Drag Reduction of Ships by Microbubbles

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ABSTRACT

Microbubbles, a skin friction reduction device, has significant effect, and is especially suited to ships. The authors constructed a circulating water tunnel for microbubble experiment and found out strong correlation between skin friction reduction and local void ratio close to the wall. The authors then carried out experiment by towing a 50m-long flat plate ship at 7m/sec in a towing tank, and obtained scale effect data of microbubbles. Based on the data, net drag reduction effect of microbubbles when it is applied to a 300m-long tanker was estimated. It was found out that at fully loaded condition net drag reduction is almost zero, that at ballast condition 2% net reduction, and that, if the reduction efficiency is doubled, net drag reduction of 5% is obtained at fully loaded condition. Further study to improve drag reduction efficiency and to solve related problems is needed.

WHY MICROBUBBLES?

Microbubbles is a drag reduction device that reduces skin friction of a solid body moving in water by injecting small bubbles into the turbulent boundary layer developing on the solid body. Microbubbles has been studied by many researchers since the pioneering work of McCormick and Bhattacharyya [1]. Fig.1 shows an example [2] of its skin friction reduction effect. The data was taken in a circulating water tunnel, where the bubbles were injected at the top flat wall and skin friction was measured by a skin friction sensor placed downstream of the injection point. The horizontal axis shows the amount of injected air and the vertical axis shows the ratio of reduced skin friction to that at non-bubble condition. This figure shows that, as the amount of injected air increases, skin friction reduction effect by microbubbles increases up to 80%.

Ships such as tankers play a major role in marine transportation. They are very large and move very slowly. They are especially suited to microbubbles. Fig.2 shows an image of the application of microbubbles to such a ship. One reason that they are suited is that their skin friction drag component occupies about 80% of the total drag. The drag of a ship that moves on the water consists of two components, i.e., wave-making drag and skin frictional drag. The wave-making drag component of such a ship is very small because they move very slowly. Another reason that they are suited is in their shape. Their shape is like a box, except for bow and stern regions. They have a wide flat bottom, and the bubbles injected at the bottom near the bow stay close to the hull bottom by buoyancy while they are carried by flow all the way to the stern. Thus the injected bubbles can cover the whole hull bottom efficiently.

In Japan, microbubbles has been studied intensively in the past few years toward its application to full-scale ships. This paper reports a review of such studies, focusing on those carried out by our group in NMRIJ.
Skin Friction Reduction Effect

Microbubbles have significant skin friction reduction effect. The authors carried out microbubble experiment using a circulating water tunnel shown in Fig. 3. In the test section, air is injected through a porous plate set on the top wall at Position 1. Measurements are carried out in the downstream locations P2, P3, and P4, each 500mm apart. At the downstream of the test section, there is a damp tank, where injected bubbles are removed by buoyancy, so that continuous microbubble experiment is possible.

A photograph of microbubbles is shown in Fig. 4. The average flow speed in the test section was 7m/sec, or 14 kts, which corresponds to typical cruising speed of a tanker. The average void ratio, i.e., the ratio of air volume to the total volume of air-water mixture, was 5.3%. The actual longitudinal length of the photo is 10mm, and the top side corresponds to the top wall of the test section. The bubbles are clustered near the top wall. The bubble diameter was 0.5mm to 1.0mm.

Fig. 5 shows the measured skin friction reduction. The horizontal axis shows $\bar{\alpha}$, the average void ratio in the test section, and the vertical axis shows the ratio of the wall skin friction with and without bubbles. As the amount of injected air increases, skin friction reduction increases, and the maximum reduction of 30% is obtained. The solid line shows the measured result by Merkle et al. [2]. The authors’ results agree with Merkle’s at higher void ratio. Fig. 6 shows the distribution of local void ratio at $\bar{\alpha}$=8%, at three streamwise locations. The local void ratio is defined as the ratio of the air volume to that of air-water mixture at a given point. This figure shows that the bubbles are clustered near the top wall and tend to diffuse as they move downstream.

Skin Friction Reduction Mechanism

Although there is no well-established theory for skin friction reduction mechanism of microbubbles, one possible mechanism is the density effect, which means that, since the density of air is about 1/1000 of that of water, the layer of clustered bubbles near solid wall cuts off shear stress on water and reduces skin friction. The results shown in Figs. 5 and 6, although the difference is small, shows that there is correlation between the magnitude of the skin friction reduction and the local void ratio near the solid wall at positions P2, P3, and P4. Guin et al. [3] also show similar results.

Another possible reduction mechanism is the turbulence suppression effect, i.e., bubbles suppress
turbulence in the boundary layer, resulting in skin friction reduction. Kato et al. [6] measured turbulence intensity very close to the solid wall in the bubbly channel flow and showed that turbulence intensity decreases as the skin friction increases. The authors think that, in reality, both mechanisms work to get skin friction reduction.

**SCALE EFFECT IN SKIN FRICTION REDUCTION BY MICROBUBBLES**

In order to be able to estimate skin friction reduction effect of microbubbles when it is applied to a full-scale ship, it is necessary to carry out large-scale experiments and find out how far in the downstream direction the skin friction reduction effect of microbubbles persists after injection. Watanabe et al. [7] measured the reduction effect by using a flat plate ship of 40m long and 60cm wide in a towing tank. The authors carried out a similar experiment using a flat plate ship of 50m long and 1m wide in their 400m-long towing tank. Fig.7 shows the flat plate ship that they used, and Fig.8 shows the distribution of skin friction reduction in the streamwise direction. It is seen that the skin friction reduction effect persists to the downstream end at both speeds of U=5m/sec and 7m/sec, which is a good sign for its application to a large ship. The skin friction reduction effect is smaller at the higher speed of 7m/sec, whose reason may be that injected bubbles diffuse from the solid wall faster at higher speeds. Further study is needed. Watanabe et al. [6] obtained higher skin friction reduction at U=7m/sec than the authors. One of the differences between the two is that they used a porous plate for bubble injection and the authors used an array-of-holes plate, which has many 1mm diameter holes arranged in arrays. Further study on this point may lead to improvement in skin friction efficiency.

Figs. 9(a), (b) show reduction of the total drag of the 50m-long ship by microbubbles [8]. The horizontal axis shows the flow rate of injected air nondimensionalized by the ship speed V and the injection area S (50cm×10cm). The vertical axis of Fig.9(a) shows the ratio of the total drag with bubbles to that without bubbles. The vertical axis of Fig.9(b) shows the ratio of the estimated skin friction of the part downstream of the air injection plate with and without bubbles. The former was estimated,
based on the assumption that the skin friction reduction occurs only in the area downstream of the air injection plate, and the latter was estimated, based on the well-established Schoenherr skin friction formula for a flat plate. These two figures show the same data with different denominators. Fig.9(b) shows that the maximum skin friction reduction of 23% is obtained at V=7m/sec.

NET DRAG REDUCTION BY MICROBUBBLES

In order to assess the applicability of microbubbles to ships, it is necessary to discuss its net drag reduction effect by taking into account the energy needed for injecting air bubbles into water. In this section, net drag reduction of microbubbles is estimated following the line of argument by Merkle [2] with slight modification.

Net Work Ratio

The net work ratio \( r_w \), i.e., the ratio of net work rate needed to propel a ship while injecting bubbles to that with no bubbles, is

\[
r_w \equiv \frac{W_{\text{net}}}{W_0} = \frac{DU_\infty + W_{\text{pump}}}{D_0U_\infty} = \frac{D}{D_0} + \frac{W_{\text{pump}}}{D_0U_\infty}
\]

(1)

where

- \( W_0 \): work rate to propel a ship in non-bubble condition
- \( W_{\text{net}} \): net work rate to propel a ship in bubble condition
- \( D_0 \): ship's drag in non-bubble condition
- \( D \): ship's drag in bubble condition
- \( U_\infty \): ship's speed. Assumed to be unchanged by bubble injection.
- \( W_{\text{pump}} \): work rate for bubble injection

\( r_w = 1.0 \) when net drag reduction is zero, and \( r_w < 1.0 \) when there is net drag reduction effect.

\( W_{\text{pump}} \) is expressed by taking into account the energy loss due to head pressure at injection point and the local pressure there.

\[
W_{\text{pump}} = Q_A \left( \rho gd + C_p \times \frac{1}{2} \rho U_\infty^2 \right)
\]

(2)

where

- \( Q_A \): air flow rate for bubble injection
- \( \rho \): water density
- \( g \): gravity acceleration

\( d \): water depth at injection point

\( C_p \): local pressure coefficient at injection point

Ship's drag \( D \) is expressed in a conventional nondimensional form.

\[
D = \frac{1}{2} \rho U_\infty^2 SC_T
\]

(3)

where

- \( S \): wetted surface area of a ship
- \( C_T \): total drag coefficient
- \( C_F \): frictional drag coefficient
- \( C_W \): wave drag coefficient
- \( C_{F_0} \): frictional drag coefficient of equivalent flat plate (having the same area and length as the ship)
- \( K \): form factor of a ship hull

Schoenherr's empirical formula is used to estimate frictional drag of the equivalent flat plate.

\[
\log(R_eC_{F_0}) = \frac{0.242 \log 10}{\sqrt{C_{F_0}}}.
\]

(4)

where \( R_e \) is the Reynolds number.

\( \bar{D} \), the drag coefficient of a ship in bubble condition, is expressed as

\[
\bar{D} = \frac{1}{2} \rho U_\infty^2 S\bar{C}_T
\]

\[
= \frac{1}{2} \rho U_\infty^2 S(\bar{C}_F + C_W)
\]

\[
= \frac{1}{2} \rho U_\infty^2 S[(1 + K)\bar{C}_{F_0} + C_W] ,
\]

(5)

where it is assumed that \( C_W \) and \( K \) do not change with bubble injection.

Thus, the net work ratio \( r_w \) is expressed as

\[
r_w = \frac{\bar{D}}{D} + \frac{W_{\text{pump}}}{DU_\infty}
\]

\[
= \frac{\bar{C}_{F_0} + r_D}{C_{F_0}} + \frac{Q_A}{U_\infty S} \frac{2}{F_d^2} + C_p
\]

\[
= \frac{1 + r_D}{1 + r_D} + \frac{Q_A}{U_\infty S} \frac{2}{(1 + K)C_{F_0}} \frac{1}{(1 + r_D)}
\]

(6)

where
\[ r_D \equiv \frac{C_W}{(1 + K)C_{F_0}} : \text{ratio of wave drag to viscous drag} \]

\[ F_d \equiv \frac{U_\infty}{\sqrt{gd}} : \text{Froude number based on water depth} \]

**How to Increase Drag Reduction Effect**

Using eq.(6), we can say that following five points are important to increase skin friction reduction effect and thus decrease \( r_W \).

1. Reduce \( r_D \), i.e., choose a hull form that has small wave drag.
2. Reduce \( \frac{C_{F_0}}{C_{F_0}} \), i.e., increase skin friction reduction effect by microbubbles.
3. Reduce \( \frac{Q_A}{U_\infty S} \), i.e., reduce injected air flow rate.
4. Increase \( F_d \equiv \frac{U_\infty}{\sqrt{gd}} \), i.e., speed up and/or make draft shallower. This is because the loss(work needed for air injection) is static(speed-independent), and the gain (skin friction reduction) is dynamic(proportional to speed squared).
5. Reduce \( C_p \), i.e., inject air at a location that has low pressure.

**Drag Reduction Estimation in Case of a Tanker**

The net work ratio \( r_W \) is estimated for a large tanker with 300m length and the speed of 14kts. Typical parameter values for this case are,

- Ship length \( L = 300m \), \( d = 20m \) (full load), \( S = 0.24L^2 \), \( U_\infty = 7m/sec \), \( K = 0.35 \), \( F_0^2 = 0.25 \), \( r_D = 0.25 \), \( C_p = 0 \), \( R_e = 2.1\times10^9 \), \( C_{F_0} = 0.0014 \)

The relation between injected air flow rate \( Q_A \) and skin friction reduction effect \( \frac{C_{F_0}}{C_{F_0}} \) is roughly estimated, using the data of a 50m-long flat plate ship shown in Fig.9(b). First, the skin friction reduction effect of a full-scale ship \( \frac{C_{F_0}}{C_{F_0}} \) is assumed to be \( \frac{C_{F_0}}{C_{F_0}} = 0.77 \), the same value as that of the 50m-long flat plate ship. Then \( Q_{AS} \) (\( S \) means "ship"), the air flow rate in full scale is estimated by multiplying \( Q_{AS} (M \text{ means "model"}) = 0.04\times0.05\times7 = 0.014m^3/s \), the air injection rate at 50m-long flat plate ship, with the area ratio \( \frac{S_S}{S_M} = \frac{21600}{0.5\times50} = 864 \) to be

\[ Q_{AS} = 12.1m^3/s \]. In this case, using eq.(4.6), the net work ratio becomes \( r_W = 1.078 \), slightly greater than 1, which means that net drag reduction is not obtained. On the other hand, in the ballast condition (empty condition), the draft becomes \( d = 12m \), then \( r_W = 0.979 \), approximately 2% net reduction being obtained. This means that, using the present level of technology, a tanker that runs between Japan and the Middle East can get net drag reduction one way. If the amount of air can be economized to half by improving techniques, the net work ratio becomes \( r_W = 0.952 \) even at full load condition of \( d = 20m \). In general, in order for an energy-saving effect not to be embedded into measurement errors, it has to be 5% at least, and therefore, this much of net drag reduction is needed.

This rough estimation suggests that, in order to put microbubbles into practical use, it is necessary to improve drag reduction efficiency at least twice as much and/or to combine the technique with other efforts such as developing a new hull form suited for microbubbles like one with very shallow draft and very wide flat bottom. Also it is necessary to take measures to prevent fouling at air injection, and to estimate influence on noise and vibration problems, and to prevent them if necessary.

The research done by the present authors and presented in this paper was carried out under research programs shown below.


Lastly, a full-scale microbubble experiment using a 105m-long ship will be carried out by the SR239 project.
REFERENCES


