Frictional Drag Reduction with Air Lubricant over Super Water Repellent Surface (2nd Report)
—Resistance Tests of Tanker and High Length-to-beam-ratio Ship Models—

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Summary

In the 1st report, a new technique for reducing frictional drag using a super water repellent surface and air-injection (SWR & A method) was proposed, and its effectiveness for two-dimensional flow was confirmed by carrying out pressure loss tests in a rectangular tube and resistance tests on a horizontal flat plate.

This paper presents the results of resistance tests applying the new technique to a tanker model of 7.2 m long and a high length-to-beam-ratio ship model of 12 m long. The results of these tests show that the new technique can significantly reduce frictional drag of the tanker model and the high length-to-beam-ratio ship model, and that frictional drag on the SWR surface of the 12.0 m high length-to-beam-ratio ship model was reduced by 75% at a speed of 6 m/sec, which is the same reduction rate obtained with the flat plate.

1. Introduction

In the 1st report1), a new concept of frictional drag reduction was proposed and its effectiveness was confirmed by conducting pressure loss tests in a rectangular tube and resistance tests on a horizontal flat plate. The new frictional drag technique makes use of the property of specific surface coating (Super water repellent surface or SWR surface), which is highly water repellent and capable to forming a thin air film over surfaces under water so as to keep the surface free from wetting. When a small amount of air is supplied to the SWR surface in water, the air is absorbed by and joins with the primary air film and spreads to form a film of air along the surface. The new technique (SWR & A method) uses this phenomenon to reduce frictional drag in water. In the 1st report, pressure loss tests in the flow through a rectangular tube, 2.5 m long and with internal dimensions of 30 mm high and 60 mm wide, showed that the frictional drag on the SWR surface was disappeared or reduced by 80% at a speed of 4 m/sec and by 50% at 8 m/sec. Resistance tests on a horizontal flat plate, 2.14 m long and 0.425 m wide, the bottom surface of which was coated with the SWR material, showed that the frictional drag of the SWR surface was reduced at the same rate as that obtained with the rectangular tube flow.

There is a strong demand for reduction in frictional drag, especially in the marine transportation business. This is because fluid frictional drag experienced by ships is very large. Ship drag is generally broken down into a wave-making resistance, a form drag, an air resistance and a fluid frictional drag. And the fluid frictional drag accounts for as much as 60 to 70% of the total drag of a cargo ship, and about 80% of a tanker. For this reason, many different methods have been tried to reduce ship frictional drag such as the micro bubble method2),3), the air sheet method4) and so on, but none of them has proved practical as yet because more energy is consumed than is saved by such drag reduction techniques. For example, the micro bubble method similar to the SWR & A method, requires a lot of energy to generate sufficient micro bubbles, and the micro bubbles tend to depart from the hull surface.

As shown in the 1st report, the SWR & A method holds promise for ship hull drag reduction because the effective downstream area is larger, the effective ship speed is higher and air supply energy requirement is less than previous methods. Accordingly, we examined the validity of the SWR & A method to ships by conducting two ship model tests; one, a 7.2 m tanker ship model to examine the three dimensional flow effect, and the other, a 12 m high length-to-beam-ratio ship model (called Pencil ship) to test effectiveness in the high speed range and look for large downstream effects.

2. Tested Ship Models

The bottom was chosen as the most effective part of a ship's surface for applying the SWR & A method because air is prevented from rising to the water surface. A tanker model was used for one of the models.
Tankers, especially VLCCs (Very Large Crude Oil Carriers), sail at speeds of less than 15 knots (7.7 m/sec) and have large flat bottoms which represent a half of the water-immersed area, and tankers’ frictional drag accounts for more than 80 percent of the total drag.

Towing tank model tests are restricted by model size and towing speed, which are limited by towing carriage power and measuring dynamo-meter capacity. Moreover, waves made by the ship model become too high to test and flow into the model when testing speed gets too high. The wave height generated by the model ship depends not only on towing speed but also ship model width. Therefore, a special high length-to-beam ratio ship model (Pencil ship) was used in order to carry out the model tests involving longer downstream length and higher speeds in the towing tank.

2.1 Super Water Repellent (SWR) surface

The bottom of the ship models were under-coated with a silicone resin paint and top-coated with the super-water-repellent paint using an airless paint blower. The SWR surface has an angle of contact with the water of more than 160°.

Fig. 1 shows a picture of the SWR surface magnified 500 times.

2.2 Tanker model

A 7.2 m long wooden tanker model in the form of a scaled 280,000 ton VLCC (length = 318 m) was used, the flat bottom of which was coated with the SWR paint or the conventional paint over an area of 3.66 m long and 0.86 m wide. The sides of the SWR surface have steps of 1.0 mm, that is the SWR surface is 1.0 mm lower than the hull bottom, to improve the air-holding characteristics. But the step at the after-end part of the SWR surface is rounded in order to let the air flow smoothly. At the fore-end part of the SWR surface, a slit nozzle of 1 mm high is located. In addition, 10 mm high side air-guarders can be attached to both sides of the SWR surface in an attempt to improve air-retention.

The model has 2 mm high studs as turbulence stimulators at station 9.5 to create turbulent flow around the model.

A mid-ship section of the tanker model with side air-guarders is shown in Fig. 2-1, and the principal dimensions of the tanker model and testing conditions are given in Table 1.

Fig. 3 shows a picture of the tanker model upside down. The white portion on the bottom is the SWR surface.

2.3 Pencil ship

A high length-to-beam-ratio ship model of 12 m long and 0.3 m wide was called “Pencil ship”, and which was made to test the effectiveness in the high speed range and look for large downstream effects. The model has a flat bottom with side air-guarders of 15 mm high on both sides to prevent the air escaping from the bottom, and the bottom was coated with the SWR paint or the conventional paint over an area 9.325 m long and 0.3 m wide.

The principal dimensions of the pencil ship are given in Table 1, and the mid-ship section of the model is shown in Fig. 2-2.

Fig. 4 shows a picture of the pencil ship turned over.
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Table 1 Tested models and conditions

<table>
<thead>
<tr>
<th>MODELS</th>
<th>LENGTH &amp; WIDTH</th>
<th>LOAD CONDITION</th>
<th>MEAN DRAFT</th>
<th>TRIM</th>
<th>S.W.R. SURFACE</th>
<th>SWR % IN TOTAL SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TANKER</td>
<td>Lpp=7.267m; B=1.28m</td>
<td>FULL</td>
<td>0.40m</td>
<td>0m</td>
<td>L=3.66m, b=0.86m, (L1=1.413m, L2=5.073m)</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BALLAST(1)</td>
<td>0.200m</td>
<td>0m</td>
<td>L=3.66m, b=0.86m, (L1=1.413m, L2=5.073m)</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BALLAST(2)</td>
<td>0.091m</td>
<td>0m</td>
<td>L=3.66m, b=0.86m, (L1=1.413m, L2=5.073m)</td>
<td>31%</td>
</tr>
<tr>
<td>PENCIL SHIP</td>
<td>Lpp=12.0m; B=0.3m</td>
<td>FULL</td>
<td>0.15m</td>
<td>0m</td>
<td>L=9.235m, b=0.3m, (L1=1.665m, L2=10.9m)</td>
<td>38%</td>
</tr>
</tbody>
</table>

Fig. 3 A 7.2 m tanker model coated with SWR paint on the bottom (turned over)

Fig. 4 A 12 m pencil ship (high length-to-beam ratio model) coated with SWR paint on the bottom (turned over)

2.4 Testing apparatus and air supply

Tests were carried out on both the conventional and the SWR surfaces to measure the effectiveness of the SWR & A method. In the case of the conventional surface, the model bottom is painted with a conventional paint and air is not supplied to the bottom surface.

The resistance tests of the tanker model with the SWR surface were carried out with and without air-guarders to examine their effectiveness.

A slit nozzle with a 0.5 mm clearance for injecting air is placed upstream of the SWR surface and the air is supplied from a compressor on the towing carriage.

The amount of the air supply, Q(l/sec), is shown in mm as the Air supply Level (AL) defined by the following equation.

\[ Q(l/sec) = U(m/sec) \times b(m) \times AL(mm) \]  

where \( U \) : air supply volume under the water pressure condition of the nozzle depth, \( b \) : ship model speed, \( b \) : width of the SWR surface, \( AL \) : air supply level.

That is, \( AL \) is an index representing the average air film thickness (mm) calculated on the assumption that the air flows uniformly at the same speed as the ship model.

3. Test Results

3.1 Frictional drag reduction rate (DR%) on the SWR surface

Ship model resistance tests were carried out on the two bottom surfaces, that is, (1) the conventional surface without air supply and (2) the SWR surface with air supply, respectively.

Fig. 5 Schematic view of ship model equipped with SWR & A technique
supply.

The frictional drag reduction rate (DR%) is calculated by the following equation.

$$DR(\%) = \frac{R_{et}-R_{sur}}{R_{et}}$$  \hspace{1cm} (2)

where $R_{et}$: the total resistance of the ship model with the conventional surface and without air injection, $R_{sur}$: the total resistance of the ship model with the SWR surface and air injection, $R_{etu}$: the total frictional drag of the area of the conventional surface to be coated with the SWR paint.

$R_{etu}$ is calculated using the following equation.

$$R_{etu}=0.5 \times \rho \times U^2 \times b \times \int_{L_1}^{L_2} C_f' \text{d}x,$$  \hspace{1cm} (3)

where $C_f'$ is Schoenherr's local frictional coefficient for conventional surface, $\rho$: water density, $U$: ship model speed, $b$: width of the SWR surface on the ship bottom, $L_1$: the distance from bow to the fore end of the SWR surface, $L_2$: the distance from bow to the aft end of the SWR surface.

$R_{et}$ and $R_{etu}$ are the recalculated values to the same speed and the same water temperature condition from the measured data.

From equation (2), it can be understood that DR% = 100% means the frictional drag on the SWR surface is 0 or perfectly disappears, and DR% = 0% means there is no frictional reduction.

3.2 Tested results of the 7.2 m tanker model

Tanker model tests were carried out under three conditions, (1) full load (no trim), (2) ballast load (no trim), and (3) ballast load (trim by stern; bow-up trim).

The quantity of the air supply to the SWR surface was $AL=1.0$.

3.2.1 Full load condition

Resistance tests were carried out under three conditions; (1) conventional surface without side air-guarders and without air injection, (2) the SWR surface without side air-guarders and with air injection, and (3) the SWR surface with side air-guarders and with air injection.

Fig. 6 Resistance test of the pencil ship (high length-to-beam ratio model) in a 220 m towing tank

Fig. 7 shows measured ship resistance in the form of total resistance coefficient defined by the following equation.

$$C_l = R/0.5 \times \rho \times S \times U^2,$$  \hspace{1cm} (4)

where $R$: measured model resistance, $\rho$: water density, $S$: ship model wetted area including the SWR surface area, $U$: ship model speed measured by a current meter in the towing tank.

Froude number is calculated with the following equation.

$$F_r = U/\sqrt{g \times L_{pp}},$$  \hspace{1cm} (5)

where $g$: gravity acceleration, $L_{pp}$: the length between the perpendiculars of the ship model.

In Fig. 7, the frictional drag coefficient of a flat plate at the ship's Reynolds number is also shown to indicate frictional resistance rate in the total resistance.

The drag reduction rate (DR%) is given in Fig. 8. It can be seen from Fig. 8 that DR% of (2), that is, without side air-guarders, decreases at $F_r$=0.15. It was observed that the air rose up from the bottom at station 6.8 to the water surface at the speed of $F_r$=0.15, but under condition (3), no air was found to rise from the bottom.

3.2.2 Ballast condition

Resistance tests under ballast load with no trim and trim by stern conditions were carried out. Both resistance tests were done with and without side air-guarders.

Figs. 9 and 11 show the total resistance coefficients of no trim and trim by stern conditions, respectively. The DR% of those conditions are given in Figs. 10 and 12. It can be seen from Fig. 10 that DR% decreases at $F_r$=0.15 under the no trim condition of ballast load, which is the same as under full load.

Figs. 11 and 12 show that DR% under the trim by stern condition is very different from that of no trim conditions under ballast and full load, namely, DR% is 0 at $F_r$=0.1 and gradually increases with speed. It was observed that the air rose up from the bottom of the model to the water surface at low speeds. However, this phenomenon was not observed at high speeds. Figs. 11 and 12 also show that the 10 mm high side air-guarders did not prevent the air from rising up.

3.2.3 Self propulsion factors

Figs. 13 and 14 show the self propulsion factors measured under full load and trim by stern ballast conditions without side air-guarders. In these figures, $\eta_r$ is the relative rotative efficiency, $w$ is the wake fraction and $t$ is the thrust reduction fraction. Namely, $\eta_r$ means the ratio of the propeller efficiency at the ship stern to the open water, $1-t$ is the ratio of ship resistance to propeller thrust and $1-w$ shows the ratio of effective speed in the propeller disk to the ship model speed.

3.3 Tested results of the pencil ship

Both resistance tests of the conventional surface and the SWR surface were carried out with side air-guarders to prevent the air from rising to the model side.
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![Graph 1](image1.png)

**Fig. 7** Total resistance coefficients of the tanker model (Full load, No trim)

![Graph 2](image2.png)

**Fig. 8** DR% of the tanker model (Full load, No trim)

![Graph 3](image3.png)

**Fig. 9** Total resistance coefficients of the tanker model (Ballast condition, No trim)

![Graph 4](image4.png)

**Fig. 10** DR% of the tanker model (Ballast condition, No trim)

![Graph 5](image5.png)

**Fig. 11** Total resistance coefficients of the tanker model (Ballast condition, Trim by stern)

![Graph 6](image6.png)

**Fig. 12** DR% of the tanker model (Ballast condition, Trim by stern)
Fig. 13 Self-propulsion factors of the tanker model (Full load, No trim)

Fig. 14 Self-propulsion factors of the tanker model (Ballast condition, Trim by stern)

walls. The SWR surface tests were done with air supply quantity of $AL=0.5$ and $AL=1.0$.

The total resistance coefficient of the pencil ship is shown in Fig. 15, and the DR% is given in Fig. 16.

4. Discussion

4.1 Effect of air injection to the normal coating surface on ship bottom

The validity of SWR & A method was tested by comparing the ship resistance under conditions of the conventional surface without air injection and the SWR surface with air injection.
In order to examine the effect of air injection on the measuring resistance, we carried out the resistance test of the pencil ship with air injection to the bottom coated with the conventional paint.

Fig. 17 shows the total resistance coefficients of the pencil ship with and without air injection to the conventional bottom surface. It can be seen that there is no difference between pencil ship resistance with and without air injection to the conventional bottom surface.

4.2 Applying the SWR & A method to a tanker model

The main point of applying the SWR & A method to ships is to know if and how the injected air can be caught on the SWR surface of the ship hull under conditions of three dimensional flow around the hull.

Figs. 8 and 10 show that the DR% of the SWR surface without side air-guarders decreases at $F_r=0.15$ under no trim conditions on both full and ballast loads, and it was observed in the experiment that air rose up from the station 6.8 bottom to the water surface at $F_r=0.15$, but not when air-guarders were placed at the sides of the SWR surface.

This is thought to be because waves generated by the ship's hull decreased the pressure at the bottom near the side wall at station 6.8. Why it happens at the speed of $F_r=0.15$ will be the object of future research.

Fig. 12 shows the influence of ship trim on the SWR & A method. At low speeds under the trim by stern condition, air can not reach the ship's stern as it rises up from the bottom to the side walls. However, this phenomenon is not observed at high speeds.

Actual tankers sail at higher speeds than the model ship speed, so air rising up under the trim condition of the model tests is not an important problem, but it calls to mind the influence of pitch and roll. Although VLCCs do not pitch and roll very much, the effect of such motions must be considered for practical applications of this method.

Figs. 13 and 14 show the effect of the SWR & A technique on the self-propulsion factors. The $1-w$ factor of the SWR surface shows higher values than that of the conventional surface. The reason is considered to be that air is taken into the propeller disk and reduces propeller load. The $1-t$ factor of the SWR surface shows a slightly lower value than that of the conventional surface, and it can be considered that the air film around the stern is changed by the propeller suction effect.

From these self-propulsion test results, it can be seen that we need to design a completely new ship hull, especially the stern form, so as to let air flow smoothly when applying the SWR & A method to actual ships.

4.3 Comparison of the DR% among the pencil ship, the horizontal flat plate and the rectangular tube test results

The pencil ship has side air-guarders and was tested under the no trim condition, then the bottom flow was expected to be a two dimensional flow, as with the horizontal flat plate and the rectangular tube tests. The comparison of DR% among the 12 m pencil ship (9.235 m SWR length), the 2 m flat plate (1.85 m SWR length) and the rectangular tube (2.5 m SWR length) tests are given in Figs. 18 and 19, based on Reynolds number and flow velocity, respectively. The Reynolds number is calculated using the SWR surface length, flow speed and the water kinematic viscosity.

The DR% of the pencil ship is lower than that of the flat plate at low speeds. In-water video observation confirmed that the air was not covered all the bottom surface because the model was heeled at low speeds. The reason is that the pencil ship is low rolling stability and is heeled by the air buoyancy on the bottom at low speeds.

It can be understood from Figs. 18 and 19 that the length of the SWR surface is not the main representative length of the Reynolds number for the phenomena of the SWR & A method.

Detailed investigation on the normalization parameters of the SWR & A method is required in the future, considering parameters of the thickness of the air layer on the SWR surface, the kinematic viscosity of air, the surface tension of water to air and so on.

5. Conclusions

In the 1st report, a new technique was proposed for reducing frictional drag using a super water repellent surface and air injection (SWR & A method). Its effectiveness for two dimensional flow was confirmed by carrying out pressure loss tests with a rectangular tube and resistance tests of a horizontal flat plate. The tested results showed that frictional drag could be reduced by 80% at the speed of 4 m/sec and 50% at the speed of 8 m/sec.
In this paper, the results of applying the SWR & A method to two ship models are shown. One of the tested ship models is a 7.2 m tanker model, the bottom of which is coated with the SWR paint and has a slit nozzle for injecting air over the SWR painted area. The other model is a 12 m pencil ship (high length-to-beam ratio model), which is used to test the effectiveness of the SWR & A method at high speeds and long bottom conditions.

The following results were obtained:
(1) The frictional drag on the SWR surface of the tanker bottom is reduced by about 40% at Froude number 0.20.
(2) The drag reduction rate (DR%) of the tanker model is affected by the air rising from the ship's bottom and shows a small DR%. For example, under the trim by stern (bow-up trim) condition on ballast load, rising air was observed and DR% was small at slow speeds, and under the no trim conditions of both full and ballast loads the DR% was very small at Froude number 0.15 and rising air was observed at the speed.
(3) Self-propulsion factors of the tanker model are affected by the SWR & A method, because the air enters the propeller disk.
(4) The frictional drag on the SWR surface of the 12 m pencil ship (high length-to-beam ratio model) is reduced by 75% at the speed of 6 m/sec.
(5) Comparison of the drag reduction rate (DR%) among the pencil ship (high length-to-beam-ratio ship model), the horizontal flat plate and the rectangular tube shows approximately same value in the figure, the horizontal co-ordinate of which is the flow velocity.
(6) The length of the SWR surface is not the main representative length of the Reynolds number for the phenomena of the SWR & A method.

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