Practical application of microbubbles to ships
--- Large scale model experiments and a new full scale experiment ----

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Abstract

To conclude the five-year project on microbubbles, a large scale experiment was carried out using a 22m-long flat plate. A slot plate was used for air injection, in order to be consistent with a full scale experiment. Reduction of local skin friction by microbubbles was measured at ten streamwise and four spanwise locations. The reduction decreased rapidly at immediate downstream of bubble injection, but maintained a certain level further downstream. The spanwise distribution of the reduction showed linear decrease in the outward direction. The void ratio distribution across the boundary layer was measured. It showed decrease in the downstream direction.

A method to estimate drag reduction by microbubbles on an infinitely long flat plate is proposed, based on existing long flat plate results. An equation to approximate the data is obtained by the least square fit.

A full scale microbubble experiment using a cement carrier, to be carried out in mid-February, is described. The experiment is tuned for the ship in fully loaded condition running at 12kt (6m/s). Bubble generators and measuring devices are installed on the ship. By injecting air at the rate 43m3/min, 7.38% drag reduction and 5.44% net power saving is expected. The result will be reported in the symposium.

1.Introduction

Microbubbles, i.e. small air bubbles injected into the turbulent boundary layer developing along a solid surface moving in water, have significant skin friction reduction effect with no harm to the environment, and are regarded as a promising drag reduction device for ships. The purpose of the study on microbubbles in the present research project is twofold. One is elucidation of their skin friction reduction mechanisms. This knowledge helps to improve the skin friction reduction efficiency and to extrapolate it to full scale. The other is for practical application of microbubbles to ships. The present paper summarizes the research for the latter purpose. A large ship such as a tanker has a very wide and flat bottom and, if air bubbles are injected near the bow, they are expected to stay close to the bottom surface by buoyancy and cover efficiently the entire bottom surface. Therefore the present research studies

In order to design microbubble devices for a full-scale ship, one must know how much drag reduction is obtained per given amount of injected air at full scale. Since the skin friction reduction effect of microbubbles persists for a long downstream distance from a point of injection, a most straightforward way to obtain such information is to carry out an experiment of a scale comparable to full scale. Watanabe et al. (1998) towed a 40m-long flat plate in a towing tank, injected air bubbles near the bow, and measured reductions of local skin friction and total drag. In the present research project, similar experiments were carried out using a flat plate as long as 50m. (Kodama et al. 2002a, Kodama et al. 2004, Takahashi et al. 2001, and Takahashi et al. 2003). These experiments showed that the skin friction reduction effect of microbubbles persists for as long as 50m. This suggests that microbubbles are more practical for a larger ship. The next chapter describes those long flat plate experiments.

Although the data obtained in experiments using long flat plates are useful, they have limitations. First, the width of the flat plates, 0.6m or 1.0m, is very small compared with their length, and therefore one has to take into account the side end effect. Second, the surface of a real ship is not always flat, and surface curvature effect should be estimated. Third, side walls of a ship is almost vertical, and surface inclination effect should be estimated. Fourth, bubbles in sea water are smaller than those in fresh water. These circumstances make full scale experiments valuable. Three years ago a full scale microbubble experiment was carried out for the first time in the world (Kodama et al. 2002 and Nagamatsu et al. 2002). Using a training ship called SEIUN-MARU of length L_{OA}=116m, 3% drag reduction and 2% net power-saving were obtained at air injection rate 40m^3/min. This clearly shows that microbubbles are promising as a drag reduction device for ships. Although the full scale experiment was carried out in a project separate from the present one, many members overlapped.

Due to the success of the SEIUN-MARU experiment and steady accumulation of experience on long flat plate experiments, it was decided to install microbubble devices in another full scale ship as a part of the present research project. The installation and full scale measurement are planned in February 2005. The third chapter describes the planning of the coming full scale experiment.

2.Large scale model experiments using long flat plates

Microbubble experiments using a long flat plate were carried out several times at NMRI, as shown in Fig.1 and, to conclude the present research project, another experiment was carried out in December 2004. In the experiment, focus was on spanwise distribution, which was not yet measured. The plate was 22m long and 1m wide. Air was injected at 3.0m from the bow end, through a slot of 5mm length and 0.5m width. The towing speed was mostly V=5m/s or 7m/s, and a few experiments were at V=6m/s, corresponding to the full scale experiment. Local skin friction was measured using skin friction sensors (2gf capacity) made by Sankei Engineering, at ten streamwise locations and at four spanwise locations (0m, 0.125m, 0.25m, and 0.375m from the centerline). Local void ratio in the boundary layer was measured using optical fiber probes of 80 μm diameter made by RBI.

Fig.2 shows the total drag reduction by microbubbles. The horizontal axis shows injected air rate expressed by the equivalent air layer thickness $t_a \equiv Q_a/(B_a V)$, where Q_a is injected air rate, B_a is the width of the slot (0.5m). R_t of the vertical axis is the total drag of the plate. At V=5m/s, the injected air formed an air sheet of a few meters in length at immediate downstream, and then the sheet broke up into bubbles. The skin friction reduction shows an irregular behavior because it reaches almost 100% in the sheet zone, but reduces to zero after break-up of the sheet. This is probably the reason for the saturation of the skin friction reduction effect at large t_a at V=5m/s. The skin friction reduction effect at V=7m/s increases rapidly at large t_a. At V=6m/s, corresponding to the full scale experiment, the formation of an air sheet was not observed, and the reduction of the total drag reaches 19% at t_a=5mm, and therefore it is expected that the conditions are similar to those at V=7m/s. It was confirmed that the use of a SP of 10mm produces results similar to those of 5mm.


Fig.1 A 50m-long flat plate for microbubble experiment

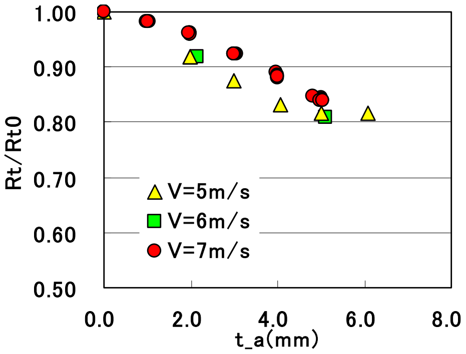
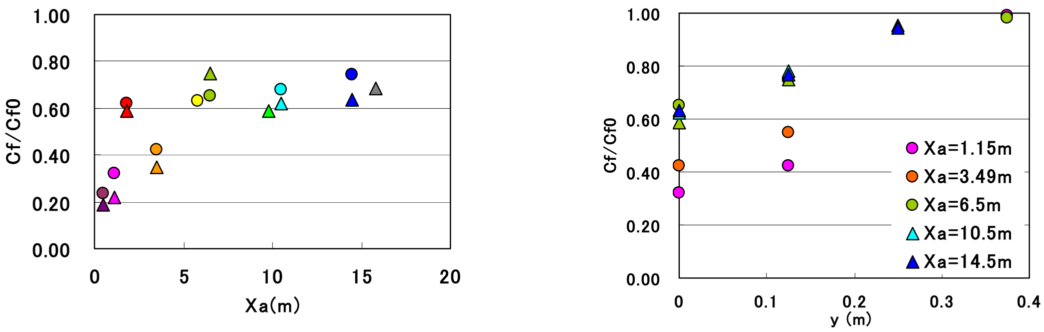


Fig.2 Total drag reduction by microbubbles.

Fig.3(a) shows streamwise distribution of the skin friction reduction. x_a is the downstream distance from the injection point. "○" and "△" denote two different tests with different sensor layout. The reduction effect shows decay in the downstream direction with some oscillation, and shows a plateau behavior after 6m. Fig.3(b) shows the spanwise distribution. y of the horizontal axis is the spanwise distance from the center. The reduction effect shows linear decrease toward the side end located at y =0.5m, and becomes zero at y=0.375m.



(a)Streamwise direction

(b)Spanwise direction

Fig.3 Distribution of skin friction reduction (V=7m/s, t_a =4mm)

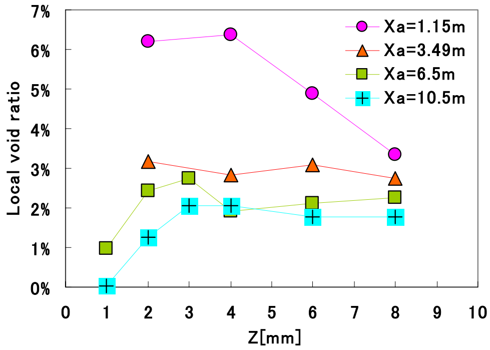


Fig.4 Local void ratio distribution (V=7m/s, t_a =1mm)

Fig.4 shows local void ratio distribution across the boundary layer. All the data were taken at the centerline. The void ratio shows monotonic decrease in the downstream direction, and the rate of decrease becomes small after 3.5m, which corresponds to the tendency of the skin friction reduction shown in Fig.3(a).

3. Estimation of drag reduction on an infinitely long flat plate

Although flat plates used in microbubble experiments are very long, full scale ships are still longer. All the available flat plate data have been collected and plotted in Fig.5 in terms of the drag reduction coefficient C_{DR} defined as

$$C_{DR} \equiv \frac{(-\Delta D)}{\frac{1}{2}\rho Q_a V} \tag{1}$$

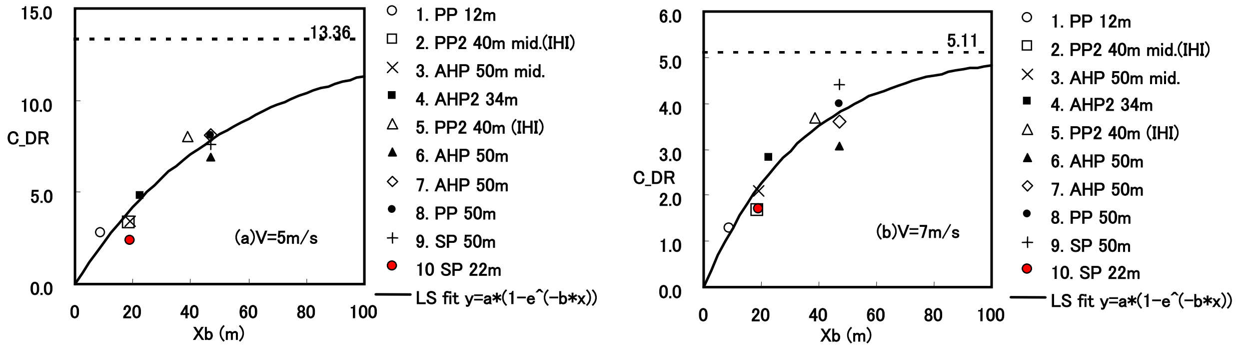
where $(-\Delta D)$ is drag reduction. x_b denotes the length of the plate covered with bubbles. The data denoted as "IHI" are those by Watanabe et al. (1998) and all the others are by NMRI. "PP" means that a porous plate was used for air injection, "AHP" means an array-of-holes plate (1mm diameter), and "SP" means a slot plate (5mm gap). The red symbols denote the present data, in which the value at V=5m/s is considerably smaller than others. The graphs also show least square fit of the form

$$C_{DR} = a[1-\exp(-bx_b)] \tag{2}$$

where values of a and b are shown in Table 1. At V=5m/s the C_{DR} value extrapolated to infinite length is considerably larger than that at x_b =40m, while that of V=7m/s is slightly larger. This tendency is consistent with that of local skin friction reduction, where, at V=5m/s, the reduction still exists at x_b =40m, and, at V=7m/s, the reduction almost vanishes there.

Table 1 Values of a and b by least square fit

	V=5m/s	V=7m/s
a (=max C_{DR})	13.356	5.111
b	0.0188	0.029



(a)V=5m/s (b)V=7m/s

Fig.5 Total drag reduction data and their least square fitting

4. A new full scale experiment

4.1 Characteristics of the experiment

The experiment will be carried out in mid-February 2005. The tested ship is PACIFIC SAEGULL, a cement carrier owned by the Azuma Shipping Co., Ltd. Its principal particulars and the photograph are shown in Table 2 and Fig.6. This type of ship is particularly suited to microbubbles. The ship is equipped with blowers and related piping for feeding air to load and unload cement. They can be used to supply air for microbubbles, and only a small amount of additional work is needed to install microbubbles. Also, a cement carrier has a box shape hull with a long parallel part, and the bubbles injected near the bow are expected to cover a large portion of the bottom surface efficiently.

Table 2 Principal particulars of PACIFIC SEAGULL

Length: L_{OA}=126.66m, Lpp=120.0m
Breadth: B=21.4m
Depth(mould): D=9.90m
draft (full): d=7.215m
Engine power (CSO): 4,488PS
Propeller: 4-bladed CPP, Diameter=3.600m
Speed (CSO): V=12.4 kt
Gross tonnage: 7,809 ton

Fig.6 PACIFIC SEAGULL

4.2 Installation of microbubble devices

(1)Bubble injectors

Air is fed by a blower of 43m^3/min capacity. Bubble injectors, which is 5m long and have small holes to inject air, are attached on both sides of the hull surface near the bow. Air is fed through pipes that penetrate the hull surface. The injectors are designed to be used only in the fully loaded condition. The sum of hydrostatic pressure, dynamic pressure, and pressure loss through pipes is made smaller than the maximum supply pressure of the blower. Using CFD for computing bubble trajectories around the ship hull at the full scale Reynolds number, bubble injectors are designed such that injected bubbles travel to the hull bottom and cover efficiently the hull surface. Since, based on the SEIUN-MARU experiment, it is expected that bubbles going into a working propeller deteriorate the propeller efficiency, the bubble injectors are also designed to avoid the bubble inflow.

(2)Measurement devices

Strain gauges were attached on the propeller shaft in order to measure thrust and torque. If the propeller-hull interaction does not change with bubbles, one can estimate drag reduction by measuring thrust.

Two mechanical type local skin friction sensors for full scale experiments were manufactured and attached on the hull bottom approximately 20m downstream of the bubble injector. LED lights are installed inside the sensor housing for illumination through the floating balance plate (20cm by 20cm) made of a transparent acrylic plate.

Since bubble trajectory information is important, twelve underwater TV cameras are attached on the hull surface. Three of them are installed above the bubble injector to monitor bubble injection. Three are installed near the two skin friction sensors, in order to observe bubble behavior over them. Two are installed on the aft part of the bottom surface, to monitor bubble movement in that area. Two are placed upstream of the propeller to monitor bubble inflow into the propeller. The last two are installed on the hull side.

4.3 Estimation of net power saving

If ship speed V is assumed constant before and after bubble injection,

$$V_{\text{bubble}} = V\,. \tag{3}$$

Let D be the drag of a ship and $(-\Delta D)$ be the drag reduction. Then

$$(-\Delta D) \equiv D - D_{\text{bubble}}\,. \tag{4}$$

W, the power needed to propel a ship, reduces with bubbles by the amount $(-\Delta W)$.

$$(-\Delta W) \equiv W - W_{\text{bubble}} = (-\Delta D)V \tag{5}$$

Then the nominal power-saving rate r_{nominal} is defined as

$$r_{\text{nominal}} = \frac{(-\Delta W)}{W} = \frac{(-\Delta D)}{D}\,, \tag{6}$$

and the net power-saving rate r_{net} is defined as

$$r_{\text{net}} = \frac{(-\Delta W) - W_{\text{pump}}}{\mathrm{W}} = r_{\text{nominal}} - r_{\text{pump}}\,, \tag{7}$$

where W_{pump} is pumping power for air injection and r_{pump} is its rate .

Using the equations derived above, the values of power-saving rates for the cement carrier is estimated. Table 3 shows estimated results. . The C_{DR} at V=6m/s is estimated by interpolating the values shown in Table 1. By injecting air at a rate 43m^3/min, the drag of the ship in the fully loaded condition will decrease by 7.38%. The pump power needed for injecting air is 1.94% of the power required to propel the ship. In summary, the net power-saving rate will be 5.44%.

Table 3 Estimated power-saving rates

item	value
C_DR	7.604
t_a (mm)	11.6
r_nominal	7.38%
r_pump	1.94%
r_net	5.44%

5.Conclusions

Microbubbles have a large potential as a drag reduction device for ships because of their significant skin friction reduction effect and freedom from pollution. In the present research project much effort has been spent on large scale microbubble experiment using a long flat plate, simulating flat bottom of a tanker, whose maximum length reaches 50m, almost comparable with a full scale ship. The skin friction reduction behavior after injection is complicated and depends to some extent on the way air is injected. The slot injection method, regarded as suitable for full scale application, has been found to be useful at speed larger than 6m/s, below which an air sheet is formed at injection point thus leading to no skin friction reduction after break-up. The general behavior of the streamwise distribution of the reduction effect is that it quickly reduces at immediate downstream of injection and shows gradual decrease further downstream. The spanwise distribution of the skin friction reduction effect shows that there is no constant reduction region and that the reduction reduces linearly toward the side end, which suggests that injected bubbles steadily diffuse toward side ends and are lost steadily across them. The local void ratio distribution across the boundary layer, measured at several downstream locations, supports this tendency because the bubbles near the solid wall quickly diffuse at immediate downstream of injection, but show gradual diffusion after that.

The total drag reduction data thus obtained are utilized to estimate the drag reduction at full scale, by first estimating drag reduction on an infinitely long flat plate. This method is purely empirical and can be regarded to be on the safe side, i.e. estimating smaller drag reduction than real, because the data suffer from the loss of bubbles due to diffusion across side ends of a flat plate, while, at full scale, the loss is expected to be much smaller. Using the data, the drag reduction of a cement carrier running at 12kt is estimated as 7.38% at air injection of 43m^3/min. This value is large enough to support practical application of microbubbles.

Cement carriers are equipped with blowers (pumps) that feed air for loading and unloading cement. They can be used to inject air for microbubbles, and therefore the installation of microbubbles to such a ship requires minimum amount of additional investment. Further, the ships have wide and flat bottom, and therefore they are particularly suited to microbubbles. Installation and running of microbubble devices are scheduled very soon, and the results of the full scale experiment will be reported at the symposium.

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