EFFECT OF MICROBUBBLE DISTRIBUTION ON SKIN FRICTION REDUCTION

Yoshiaki Kodama
Ship Research Institute
6-38-1, Shinkawa, Mitaka
Tokyo 181-0004, Japan
kodama@srimot.go.jp

Abstract - Microbubble experiments were carried out using a small circulating water tunnel. The skin friction reduction up to 40% was obtained. The local void ratio was measured using two methods, one by inserting a suction tube in the test section, and the other by counting the bubbles from photographs. The results suggest that the local void ratio near the wall is a dominant factor for the skin friction reduction.

I. INTRODUCTION

It is well known that small bubbles called microbubbles injected into the boundary layer on a solid wall reduce the skin friction significantly[1]. But the energy needed for injection is not nominal, and the net drag reduction is difficult to obtain when it is applied to full-scale ships. Therefore, it is necessary to reduce the amount of air and/or increase the drag reduction by studying the drag reduction mechanism. Recently, studies on microbubbles have been carried out in Japan experimentally[2] and numerically[3]. The author's group are studying the mechanism and the scale effect of microbubbles[4], in order to apply the technique to full-scale ships. In this paper, some recent experimental results will be shown.

II. EXPERIMENTS

II.1 Test facility

A small circulating water tunnel specially designed for microbubble study was constructed (Fig.1). The air is injected in the test section to generate microbubbles. At downstream of the test section there is a dump tank, in which the injected bubbles are removed by buoyancy, thus making continuous tests possible.

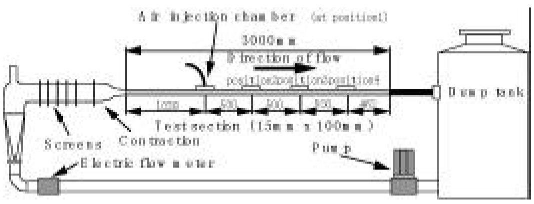


Fig.1 A small circulating water tunnel for testing microbubbles

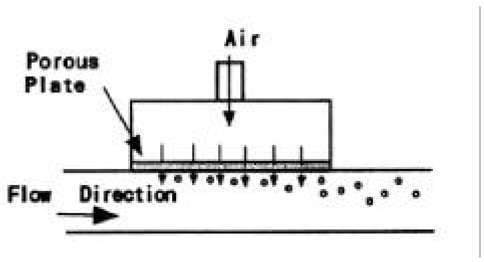


Fig.2 Bubble generation using a porous plate

The tunnel has a test section of 100mm times 15mm times 3000mm in size. The bubbles are generated by injecting air through a porous plate made of metal with nominal pore raduis of 10mum (Fig.2). The plate is located at 1038mm downstream from the upstream end of the test section, where the flow is fully developed. This location will be called Position 1. At three consecutive locations, 500mm apart from each other, various measurements are possible. These locations will be called Positions 2, 3, and 4 in the downstream order.

The amount of injected air is represented by the average void ratio α_a defined as

$$\overline{\alpha}_a \equiv \frac{Q_a}{Q_a + Q_w} \qquad (1)$$

where

Q_a : & air flow rate

Q_w : & water flow rate

II.2 Bubble photographs

Photographs of the microbubbles were taken using a high-definition CCD camera (Fig.3)(5). A YAG laser was used as a light source, taking advantage of its short duration. The light sheet was placed 30mm from the plane of symmetry toward the camera, in order to get a better image. Fig.4 shows the photos at $\alpha_a{}^1$=0.05 in Positions 2 and 3. The flow is from right to left. The top end of each photo corresponds to the upper wall of the test section. The vertical length of the photo corresponds to 10mm. The bubbles are clustered near the top end, where the bubbles were generated. The size of the bubbles are mostly less than 1mm in diameter, although it depends on the flow speed.

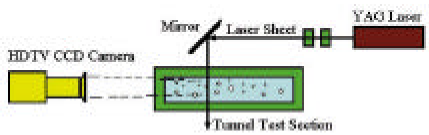
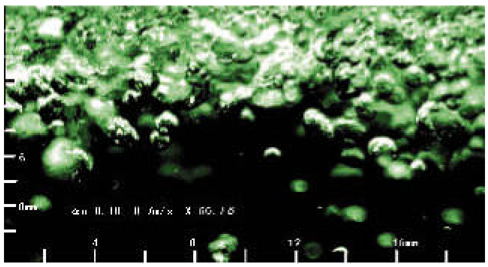
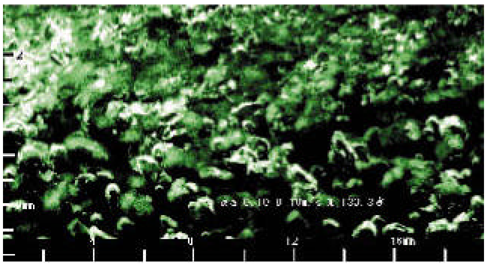


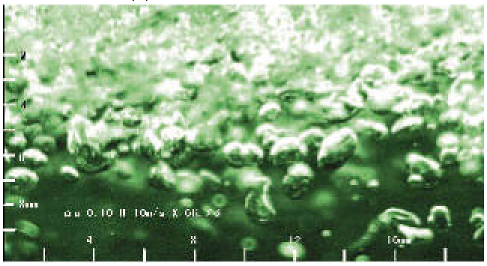
Fig.3 Camera and light source layout(5)



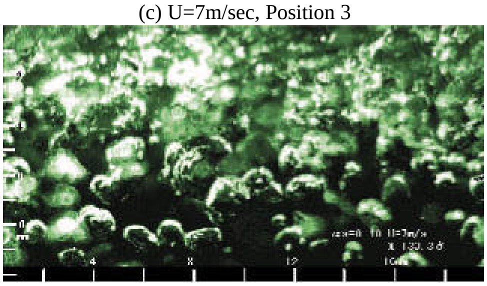
(a) U=7m/sec, Position 2



(b) U=10m/sec, Position 2



(c) U=7m/sec, Position 3



(d) U=10m/sec, Position 3

Fig.4 Photographs of microbubbles at α_a=0.053(5)

II.3 Skin friction

A skin friction sensor is useful in measuring skin friction directly(6). A sensor of 2 grams full scale was used for measuring skin friction with or without bubbles (Fig.5). The sensor was placed on the plane of symmetry of the test section.

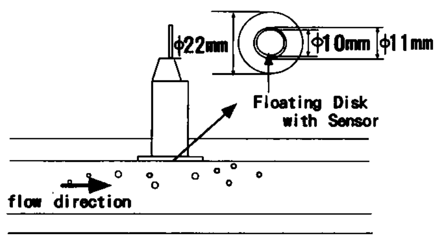


Fig.5 Skin friction sensor

In Fig.6,the measured Cf values are shown as the ratio to C_{f0}, the Cf value in the non-bubble condition. When the air is injected, the flow speed increases, and therefore, in the bubble condition, the C_{f0} value was corrected as a function of Qa using the following formulae.

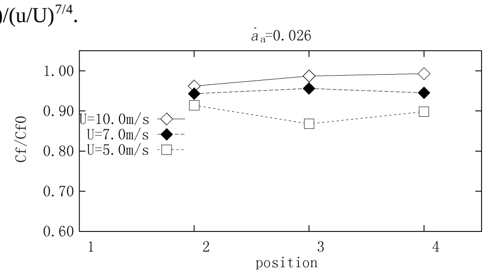
$$C_{f_0}(Q_a) = C_{f_0}(0)\frac{\tau(u)}{\tau(U)} \qquad (2)$$

$$\tau(f) = 0.03325\rho\nu^{1/4}f^{7/4}r^{-1/4} \qquad (3)$$

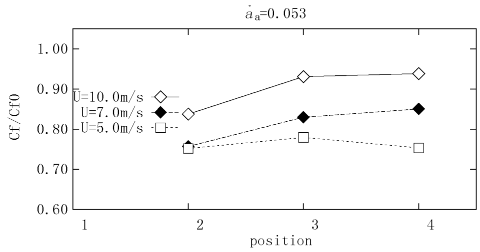
where

C_{f0}(Qa) : Corrected C_{f0} at the air flow rate Qa.
U : Average flow speed at Qa=0.
u : Average flow speed at Qa>0.
r : Hydraulic radius.

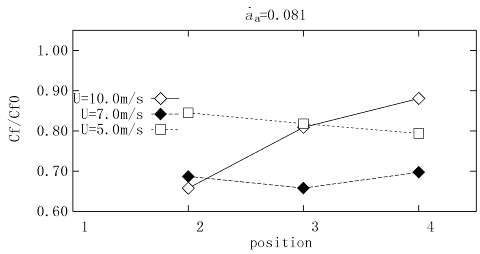
The eq.(3) can be derived from the empirical Blasius formula(7). The above two equations result in multiplying $C_{f0}(0)/(u/U)^{7/4}$.



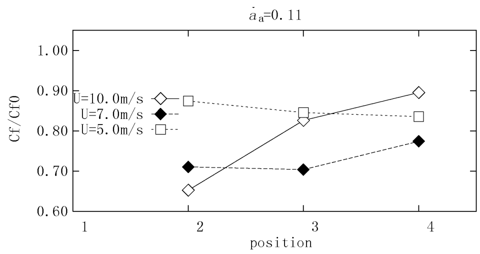
(a) α_a=0.026



(b) α_a=0.053



(c) α_a=0.081



(d) α_a=0.11

Fig.6 Skin friction reduction.

The skin friction was measured at three speeds in three downstream locations, changing the rate of bubble injection. At U=10m/sec, the skin friction reduction increases as α_a increases, saturating at α_a =0.081 and 0.11 and reducing rapidly in the downstream direction. At U=7m/sec, the overall tendency is similar to that at U=10m/sec, except that the reduction persists longer in the downstream direction. At U=5m/sec, the tendency is different from the other two, i.e., the reduction saturates at small α_a values and appears to increase in the downstream direction. In total, the microbubbles are the most effective at U=7m/sec.

What is difficult to understand is that, at α_a=0.026 and 0.053, the skin friction reduction is consistently r at smaller U.

Generally the bubble size is greater at lower speeds due to the smaller shear stress acting on the porous plate where the bubbles are generated, and, if it is true that smaller bubbles cause r skin friction reduction, the tendency should be the opposite.

II.4 Local void ratio

In order to clarify that point, it is necessary to measure local properties. Thus the local void ratio αa was measured using a suction tube system (Fig.7) similar to the one used in ref.6. A small tube with a flat opening was placed in the test section. The tube was connected to a vacuum pump for suction through two chambers to measure air volume and water volume separately.

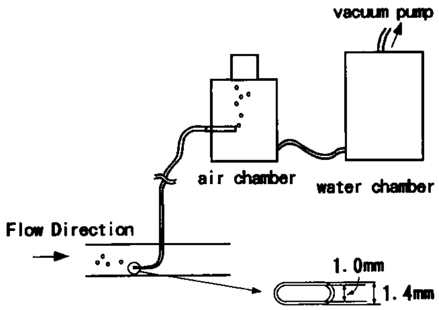
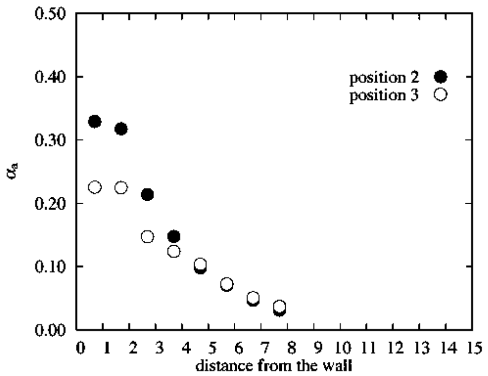
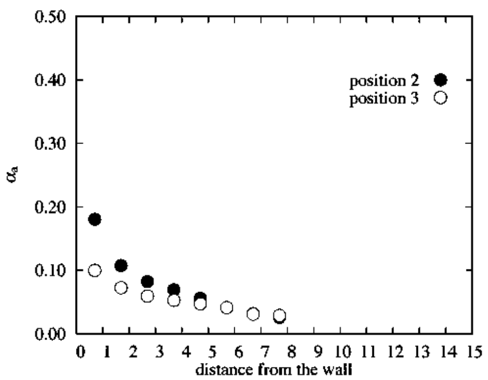


Fig. 7 Suction tube for measuring local void ratio



(a) U=7m/sec



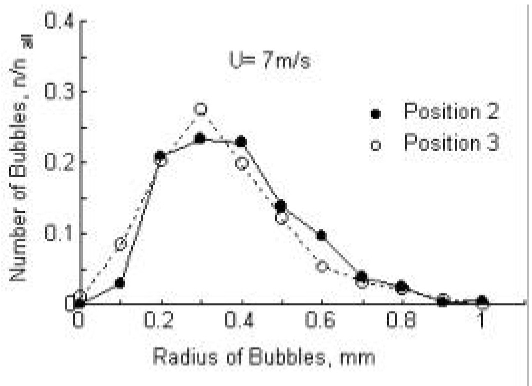
(b) U=10m/sec

Fig.8 Local void ratio αa at $\underline{\alpha}a$=0.053.

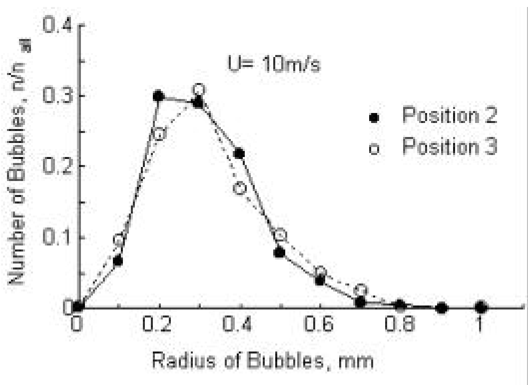
The measurements were made at two speeds in two locations at $\underline{\alpha}a$=0.053 (Fig.8). At U=7m/sec, αa closest to the wall is greater in Position 2 than in Position 3, which, together with the results shown in Fig.6(b), suggests that the local void ratio near the wall is the dominant factor for skin friction reduction. The αa values closest to the wall at U=7 and 10m/sec and in Positions 2 and 3 correlate well with the Cf/Cf_0 values in those conditions. But here is another mystery; the integrated αa at U=10m/sec is clearly smaller than that at U=7m/sec. They should be about the same because $\underline{\alpha}a$ was kept the same.

II.5 Measurements using photographs

The distribution of the bubbles was measured at $\underline{\alpha}a$=0.053 from the photographs as shown in Fig.4. The measurement volume was 18.75mm times 10mm times 1mm, the size of the photo and the thickness of the laser sheet. At each condition the number and size of the bubbles were obtained by counting in eight photos and averaging. The average number of counted bubbles was 111.9 at U=7m/sec and 144.1 at U=10m/sec.



(a) U=7m/sec.



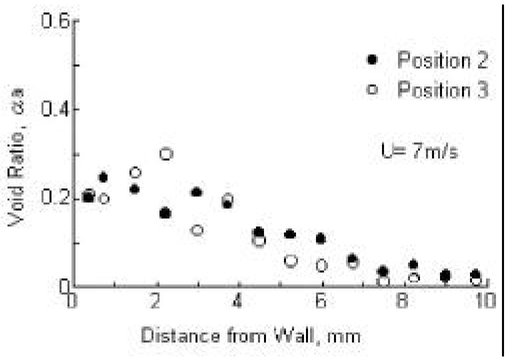
(b) U=10m/sec.

Fig.9 Bubble radius distribution. $\underline{\alpha}a$=0.053.

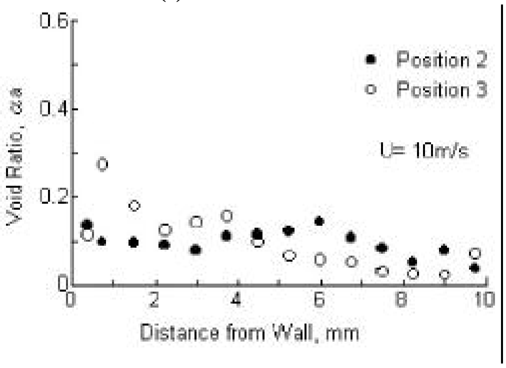
Table 1 Mean bubble radiusms

U \ Position	2	3
7 m/sec	0.38	0.34
10 m/sec	0.31	0.33

Fig.9 shows the bubble radius distribution and Table 1 shows the mean bubble radius. The bubble radius is distributed between zero and 0.8mm. There is no significant difference in Positions 2 and 3. The bubble size is slightly smaller at the higher speed.



(a) U=7m/sec.



(b) U=10m/sec.

Fig. 10 Local void ratio distribution in depthwise direction.

Table 2 Void ratio integrated in half depth.
α_a=0.053 & α_a H/2=0.10ms

Position / U	2	3
7 m/sec	0.118	0.094
10 m/sec	0.111	0.093

Fig.10 shows the local void ratio. Oscillations in the distribution suggest that the number of photographs used in each condition (i.e. 8) was not enough. At U=7m/sec, the distributions in Positions 2 and 3 are similar, and they are comparable to those in Fig.8(a). At U=10m/sec, Position 3 seems to have higher void ratio near the wall, which is in contradiction to that shown in Fig.8(b).

Table 2 shows the integrated void ratio, which was obtained by summing all the bubble volume and dividing by the measurement volume. The corresponding average void ratio termed as α_a H/2 is obtained using eq.(1) where Q_w this time is the flow rate in the upper half of the test section. Thus α_a=0.053 corresponds to α_a H/2=0.10. The integrated void ratios are in good agreement with α_a H/2, suggesting the reliability of this method based on photographs.

This result suggests that the suction tube method whose results are shown in Fig.8 has a problem, especially at U=10m/sec. Further study is needed in this point.

III. CONCLUSIONS

The skin friction was measured in a circulating water tunnel at various flow conditions with or without bubbles. The local void ratio was measured using two methods. They suggest that the local void ratio close to the wall is a dominant factor for skin friction reduction due to microbubbles. Further studies are needed for clarifying the mechanism for skin friction reduction by microbubbles, and for reducing the amount of bubbles needed, in order to put the method into practical use.

IV.REFERENCES

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