Mechanisms and Scale Effects of Skin Friction Reduction by Microbubbles

Takahito Takahashi, Akira Kakugawa, Shigeki Nagaya, Tsuyoshi Yanagihara, and Yoshiaki Kodama Ship Research Institute

Studies on microbubbles were carried out, aiming at its application to full-scale ships. In the basic studies using a circulating water tunnel, it was found out that the local void ratio near the solid wall is important for skin friction reduction.

Experiments in combined microbubble-surfactant conditions were made. The combined effect was not observed, but surfactants helped to generate smaller bubbles. The comparison of non-surfactant and surfactant experiments seems to indicate that the bubble size does not influence the skin friction reduction effect by microbubbles.

Experiments using a 50m-long flat plate ship were carried out in a towing tank. Bubbles we re injected at two streamwise locations to find out the effect of the boundary layer thickness. It was found out that the boundary layer thickness has little effect and that the distance from the injection point is the most important factor.

1. Introduction

Microbubbles, which are small bubbles injected into the wall turbulent boundary layer, is a device for reducing skin friction acting on a solid body advancing in water. Its skin friction reduction effect reaches up to 80% in tests using a circular water tunnel [1], and therefore it is regarded as a promising device applicable to full scale ships. But at the same time, the energy needed for injecting bubbles at the hull bottom is not small because large ships have large water depth against which bubbles have to be injected. Therefore it is important to reduce the amount of injected air in order to put microbubbles to practical use [2]. In this project we aim at reducing the amount of injected air by half (in other words increasing the skin friction reduction effect twice), by elucidating and utilizing the mechanism of skin friction reduction by microbubbles. During the past few years we conducted microbubble experiments using a circulating water tunnel, and we have confirmed that the local void ratio close to the wall has strong correlation with skin friction reduction [3]. In this fiscal year of 2000, we conducted another experiments of microbubbles using the circulating water tunnel, by adding surfactants to water, in order to get combined effects of microbubbles and surfactants, and to increase information on the interaction of microbubbles with wall turbulence. These works will be described in the next chapter.

Another important factor to be investigated for applying microbubbles to full-scale ships is the scale effect. Especially, the persistence of the skin friction reduction effect by microbubbles in the downstream direction from the injection point is needed to estimate the overall efficiency of microbubbles in drag reduction. Therefore we carried out experiments by towing a 50m-long flat plate ship at the maximum speed of 7m/sec in the 400m-long towing tank. It was found out that the skin friction reduction by microbubbles persists up to the downstream the end of 50m-long ship [4],[5]. In the practical application of microbubbles to a full-scale ship, the design and location of bubble injection to get maximum drag reduction is important. Different locations in the streamwise direction on the hull correspond to different boundary layer thickness, and therefore it is necessary to find out the effect of boundary layer thickness on the skin friction reduction effect by microbubbles. This fiscal year, another experiment using the 50m-long flat plate ship was carried out to investigate the effect stated above,

by injecting bubbles either at the bow, where the boundary layer is very thin, or at the middle, where the boundary layer is well developed. The results will be shown in Chapter 3.

2. Basic experiments using a circulating water tunnel

2.1 Experimental apparatus

The experiments were carried out using the high speed circulation water tunnel shown in Fig. 1[6]. The test section has the following inner dimensions, the width 100mm, the height 15mm, and the length 3000mm. Fig.2 shows the detail of the air injection chamber. Air was injected into the flow through a plate with many regularly-spaced 1.0mm diameter holes called an array-of-holes plate shown in Fig.3. The width and length of the injection part was 72mm, and the pitch of the holes are 2.5mm in the streamwise direction and 1.875mm in the spanwise direction, resulting in the total of 277 holes. It was set at the position of 1028mm from the inlet of the test section. The bubbles produced by the array-of-holed plate were about 1mm in diameter. The local skin friction was measured directly using the shear stress sensor shown in Fig.4, whose capacity was 2gf and diameter is 10mm. Photographs of the microbubbles were taken using the setup shown in Fig.5. A YAG laser was used as a light source, whose light sheet penetrates the test section at the position 30mm from the side wall, where a CCD camera is placed outside.



Fig.1 The high-speed circulating water tunnel

Fig.2 Air injection chamber



Fig.3 An array-of-holes (AOH) Fig.4 Skin friction sensor plate. Hole diameter=1mm.

Fig.5 Layout of camera and light source

2.2 The relation between void ratio and skin friction reduction

The skin friction was measured at three speeds in three streamwise locations. The results are shown in Fig.6. Modification of the data to compensate the wall effect was applied as described in [3]. The horizontal axis shows the average void ratio in the test section defined as

$$\overline{\alpha}_a = \frac{Q_a}{Q_a + Q_w} \tag{1}$$

where Q_a : volumetric flow rate of air in the test section

 Q_W : volumetric flow rate of water in the whole test section of 100mm × 15mm

At all the three speeds, the skin friction reduction increases as the amount of injected air increases. At the average flow speed V=5m/sec, measured values at three locations agree well with each other, and agree with the average curve of measurements by Merkle [7], which is shown as

$$\frac{C_f}{C_{f_0}} = 0.8e^{-4\overline{\alpha}_a} + 0.2 \tag{1}$$

where $\overline{\alpha}_a$ is the average void ratio in the test section. At V=7m/sec, measured values at three locations are different from each other. At V=10m/sec, although the measured values at three locations agree well with each

different from each other. At V=10m/sec, although the measured values at three locations agree well with each other, they consistently deviate from Merkle's curve.



Fig.6 Skin friction reduction by microbubbles (Array-of-holes plate)

The local void ratio $\frac{Q_a}{Q_a + Q_w}$ was measured using a sution tube system similar to the one used by Guin

[8]. The measured results, which have been adjusted so that the air volume integrated throughout the channel height agrees with that measured at the injection point, are shown in Fig. 7. By comparing the data with that in Fig.6, it is clear that the local void ratio close to the wall has strong correlation with the skin friction reduction.



Fig.7 Local void ratio (Array-of-holes plates)

2.3 Use of surfactants for combined microbubble-surfactant effects

Surfactants are known to have significant skin friction reduction effect at relatively low speeds. Kawaguchi et al.[9] conducted drag reduction experiment in the test section of 500mm width and 40mm height using surfactants, where CTAC (Cetyltrimethyl Ammonium Chloride) was used as surfactant and Salicylic acid was used as solvent. At CTAC concentration of 50ppm, they obtained skin friction reduction in the flow speed range 0.5m/sec to 1.8m/sec, with the maximum reduction of 80% at flow speed around 1.3m/sec.

In our experiments CTAC was added to water with concentration up to 40ppm and the speed range up to 10m/sec. Fig.8 shows skin friction reduction as a function of average void ratio at three different CTAC concentration including non-CTAC condition, at V=5m/sec. It is seen that the effect of CTAC on skin friction reduction effect by microbubbles is very small at this flow speed. Fig.9 shows the skin friction reduction effect as a function of flow speed. At the flow speed range lower than 4.0m/sec, CTAC seems to have some skin friction reduction effect. Fig. 10 shows comparison of bubbles with or without CTAC condition. It is clearly seen that at the CTAC concentration of 40ppm, the bubbles are smaller than those in the non-CTAC condition. Considering this with the fact that the skin friction reduction effect by microbubbles is not influenced at all by the CTAC concentration, it seems that the skin friction reduction effect by microbubbles is not influenced by the difference in the bubble size.





(a) CTAC 0ppm



Fig.10 Photographs of microbubbles (V=5m/s, Qa/(Qa+Qw)=0.116)

^{3.} The scale effect of mictobubbles

3.1 Experimental setup

In order to obtain data on the streamwise persistence of the skin friction reduction effect of microbubbles over a distance as long as possible, a 50m-long flat plate ship shown in Fig.11 was constructed. Air was injected through array-of-holes plates at two streamwise locations, i.e. one at 3.0m from the front end and the other at 31.0m from the front end. The injection plate had 1mm diameter holes spaced in the same way as that used in the water tunnel). The size of the injection plates was 500mm wide, 100mm long, 4mm thickness.

In order to reduce the ship's drag, the width was limited to 1.0m, and the water depth was 45mm. The bottom of the ship was flat everywhere. The body of the model ship was made of urethane foam, and the frames were made of aluminum channels. The whole body was constructed by connecting 4m-long blocks. The bottom of the ship had transparent acrylic windows (700mm x 700mm) for observing microbubbles, and each window was 4 meters apart.

The local skin friction was measured using skin friction sensors S10W-2, whose capacity was 2gf, produced by SANKEI ENGINEERING. They were attached to each window. Their locations P1(Position1), P2, P3, P4, P5, and P6 correspond to 3.5m,4.8m,8.8m,31.5m,32.8m,36.8m from the front end of the ship. The relative positions of (P1-P3) to the bow injection point and those of (P4-P6) to middle injection point were the same. Total resistance was measured using a load cell (capacity 500kgf).



Fig.11 50m long flat plate ship for microbubble experiments

3.2 Experimental results

(a) Total drag

The measured total drag of the 50m-long flat plate ship is shown in Fig. 12. The vertical axis shows Ct,

the nondimensionalized total drag $C_t = \frac{R_t}{\frac{1}{2}\rho V^2 S}$,

where S is the wetted surface area. Cf_0 is the Schoenherr skin friction curve, an experimental curve that shows the drag of a flat plate with the same area and length. The form factor k was determined as 0.14, based on the Prohaska's method. The horizontal axis shows the Froude number, i.e., the ship's speed. The fact that $(1+k)Cf_0$ curve agrees well with experiments shows that the wave-making drag component of this ship is small.

Fig.13 shows the reduction of total drag by



Fig.12 Total drag of a 50m-long flat plate ship

microbubbles at two speeds. Air was injected at bow. The horizontal axis shows the nondimensionalized injected air flow rate where the injection area $S(=0.05m^2=0.5m*0.1m)$. The vertical axis shows the ratio of total drag to that at non-bubble condition. The maximum reduction of 13% was obtained at V=5m/s. Fig.14 shows the same data with different normalization in the vertical axis. This time the vertical axis shows the ratio corresponding to the estimated skin friction of the area downstream of the injection plate, i.e., the area where skin friction reduction by microbubbles is expected. Rf0 value, i.e. the integrated skin friction value in the non-bubble condition was estimated using the Shoenherr experimentaql formula. The maximum reduction of 35% was obtained at V=5m/s.



Fig.13 Total Drag reduction (50m model ship, Air injection at bow)

Fig.14 Integrated skin friction reduction (50m model ship, Air injection at bow)

(b) Local skin friction

Fig. 15 shows the measured local skin friction at two air injection rate and at two speeds. Air was injected at bow. The vertical axis shows the skin friction value as a ratio to that at the non-bubble condition, and the horizontal axis shows the distance from the front end. The reduction is the largest right after the point of injection and gradually decreases in downstream, but still exists at the most downstream point. As q increases, the skin friction reduction increases. The reduction is greater at V=5m/s than at V=7m/s.



Fig.15 Local skin friction (Air injection at bow)

(c) The effect of boundary layer thickness

Fig.16 shows the effect of boundary layer thickness in skin friction reduction by microbubbles at two speeds. Air was injected either at bow (denoted as "bow" in the figures) or at middle (denoted as "middle"

in the figures). At V=5m/sec, the boundary layer thickness is estimated to be 4cm at P1 and 26cm at P4. The locations of P1, P2, and P3 relative to the bow injection point are the same as those of P4, P5, and P6 relative to the middle injection point, making direct comparison of the data of the same symbol but with different colors possible. Although at the nearest points of P1 and P4 the skin friction reduction is slightly greater in the middle injection case at V=5m/sec, they agree well with each other in general, which means that the distance from the injection point is the most important factor and that the boundary layer thickness has little effect on the skin friction reduction effect of microbubbles.



Fig.16 Local skin friction reduction (Air injection from the bow or the middle)

Lastly, some photographs of microbubbles are shown in Figs. 17 and 18. Figures (a) show the photos at P1 in the bow injection case. Figures (b) show those at P4, again in the bow injection case. Figures (c) show those again at P4, but in the middle injection case. In the bow injection case, the bubbles are dense at P1, but less dense and slightly larger at P4. By comparing (a) and (c), it seems that bubbles are more uniformly distributed in the bow injection case.



(a) P1 Bow

(b) P4 Bow

(c) P4 Middle

Fig.17 Photos of microbubbles. V=5m/sec, q=0.04



(a) P1 Bow

(b) P4 Bow

(c) P4 Middle

Fig.18 Photos of microbubbles. V=7m/sec, q=0.04

4. Conclusions

Previous studies confirmed that the local void ratio near the solid wall is the most important factor for skin friction reduction.

Combined microbubbles and surfactants experiments were carried out. A slight effect of surfactants in the presense of microbubbles was observed at low speeds. Surfactants clearly decreased the bubble size. In order to increase the applicability of microbubbles to full-scale ships, it is important to increase the efficiency in skin friction reduction, and thus to reduce the amount of injected air. It was originally anticipated that reducing the bubble size increases the efficiency. But the experimental results using surfactants seems to indicate that bubble size does not influence the skin friction reduction effect. Of course this is only a preliminary result, and further comprehensive tests need to be made.

Microbubble experiments using a 50m-long flat plate ship was carried out in the 400m-long towing tank. The effect of the boundary layer thickness on the skin friction reduction by microbubbles was tested by injecting air at two different streamwise locations, i.el. at the bow and at the middle. It was found out that the distance from the injection point is the most important parameter, and that the boundary layer thickness has little effect on the skin friction reduction by microbubbles. Some observations of bubble size were made.

A part of this study was carried out as the SR239 research project by the Shipbuilding Research Association of Japan. The project plans to carry out a full-scale microbubble experiment using a 105m-long ship in this September. The current results will be utilized in the test.

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