler velocimetry (LDV) and a thermal film velocimeter, Dubnishchev et al. (1975) measured bubble concentrations and velocity profiles for a two-phase flow. They noted that the volumetric gas concentration was equal to zero in a viscous sublayer, and the maximum value occurred at $\overline{y} = y/2H = 0.1$, where y is the distance from the wall of the test section and H is its height. Bogdevich et al. (1977) conducted a study on microbubbles released in a turbulent boundary layer between two flat plates. They concluded that the Reynolds number is a significant parameter for drag reduction and that a large Reynolds number is indicative of sufficient drag reduction. Merkle and Deutsch (1989) investigated the interaction between small bubbles and a liquid turbulent boundary layer. They found that microbubbles must be distributed in a buffer layer in a manner similar to polymers to achieve drag reduction. A few years latter, Merkle and Deutsch (1992) examined numerous experimental findings to identify the capabilities for reducing skin friction and proposed two parameters related to drag reduction: void fraction and the Froude number. Madavan et al. (1984), who performed an experiment examining microbubble drag reduction between two flat plates, achieved an 80% reduction in drag. Using models of ships, Larrarte et al. (1995) analyzed the impact of ship size on microbubbles injected into the bottom of ship hulls. They concluded that ship size does not alter the bubble trajectories. Furthermore, Larrarte et al. also demonstrated that the bubbles would be swept into the flow when the Froude number is sufficiently high, whereas the bubbles will escape laterally and rise due to the buoyancy when the Froude number is low. Takahashi et al. (1995, 2000), who conducted experiments using 12 and 50 m-long flat plate ship models, pointed out that drag reduction could be as high as 50% and 32%, respectively. Wu et al. (2007) conducted tests on model vehicles on the water surface and submerged, under various sizes of a porous medium, and at different flow speeds. The best drag reduction efficiencies were 26% for a 1 μm porous medium and 23% for a 10 μm porous medium when the flow speed was 7 m/s. The experiments mentioned above were all based on the one-factor-at-a-time experiments, and therefore all suffered from the same limitation, which is not able to investigate the interaction between variables. Hence, predicting the optimum condition of parametric level for the microbubble technique of drag reduction has not yet been rigorously investigated.

Many numerical studies have attempted to elucidate the interaction between a liquid turbulent boundary layer and microbubbles. Among these studies, some have utilized direct numerical simulation (DNS) (e.g., Kawamura and Kodama, 2001, 2002; Sugiyama et al., 2002), whereas some used the two-fluid model (e.g., Drew, 1983; Murai and Matsumoto, 1996), and others created a simple model employing two phases to simulate the interaction between bubbles and liquid turbulent flow (e.g., Legner, 1984; Madavan et al., 1985b; Marie, 1986). However, the mechanism by which gases affect the turbulent boundary layer and reduce skin resistance has not been clearly realized. Additionally, very fine cells (a large amount of computational cells) are required to directly resolve the Navier–Stokes equation for two phases of turbulent flow under the condition of a high Reynolds number flow. Current computer processing capability is insufficient to process such a resource intensive computation. Consequently, most numerical studies are in their infancy, and their results cannot be applied to the engineering field.

The design of experiment (DOE) can systematically assess the effects of parametric levels on the response. It is known as the robust parametric design and its application is to find the optimal level of quality, by taking into account that quality may be affected by the design, the production, and/or disturbance from the environment. The controllable factors are the parameters that its levels can be set up for because they are provided with the technique. Therefore, the amount of air injected, the area of the air injection and the microbubble size are treated as the controllable factors. However, though a factor possesses the technique, if it is not meaningful that the level of the factor is selected, that is, it is not controllable; then this factor is referred to as the indicative factor. Hence, in this investigation, the mean flow velocity was considered as an indicative factor because it is expected that any new device that is developed for drag reduction can provide the same efficiency on drag reduction for any level of the flow velocity. That is to say, to select a special level of the flow velocity for designing a device of the drag reduction, in practice, has no meaning. For the robust parametric design, the Taguchi method is usually adopted initially to plan a minimum number of experiments and determine the experimental condition having the least variability as the optimum robust condition. The introduction to the Taguchi method can be referred to Roy (1990) and Ross (1996). The Taguchi method frequently applies the part-factorial experiment instead of the full-factorial experiment, it implies less experiments and lower experiment cost, but the gain is highly credible. Therefore, the Taguchi method is widely adopted in industry. Numerous researches applying the Taguchi method in various application fields have been published. For example, Kim et al. (2007) used the Taguchi orthogonal array method to evaluate the effect of several factors on the particle size and the size distribution for the synthesis of zinc oxide (ZnO), and obtained the ZnO nanoparticles (about 30 nm) by using optimal conditions. Using the Taguchi method, Nikbakht et al. (2007) investigated the effect of operating parameters on the concentration of citric acid in an effort