EXPERIMENTAL STUDY ON DRAG REDUCTION BY MICROBUBBLES USING A 50M-LONG FLAT PLATE SHIP

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ABSTRACT

Microbubble experiments were carried out in a 400m-long towing tank using a flat plate ship of up to 50m in length, aiming at its application to full-scale ships. The measured skin friction using skin friction sensors showed that the skin friction reduction persisted up to the downstream end of the 50m-long ship. The local void ratio distribution across the boundary layer was measured using a suction tube method, and it was found that the local void ratio close to the wall had strong correlation with skin friction reduction. Bubbles were injected at two different streamwise positions, in order to find out the effect of the boundary layer thickness on the skin friction reduction. It was found out that the distance from the injection point was dominant and that the boundary layer thickness had little effect.

INTRODUCTION

Microbubbles, small bubbles injected into the turbulent boundary layer of water, is a skin friction reduction device acting on a solid body advancing in water(Merkle, 1990). The skin friction reduction effect by sub millimeter microbubbles reaches up to 80% in tests using a circular water tunnel (Madavan, 1985) 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, such as 20m, 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 (Kodama,1995). We aim at reducing the amount of injected air by half (in other words doubling the skin friction reduction effect), by elucidating and utilizing the mechanism for skin friction reduction by microbubbles. During the past few years we conducted microbubble experiments using a circulating water tunnel, and have confirmed that the local void ratio close to the wall has strong correlation with skin friction reduction (Kawashima,1995, Kodama, 2000).

To assess the applicability of microbubbles to full scale ships, it is important to know the scale effect, especially to know how long the skin friction reduction persists in the downstream direction after injection. Watanabe et al. (1998) carried out a pioneering experiment on microbubbles using a flat plate ship 40m long and 0.6m wide. This paper summarizes our research on microbubbles using a flat plate ship still larger than Watanabe's, in a 400m-long towing tank. We first conducted microbubble experiments by towing a 12m-long flat plate ship, 1.0m wide, at the maximum speed of 7m/sec. In the experiment the relation between skin friction reduction and the local void ratio distribution in the boundary layer was investigated. Next we carried out experiments using a 50m-long flat plate ship, being constructed by adding a parallel part to the 12m-long ship. In the experiment the persistence of the skin friction reduction by microbubbles in the downstream direction was investigated (Takahashi 1999, Kodama 1999). The effect of the boundary layer thickness on the skin friction reduction effect was also investigated by injecting bubbles at two streamwise locations, one near the bow and the other in the middle.

EXPERIMENTAL SETUP

The experimental setup for the tests using either a 12m-long or a 50m-long flat plate ship is described.

Model Ships

Fig.1 shows the 12-long flat plate ship. The body of the model ship was made of urethane foam and the frames were made of aluminum channels. In order not to increase the ship's drag, the width was limited to 1.0m, and the water depth was 45mm. The whole bottom of the ship was made flat and painted to have smooth surface.

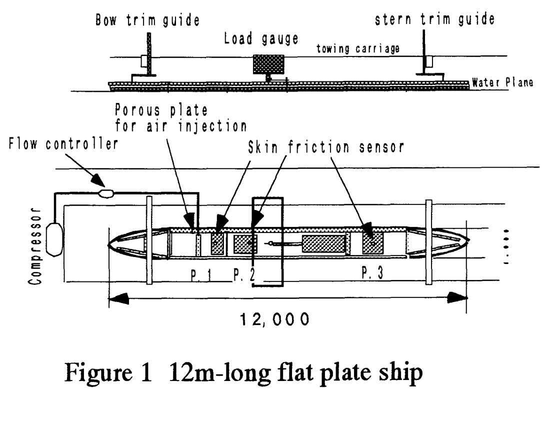


Figure 1 12m-long flat plate ship

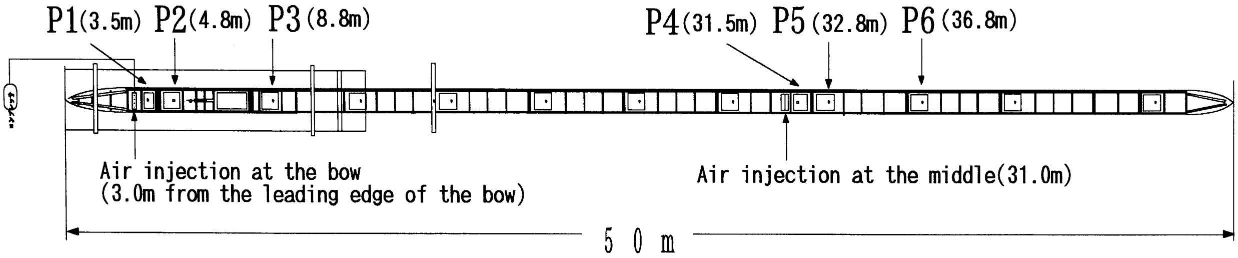


Figure 2 50m-long flat plate ship

The bottom of the ship had transparent acrylic windows (700mm x 700mm) for observing microbubbles, and each window was 4 meters apart.

Fig. 2 shows the 50m-long flat plate ship, which was constructed by adding, to the 12m-long ship, parallel parts, each of which was 4m long. The whole body was put on the water in 8m-long units, one by one after connection.

Table 1 summarizes the air injection, the skin friction measurement, and the local void ratio measurement, which will be described in the following.

Table 1 Measurements on 12m-long and 50m-long flat plate ships

Items		12m model	50m model
Air injection	Plate type	Porous plate (2 μ m dia.)	Array-of-holes plate (1mm dia.)
	Locations	Bow (3.0m from bow end)	Bow (3.0m), Middle(31.0m)
Skin friction sensors	Type	S25W-10	S10W-2
	Locations	P1, P2, P3	P1, P2, P3, P4, P5, P6
Local void ratio	Locations	P1, P3	none

Air injection

In the case of the 12m-long flat plate ship, the air was injected through a porous plate, 0.1m long, 0.5m wide and 4mm thick, with nominal pore diameter of 2 μ m, located at 3m downstream from the bow. According to the observation the size and number of the generated bubbles were not uniform on the porous plate. Moreover the pressure loss across the plate was not nominal. Therefore, in the case of the 50m-long flat plate ship, the air was injected through an array-of-holes plate, which has 1mm diameter holes lined in arrays with pitch of 5mm in the streamwise direction and 3mm in the spanwise direction. In the 50m-long ship two array-of-holes plates were set at two different streamwise locations, i.e. one at 3.0m downstream from the bow end and the other at 31.0m. The size of bubbles generated through the array-of-holes plate was more uniform than that those generated through a porous plate. The size of the bubbles generated by the two plates was almost the same.

Local skin friction

Local skin friction was measured using skin friction sensors produced by the Sankei Engineering. With the 12m-long flat plate ship the skin friction sensors S25W-10 whose capacity is 10gf were used. They were attached to transparent acrylic windows. Their locations P1 (Position1), P2 and P3 correspond to 3.5m, 4.8m, and 8.8m from the bow end of the ship (Fig.1). Afterwards we found S10W-2, whose capacity is 2gf and the sensing disk diameter is smaller than that of S25W-10, was more reliable than S25W-10 at high speed through calibration and by comparing the measured skin friction values with theoretical values based on the 1/7th-power law. Therefore correction factors were estimated and applied to the measurements.

With the 50m-long flat plate ship the sensors S10W-2 whose capacity is 2gf were used. Their locations P1, P2, P3, P4, P5, and P6 correspond to 3.5m, 4.8m, 8.8m, 31.5m, 32.8m, 36.8m from the bow end of the ship (Fig.2). The relative positions of (P1-P3) to the bow injection point are the same with those of (P4-P6) to the middle injection point.

The total resistance was measured using a load cell (capacity 500kgf).

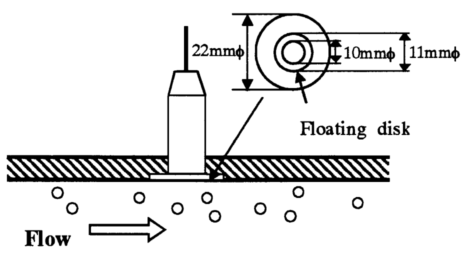


Figure 3 Skin friction sensor (S10W-2)

Local void ratio

The local void ratio $\frac{Q_A}{Q_A + Q_W}$ was measured using a suction tube system (Guin 1996), where Q_A

is the air volume and Q_W is the water volume. The system is shown in Fig.4. A suction tube with 1.2mm inner diameter and 1.6mm outer diameter was placed at the bottom of the ship, facing upstream. The mixture of air and water was collected by the suction of a vacuum pump connected to the tube. The air volume Q_A was measured in the Tank A, while the total volume $Q_A + Q_W$ was measured in the Tank B. The pressure of the vacuum pump was adjusted so that the rate of suction is equal to the flow velocity at that location in the non-bubble condition. The measured air volume integrated across the boundary layer, assuming uniform distribution in the spanwise direction, agreed well with the injected air volume measured separately.

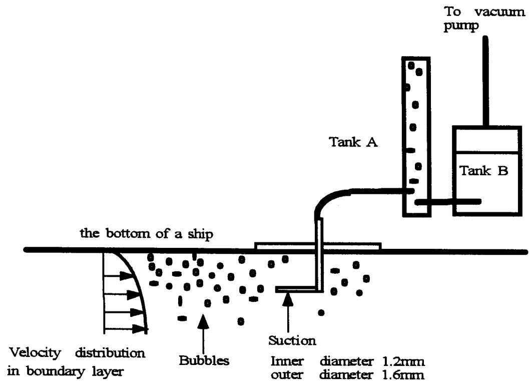


Figure 4 Local void ratio measurement system

RESULTS OF EXPERIMENT

12m-long flat plate ship

Skin friction reduction

Fig. 5 shows the measured local skin friction at speeds V=5m/sec and 7m/sec and at locations P1, P2, and P3. Air was injected through a porous plate. The horizontal axis shows the nondimensionalized injected air flow rate q, i.e. the injected air volume Q normalized by the injection area S $(= 0.5m \times 0.1m \ = 0.05m^2)$ and the ship speed V. The vertical axis shows the skin friction value as a ratio to that at the non-bubble condition. The general tendency is that skin friction reduction increases as the injected air increases, and that the reduction is greater at the lower speed. At V=5m/sec, the skin friction ratio became almost 0.2 at P.1, which is because the large air sheet formed by the injected air covered the sensor. Fig.6 shows the persistence of skin friction reduction at V=7m/s at two nondimensionalized injected air flow rate. As the distance from the air injection point increases, the skin friction reduction decreases. The local skin friction reduction $1 - C_f / C_{f_0}$ at q =0.019 goes down quickly from 32% at P.1 (0.5m from the injection point) to 13% at P3(5.8m). In order to investigate the reason, the local void ratio was measured at the two locations.

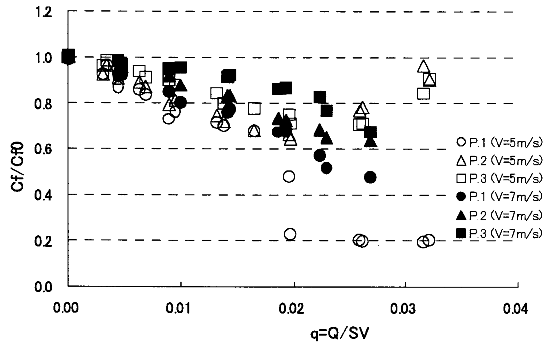


Figure 5 Local skin friction reduction (12m-long flat plate ship)

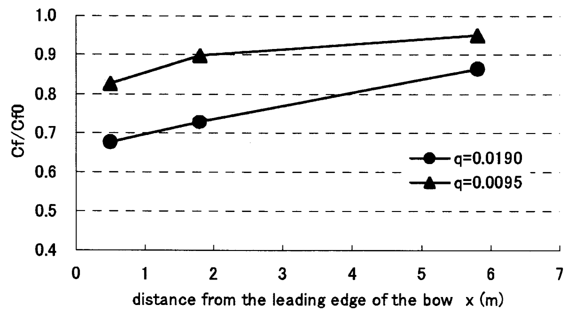


Figure 6 Streamwise distribution of local skin friction reduction (12m model, V=7m/s)

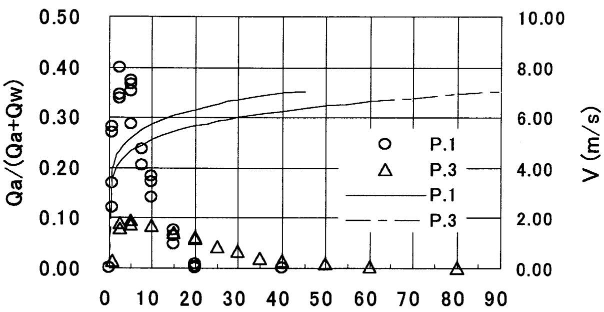


Figure 7 Local void ratio (12m model, V=7m/s)

Local void ratio

Fig.7 shows the measured local void ratio at V=7m/s and at the air flow rate of q =0.019 (Q=400L/min). The horizontal axis shows the distance from the ship bottom in mm. The lines show the velocity profiles by 1/7th power law. At P1, the bubbles are clustered near the solid wall, while at P3, the bubbles are diffused into the boundary layer. The result shows the same tendency as that found in the small high speed water tunnel (Kodama 2000). It is clear that the local void ratio close to the wall has strong correlation with the skin friction reduction.

50m-long flat plate ship

Total drag

The measured total drag of the 50m-long flat plate ship is shown in Fig. 8. The vertical axis shows the nondimensionalized total drag C_t

$$C_t = \frac{R_t}{\frac{1}{2}\rho V^2 S}$$

where S is the wetted surface area of the ship. C_{f_0} in the figure is the Schoenherr skin friction curve, an experimental curve that shows the drag of a flat plate with the same length and the surface area. The horizontal axis shows the Froude number $F_n = V/\sqrt{gL}$, i.e., the ship's speed. The form factor k was determined as 0.14, based on the Prohaska's method. The fact that the $(1+k)C_{f_0}$ curve agrees well with the experiments shows that the wave-making drag component of this ship is small and suggests that the viscous flow structure on the plate is similar at all speeds.

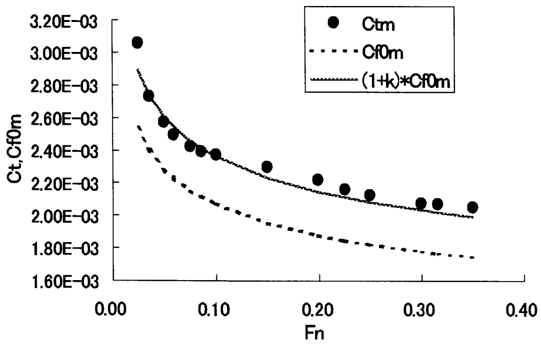


Figure 8 Total drag of a 50m-long flat plate ship

Skin friction reduction

Fig.9 shows the reduction of total drag by microbubbles at two speeds. Air was injected at bow (3.0m from bow end). The horizontal axis shows the nondimensionalized injected air flow rate. The vertical axis shows the ratio of the total drag to that at the non-bubble condition. The reduction is greater at the smaller speed, and the maximum reduction of 13% was obtained at V=5m/s. Fig.10 shows the same plot, except that the vertical axis shows R_f/R_{f_0}, the ratio of the bubble to non-bubble values of the estimated skin friction of the flat plate downstream of the injection plate. R_{f_0} is estimated using the Schoenherr skin friction formula, and

$$R_f = R_{f_0} - \Delta R_f = R_{f_0} - \Delta R_t$$

where ΔR_f, the reduction in R_f due to bubbles, has been assumed to be equal to ΔR_t, the reduction in the total drag. In other words, since the area to be covered with microbubble is 47% of the total wetted surface area, the drag reduction ratio shown in Fig.10 is roughly $(1+k)/0.47$ times larger than that shown in Fig.9, resulting in the maximum reduction of 38% at V=5m/s.

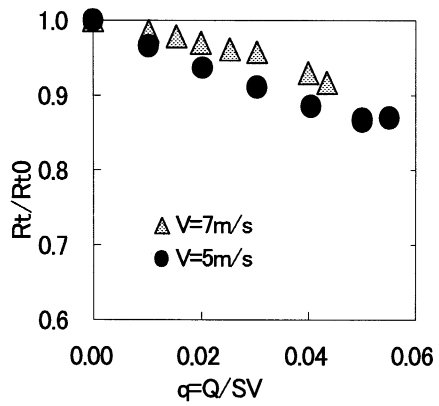


Figure 9 Total drag reduction (50m model, Air injection at bow)

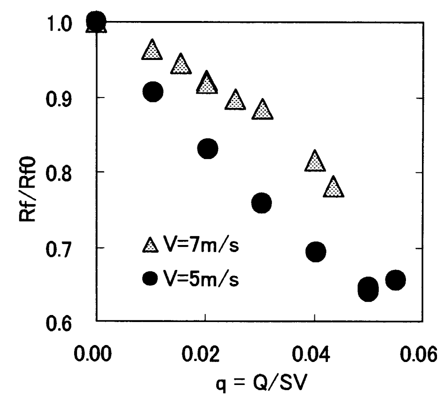
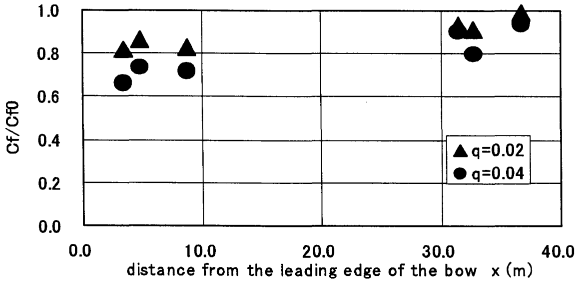


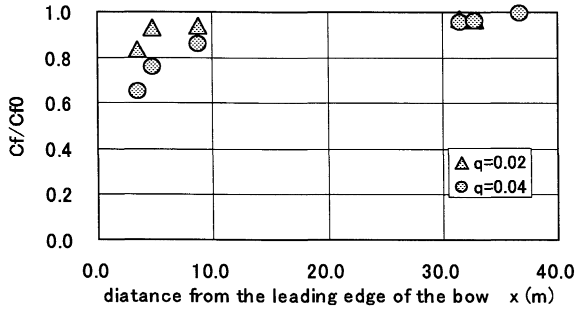
Figure 10 Skin friction reduction downstream of the injection plate (50m model, Air injection at bow)

Local skin friction

Fig.11 shows the measured local skin friction at two air injection rates and at two speeds. Air was injected at bow (3.0m from the bow end). The vertical axis shows the ratio of the local skin friction to that at the non-bubble condition, and the horizontal axis shows the distance from the bow 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. Those tendencies are similar to those by Watanabe(1998).



(a) V=5m/s



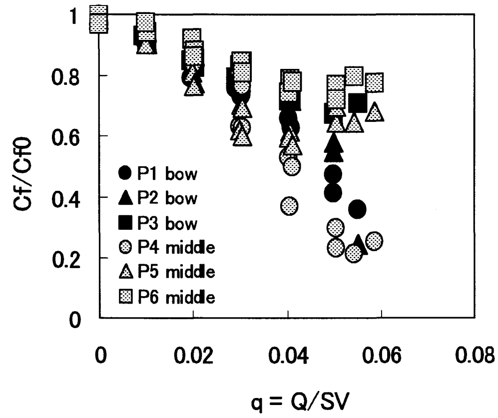
(b) V=7m/s

Figure 11 Local skin friction (Air injection at bow)

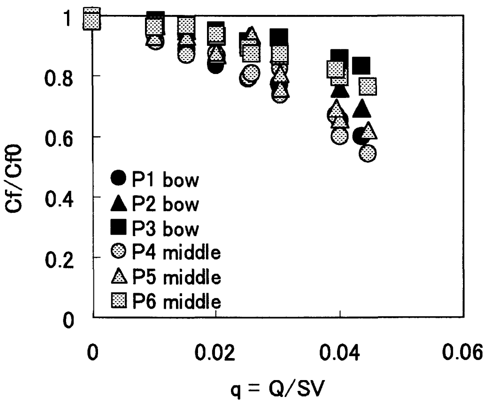
The effect of boundary layer thickness

Many of the skin friction reduction measured in circulating water tunnels are plotted as a function of the average void ratio in the channel(Kodama, 2000). And in the case of outer flows the channel half width is replaced by the boundary layer thickness. In the estimation of necessary air flow rate with full scale ships, the use of the average void ratio in the boundary layer can lead to a very large value, since the boundary layer thickness becomes very large. Therefore, in order to find out the importance of the boundary layer thickness in the skin friction reduction effect by microbubbles, an experiment using the 50m-long flat plate ship, in which the air was injected at two different streamwise locations, one at bow (3.0m from the bow end) and the other at middle (31.0m from the bow end), was carried out.

Fig.12 shows the results at two speeds. The data corresponding to the bow injection is denoted as "bow", while those corresponding to the middle injection point is denoted as "middle". The horizontal axis shows the injected air flow rate. At V=5m/sec, the boundary layer thickness is estimated to be 4cm at P1 and 26cm at P4 by the 1/7th-power law. 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. 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 important and that the boundary layer thickness has little effect on the skin friction reduction effect of microbubbles.



(a) V=5m/s



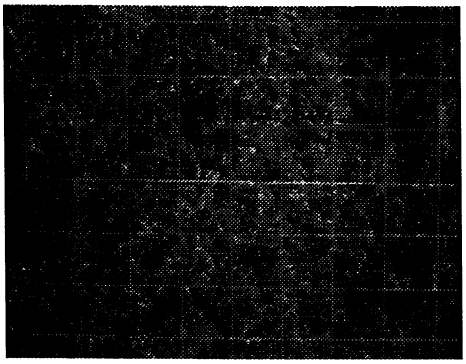
(b) V=7m/s

Figure12 Local skin friction reduction (Air injection from the bow or the middle)

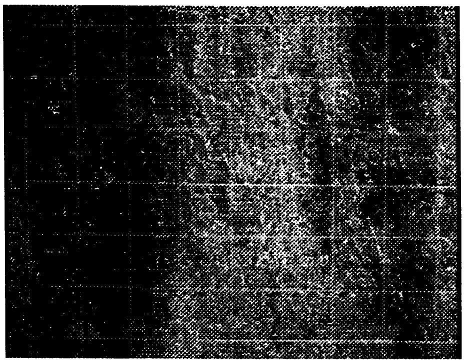
Photographs of microbubbles

Lastly, some photographs of microbubbles are shown in Fig.13. They were taken through acrylic windows at the bottom. The flow is from top to bottom. The white gridlines in the photographs are 10mm apart. Fig.(a) shows the photograph at P1 in the bow injection case. Fig.(b) shows that at P4, again in the bow injection case. Fig.(c) shows that 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 Figs.(a) and (c), the bubbles seem more uniformly distributed in the bow injection case. The diameter of most bubbles were from 2 to 3mm in Fig.(a) and from 3 to 4 mm in Fig.(c)

(a) P1 Bow



(b) P4 Bow



(c) P4 Middle

Fig.13 Photos of microbubbles. V=7m/sec, q=0.04

CONCLUSIONS

Studies on microbubbles were carried out in a 400m-long towing tank using long flat plate ships, in order to find out the scale effect of the skin friction reduction effect. First a 12m-long flat plate ship was used, and the skin friction reduction and the local void ratio distribution were measured. The local void ratio close to the wall had strong correlation with the skin friction reduction. Next, after the improvement of an air injection plate and shear stress sensors, experiments using a 50m-long flat plate ship were carried out in order to elucidate the scale effect of microubbles. It was found out that the skin friction reduction by microbubbles persists up to the downstream end of the 50m-long ship. 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.e., at the bow and at the middle. It was found out that the skin friction reduction effect was a function of the distance from the injeciton point, and that the boundary layer thickness had little effect on the skin friction reduction by microbubbles. Further study is needed to increase the skin friction reduction effect of microbubbles.

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 September 2001. The current results will be utilized in the test.

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