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On the Drag Reduction of a Passenger Ship with Air Cavity

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Abstract

It is known that lubrication effect of an air cavity can reduce a drag of a ship. The present study intends to utilize the phenomena for the drag reduction of a passenger ship now operating in a lake. A scaled model of the ship has been tested in a towing tank to study changes in the resistance characteristics of the model when air cavities are formed under the bottom of the model. Model experiments have been performed to determine adequate air supply rates, proper shapes and locations of air supply nozzles. It is shown that energy saving of more than 10% can be achieved at the design speed of the ship even after excluding additional power consumed for air supplying. Multiple air supply nozzles, if allocated properly, are more effective than single one in resistance reduction of the ship.

Keywords : Drag reduction, Air cavity, Air supply nozzle, Energy saving

1 Introduction

Drag reduction is an important engineering subject and papers on the resistance reduction of practical ships are not scarce in these days. Micro-air bubble injection techniques, for example, are considered to be one of the most effective methods. They cause no environmental pollution and it has been reported that more than 80% of local skin friction of a flat plate is reduced.[Guin et al., 1996][Madavan et al., 1985] However, these techniques have been applied mostly on flat plate problems and their effectiveness on general three-dimensional bodies such as a ship have to be investigated yet. The interaction between ship boundary layer and micro-bubbles has to be analyzed before the bubbles can be efficiently injected into the layer since the bubbles inside the boundary layer may reduce frictional resistance but those outside may increase the form drag.[Doi et al., 1991][Yim et al., 1996]

An air cavity can be artificially formed behind a backward-facing step by supplying air For a ship having a step on her bottom, an attached air cavity can be formed behind the step and it can reduce the form resistance as well as the frictional one of the ship.[Butuzov et al., 1997][Bushnell et al., 1990][Sato et al., 1997] It has been already reported that the total resistance of a semi-planing boat having a step on her bottom is reduced about 20% in model experiments.[Go et al., 1997][Kim et al., 1997]

In the present study, a passenger ship operating in Chungju lake has been chosen to investigate effectiveness of an air cavity upon the drag reduction of a practical ship. A slanted backward-facing step for air injection is installed on the bottom of the ship. The slanted face of the device

Table 1. Principal particulars of the ship.

		Ship	Model
LOA	(m)	55.0	2.2
LBP	(m)	53.0	2.12
Breadth	(m)	10.0	0.4
Depth	(m)	2.0	0.08
Draft	(m)	1.15	0.046
LCB:f+	(m)	-1.645	-0.0658
Disp. Vol.	(m^3)	396.765	0.02539
WSA	(m^2)	506.875	0.811
C_b		0.6561	
Scale Ratio,	λ	25	

must have a small slope to minimize the increase in the form resistance but have a large height to form longer air cavity behind it. Effort has been concentrated in selecting the optimum configuration of the air supply device. Extensive experimental studies have been done to determine the relation among air supply rate, shape and location of the device, size of air cavity and resistance reduction. A configuration of multiple air supply devices has been also tested in an effort to enlarge the region covered by the air cavity.

2 Model Ship

2.1 Ship Chracteristics

A passenger ship now in service has been selected for the present study. The principal particulars and body plan of the ship is given in Table 1 and Figure 1, respectively.

The ship is adequate for the investigation since she has a relatively large beam-draft ratio and hence the area of the bottom is large enough to show profound reduction in the frictional resistance. The ship has a dead rise of about 3.5° and the parallel middle body starts from nearly 6 ST. A raised transom stern is adopted to direct the incoming flow to the propulsor when the ship operates at the full load condition. The ship also has small motion responses and changes in hull attitudes and is suitable for generating and keeping a stable air cavity.

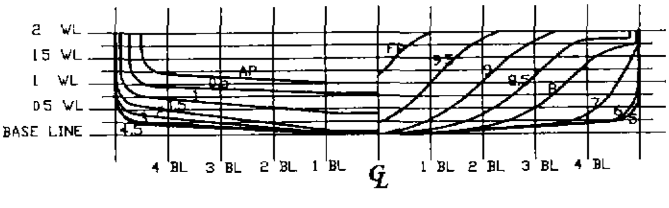


Figure 1. Body plan of the ship.

2.2 Flow Characteristics

Determining an adequate location of the air supply nozzle requires understanding of flow field around the model. Hence a scaled model is constructed and flow characteristics around the model have been tested in a towing tank. Figure 2 shows the limiting streamlines observed in a paint test

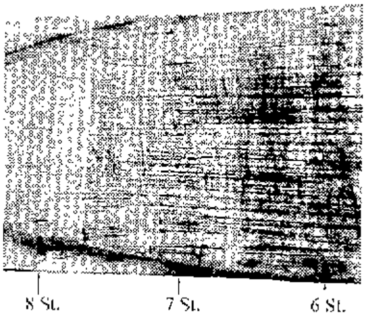


Figure 2. Limiting streamlines along the fore part of the hull surface.

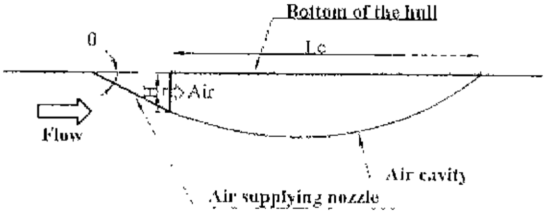


Figure 3. Conceptual drawing of an air injection device.

at the model speed of 1.543 *m/s* which corresponds to the cruising speed of 15 *knots*. The limiting streamlines near 7 *ST* appear to be almost parallel to the advancing direction of the model and the flow nearly uniform. Generation of stable air cavity necessitate these flow conditions and the location of the device has been determined to be 6 *ST*.

3 Air Supply Device

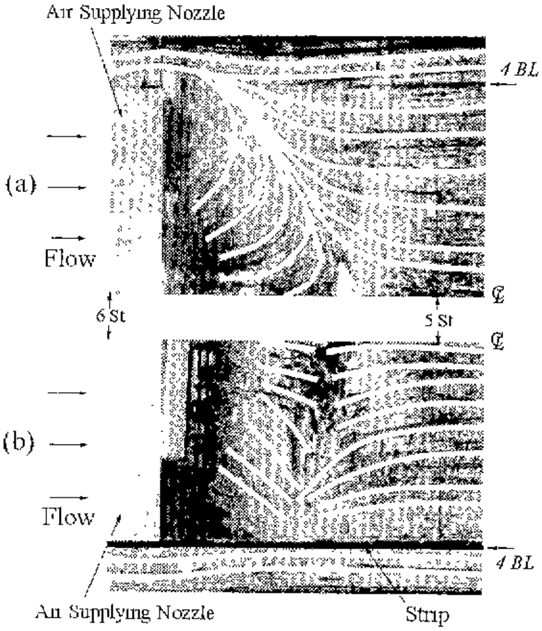


Figure 4. Limiting streamlines on the rear of air injection nozzle.
(a) without side strip (b) with side strip

The shape of the air supply device should be designed in such a way that an air cavity attached behind it spreads as wide as possible and that increase in the form resistance to be minimized.

The conceptual drawing of the device is shown in Figure 3. Several devices having different nozzle heights (H) and slopes (θ) have been made and installed on the bottom at 6 *ST*. The model with air supply device has been tested at the towing tank of Seoul National University to measure the variations in resistance and in characteristics of air cavity. Tests *I*, *II* and *III* in Table 2 show the influence of the nozzle slopes on the resistance characteristics when the height of the nozzle has been fixed. And the tests *III* and *IV* have been performed with constant slope and show the effect of the nozzle height on the resistance reduction. When no air is supplied through the nozzle, the form resistance due to the presence of the air supply device increases with its height and, if the height is the same, grows with the slope. Streamlines passing over the

Table 2. Effects of the device geometry on the resistance.
$(V_M = 1.543m/s, Q_{Air} = 100liter/min)$

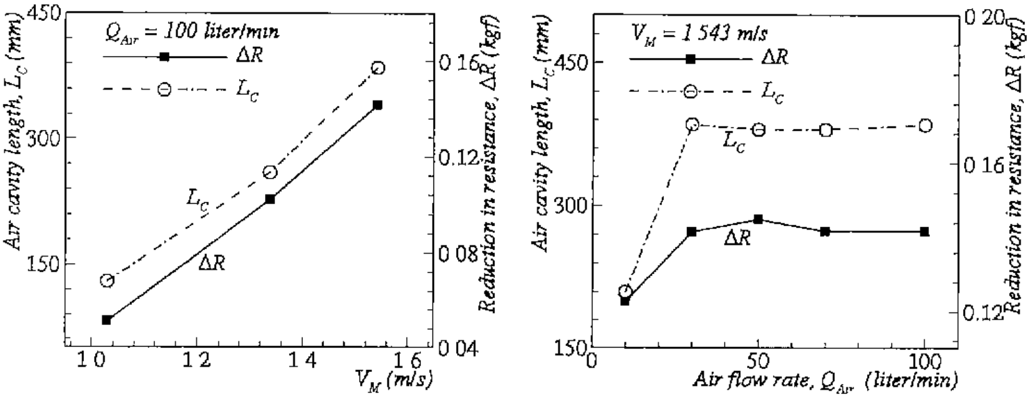
No. of device	H (mm)	$\theta(°)$	$\frac{R_{TM,NA}}{R_{TM,B}}$	$\frac{R_{TM,A}}{R_{TM,NA}}$	$\frac{R_{TM,A}}{R_{TM,B}}$	$L_C(mm)$
I	10	30	1.24	0.92	1.14	130
II	10	16.6	1.18	0.92	1.08	130
III	10	11.5	1.12	0.95	1.06	110
IV	7	11.5	1.08	0.94	1.01	90
V	17	20	1.49	0.85	1.27	150
$II + Strip$			1.18	0.83	0.98	340

$R_{TM,B}$: Total resistance of bare hull
$R_{TM,NA}$: Total resistance of ship with device and without air supply
$R_{TM,A}$: Total resistance of ship with device and air supply
L_C: Air cavity length

device reattach to the bottom at the downstream to form re-circulating flow field in between. Since the pressure at the region is relatively low, an air cavity forms easily if air is injected inside the region. In earlier works on back step problems, it has been shown that the higher the step becomes the longer the reattachment length grows.[Durst et al., 1982][Papadopoulos et al., 1995] If three-dimensional effect at the both ends of the step is suppressed, the reattachment length increases further and the secondary vortices behind the step are weakened.[Papadopoulos, et al., 1995] It may be then expected that the length of the air cavity will be increased and hence the resistance decreased as the device becomes higher. In this respect, the longitudinal barrier strips of 15 *mm* in height are attached at the both ends of the device to prevent air leakage and to suppress the three-dimensional effects. The strips are parallel to the flow direction and extend from 6 *ST* to 2 *ST*. Figure 4 shows limiting streamlines around the device with and without the strips when air is not supplied. It is readily seen that the strips suppress the three-dimensional effects and lengthen the reattachment line. If air is supplied through the nozzle, an attached air cavity is formed behind the device and causes reductions in frictional and eventually total resistance of the ship. The higher the device is, the larger air cavity can be formed behind it but as shown in Table 2, the increase in form resistance may overwhelm the reduction in frictional resistance if the height exceed some limit. As also seen in Table 2, the length of the air cavity formed behind device *II* becomes about 2.5 times longer if strips are attached at the both ends (*II + strip*).

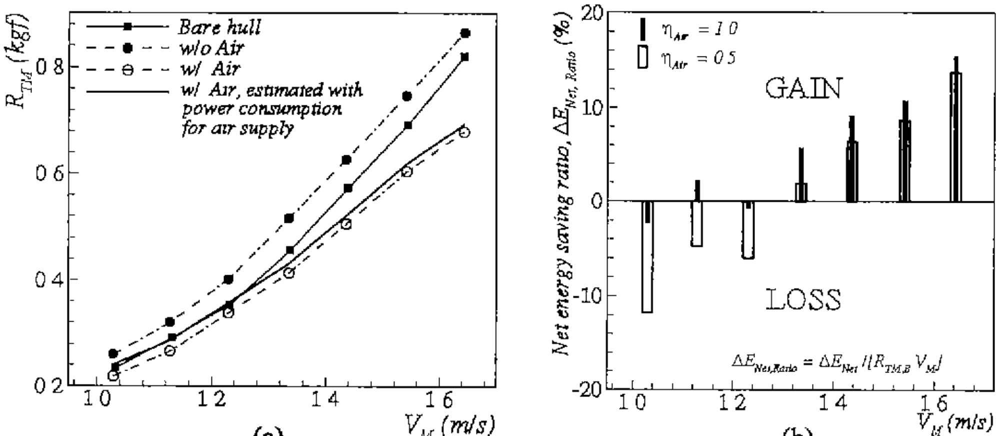
4 Resistance Reduction with Air Cavity

Based on the results discussed above, the device for air supply has been decided to have the following characteristics: the nozzle height of 10 *mm* and slope of 3°. The device is attached on the bottom of the ship at 6 *ST* where the width of the device is about 80% of the ship breadth. In addition, the strips of 15 *mm* in height have been attached at the both ends of the device.



(a) (b)

Figure 5. Resistance and air cavity length at the various towing speeds.



(a) (b)

Figure 6. Resistance reduction and net energy saving due to an air cavity.

4.1 Resistance and Air Cavity Length

Figure 5(a) shows the changes in resistance and air cavity length due to the changes in towing speeds when air supplying rate is fixed at 100 *liter/min*. It is clear from the figure that cavity length increases and total resistance decreases if towing speed becomes higher. Figure 5(b) shows the changes in resistance reduction and in air cavity length at various air supply rates when towing speed is held constant. For the air supply rate exceeding 30 *liter/min*, no significant changes in the air cavity length and drag are found.

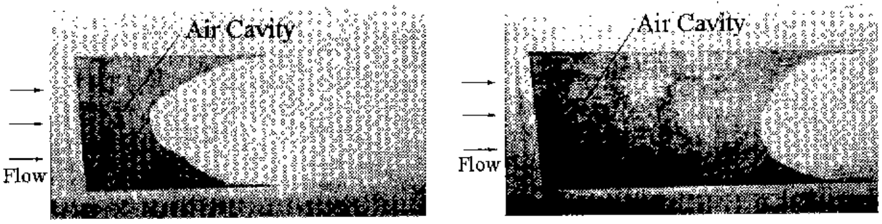
4.2 Energy Saving with an Air Cavity

The net saving in energy due to an air cavity can be evaluated as follows if considering the power consumed for air supply[Bushnell et al., 1990][Sato et al., 1997]:

Table 3. Pressure and local skin friction coefficients measured along the centerline. (V_M=1.543 m/s, Q_{Air}=30 $liter/min$)

x	C_p		$C_f \times 10^3$	
(mm)	No Air	Air	No Air	Air
-107	-0.049	-0.058	2.969	2.781
13*	-0.115	-0.016	-	-
161*	0.016	-0.033	1.690	0.2508
321*	0.033	-0.066	2.655	0.2508
482	-0.082	0.082	3.466	3.590

x : Distance from 6 $St.$ (mm, downstream: +)
* : location inside air cavity(L_C=385 mm)



(a) (b)

Figure 7. Typical shapes of an air cavity. (a) V_M = 1.029 m/s (b) V_M = 1.543 m/s

$$\Delta E_{Net} = R_{TM,B}V_M - (R_{TM,A}V_M + P_{Air}), \tag{1}$$

$$P_{Air} = \frac{\rho_w g T Q_{Air}}{\eta_{Air}}, \tag{2}$$

where ΔE_{Net} is the energy per unit time saved, P_{Air} is the power for air supply, ρ_w is the density of water, g is the gravitational acceleration, T is the draft of the ship, Q_{Air} is the rate of air supply, and η_{Air} is the overall efficiency of the air supplying system.

Figure 6(a) shows the 4 $\sim$ 17% reduction in total resistance of bare hull in the tested range of the model speed. Since the supplied air does not significantly affect the wave resistance characteristics[Doi et al., 1991][Yim et al., 1996], the reduction may be contributed to the air cavity attached on the hull bottom and resulting reduction in the frictional resistance. Table 3 also shows pressures and local skin frictions measured along the centerline of the model decrease remarkably inside the region covered with air cavity. Figure 6(b) show the net energy saving ratio estimated by equation (1) when the overall efficiency of the air supplying system is assumed to be 1 and 0.5, respectively. The results indicate that the energy saving surpasses the power consumption for air supplying if excluding the low speed region. When the speed of the model is 1.543 *m/s*, about 10% of the energy necessary for the bare hull can be saved. Figure 7 shows the typical shapes of the air cavity observed when the rate of air supply is 30 *liter/min*. It is found that the size of an air cavity is directly related to the amount in drag reduction.

4.3 Additional Air Supply Device Downstream

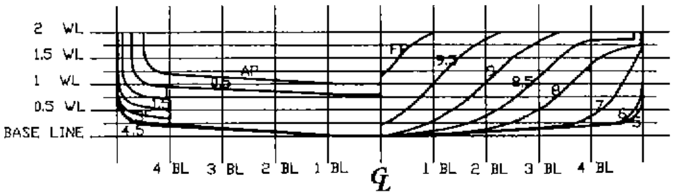


Figure 8. Body plan of the modified ship.

It may be possible to achieve additional reduction in the resistance if increasing the area covered with the air cavity.

But the results show that rear part of the bottom, especially the region between 0.5 *ST* and 3 *ST* is never covered with air cavity. Hence, the model has been modified slightly as shown in Figure 8 to enlarge the region covered with air cavity. Two air supply devices have been installed at 7 *ST* and 4 *ST* in row. As shown in Figure 9, the device attached at 4 *ST* achieves additional reduction in resistance even though it is located downstream of the another device. But the shapes of air cavities observed at the towing speed of 1.543 *m/s* indicate that the area covered by the rear air cavity is smaller than that of the front one (Figure 10). Further researches, therefore, seem to be necessary to find the interference between two air cavity systems and to improve the rear cavity formation.

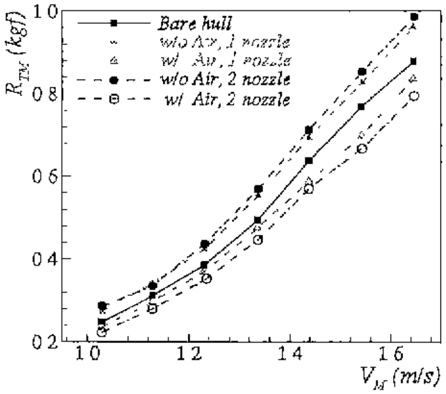


Figure 9. Resistance reduction of the modified ship with air cavities.

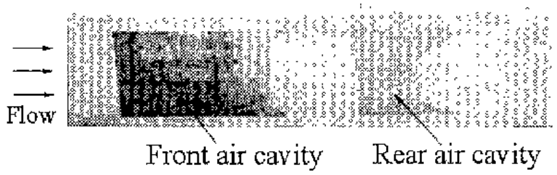


Figure 10. Two cavities formed on the bottom of the modified ship ($V_M = 1.543$ m/s).

5 Conclusions

The resistance reductions due to the air cavities have been investigated. A passenger ship now in service at Chung-Ju lake is chosen for the purposes. The following conclusions are made from the experimental results performed in the present study:

(1) The total resistance of the model ship is reduced by the maximum of 17% at the service speed. This reduction is equivalent to the energy saving of about 10% even after deducting the energy consumed for air supplying.

(2) The longer air cavity could be produced with the higher air supplying nozzle. But the height of the nozzle should be chosen carefully since form drag also increases with the increase in the height.

(3) The longer air cavity is formed beneath the hull and air lubrication effect becomes more profound if speed of the ship becomes faster.

(4) Longitudinal barrier strips attached to the both ends of the device play an important role in lengthening the cavity by preventing air leakage and by suppressing three-dimensional effects.

(5) An additional air supply device installed downstream of the first one increases the area covered with air cavity.

The air cavity formed beneath the hull may affect not only the resistance but also the motion, maneuvering and propulsion characteristics of a ship. Hence, comprehensive investigations should be performed on these aspects before practical applications of the phenomena.

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