Power-saving device for air bubble generation using a hydrofoil to reduce ship drag: Theory, experiments, and application to ships

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A R T I C L E   I N F O

Keywords: Ship, Drag reduction, Hydrofoil, Multiphase flow, Bubble

A B S T R A C T

We have developed a new power-saving device to reduce the drag of a ship’s hull using small bubbles. The device reduces the energy required for bubble generation. The device, which consists of angled hydrofoils with air introducers, uses the low-pressure region produced above the hydrofoil as the ship moves forward to drive atmospheric air into the water. We describe the device principles obtained from simple fluid dynamic theory, and, through experiments performed in a small towing tank, show the fundamental air entrainment and bubble generation processes for the flow behavior around a hydrofoil beneath a free surface. We also present a semi-empirical scaling process for practical application to full-size ships to estimate the net drag reduction achieved by this device. Finally, the results of a series of full-scale tests are reported and show that, with correct operation, our device can produce a net power saving of 5–15% for ships.

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1. Introduction

Over the past few decades, the mechanism of air lubrication has been investigated for reduction of the friction drag on a ship’s surface and to reduce CO2 emissions. Three physically different air lubrication techniques have been identified: air cavity, air film, and small bubble methods. The classification of the working principle in these different drag reductions was explained by Ceccio (2010). The small bubble method, which utilizes functions of micro- to sub-millimeter bubbles, has an advantage over the air cavity and air film-based methods in that it reduces friction without requiring any change in the form of the ship’s hull. Another advantage is its large impact to the drag reduction ratio per void fraction supplied into the boundary layer. The impact is ordinarily larger than unity, and reaches 100 on ideal conditions as reviewed by Murai (2014). Researchers in this field use the term “microbubble drag reduction” as they expect turbulence modification realized by eddy-suppressing small bubbles inside turbulent boundary layer. Practical application of microbubble method to ship drag reduction has been actively studied in recent years because of the potential energy savings and the environmental benefits in terms of marine pollution. Kodama et al. (2008) reported approximately 10–15% saving of the total energy consumption for an experimental ship. Mizokami et al. (2010) also succeeded in about 10% fuel saving as bubbles were injected below a vessel with wide flat bottom surface. Their ships of air lubrication system are already in commercial uses. For challenging further improvement of drag reduction, Mäkiharju et al. (2012) proposed high-void fraction type of air-layer drag reduction and estimated its usefulness to large tankers. Jang et al. (2014) also reported 5–6% net power saving estimated for a bulk carrier as they scaled their towing model ship experiments considering the power for bubble injection.

One of concerns toward further improvement of microbubble method is the fact that the energy required to supply air bubbles using conventional bubble generators is quite significant, and it occupies 3–10% of the total energy consumption of a ship dependent on the depth of bubble generation. This explains that the required power for bubble generation in worse operations cancels out the power saved by drag reduction. For example, the theoretical estimate of the energy loss due to the adiabatic compression of air, i.e., the ratio of the internal energy increase ∆U to the work done in the adiabatic compression of air L_{total}, is given by

\[
\frac{\Delta U}{L_{total}} = \left( \frac{K-1}{K} \right) \frac{C_v}{R} \frac{T}{T_0}
\]

where \( C_v \), \( R \), and \( \kappa \) are the heat capacity at constant volume, the gas constant, and the heat capacity ratio, respectively. From Eq. (1), the energy loss due to the adiabatic compression of air is approximately 71% at 20 °C (\( R=287 \) J kg\(^{-1}\) K\(^{-1}\), \( C_v=718 \) J kg\(^{-1}\) K\(^{-1}\), and

http://dx.doi.org/10.1016/j.oceaneng.2014.11.019

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applications, which will provide information to optimize the device and lead to further improvements.

2. Theory

2.1. Threshold of air entrainment by a hydrofoil beneath a free surface

When the hydrofoil of a WAIP attached to a ship’s hull moves at a constant velocity $U$, water flows over the hydrofoil surface; a low-pressure region is then produced over the upper surface of the hydrofoil (Murai and Takahashi, 2008). The magnitude of the negative pressure $\Delta P$ depends on the flow speed, type of hydrofoil, the angle of attack, and also the depth of the hydrofoil from the air–water interface. The atmospheric air is entrained when the magnitude of the negative pressure is higher than the hydrostatic pressure of the water at the depth of the WAIP installation (Murai et al., 2010):

$$\Delta P = C_F \frac{1}{2} \rho U^2 \geq (\rho - \rho_{\text{air}})gH \geq \rho gH,$$

(2)

where $C_F$, $\rho$, $\rho_{\text{air}}$, and $g$ are the negative pressure coefficient of the hydrofoil, the density of water, the density of air, and the gravitational acceleration, respectively. Note that $\rho \gg \rho_{\text{air}}$. From Eq. (2), we can estimate the critical velocity for air entrainment $U = U_C$:

$$U_C \approx \sqrt{\frac{2gH}{C_F}}.$$

(3)

In this simple formula, $C_F$ is not defined as a point wise value on the hydrofoil surface but is given by average value of local negative pressure coefficient distribution in the region between the hydrofoil and the outlet of air induction pipe (AIP). Thus, the WAIP is designed to provide strong negative pressure region between the hydrofoil and AIP so that the above-given critical velocity $U_C$ is lowered as small as possible.

Fig. 2 shows an experiment that demonstrates the effect of the towing velocity on the air entrainment by the WAIP (Kumagai et al., 2010). When the towing velocity $U$ was smaller than the

![Fig. 1. Winged air induction pipe (WAIP): (a) photograph; (b) schematic drawing of the WAIP cross-section. The hydrofoil is a NACA 0015 foil with a chord length of 100 mm, span-wise length of 240 mm, and angle of attack $\alpha = 12^\circ$.](image-url)

![Fig. 2. Oblique upward views showing the thresholds for air entrainment by the WAIPs in towing tank experiments. The WAIP moves from right to left. (a) No air entrainment ($U < U_C$); (b) around the critical velocity $U_C$; (c) air entrainment and subsequent bubble formation ($U > U_C$).](image-url)
critical value $U_c$, no air entrainment was observed (Fig. 2a). Simple theory enabled prediction of the air entrainment threshold (Fig. 2b), and the volume of air bubbles increased with increasing towing velocity (Fig. 2c).

### 2.2. Power required for bubble generation

The air entrainment capacity of a hydrofoil depends on $C_P$: a higher $C_P$ enables deeper release of the air at a given cruising velocity (Eq. (3)). However, the drag effect of the hydrofoil when installed on the ship's hull should also be considered when we discuss the net power saving performance for the ship. As a first-order approach, we consider a hydrofoil moving at a constant velocity $U$ under the water surface. The total power $W$ necessary for air entrainment at an air-volume flow rate $Q$ into the water can be described as

$$ W = W_0 - W_L + W_D. $$

Here, $W_0$ is the power required for air release at a water depth $H$, i.e.,

$$ W_0 = \rho g H Q. $$

Here we consider only the potential energy for air-blowing into water since WAIP system does not require air compression (see Eq. (1)). $W_L$ in Eq. (4) is the power saved by the negative pressure generated above the hydrofoil, where

$$ W_L = C_U^4 \rho U^2 Q, $$

and $W_D$ is the power consumed in overcoming the drag force of the hydrofoil that is protruded from the ship's hull, where

$$ W_D = C_D U^2 A. $$

where $C_D$ and $A$ are the drag coefficient and the projected area, respectively, of the adopted hydrofoil. From Eqs. (4)-(7), the total power $W$ required for air induction into the water via the hydrofoil-supporting mechanism can be rewritten as

$$ W = \rho B \left( g H Q U - \frac{1}{2} \left( \frac{A}{B C_D} - \frac{L}{h_b} C_D \right) U^4 \right). $$

Here, the air volume flow rate is alternatively given by $Q = \alpha B U$, where $\alpha$ and $B$ are the mean void fraction and the vertical cross-sectional area, respectively, of the air bubble-mixed layer over the ship's hull. Eq. (8) tells us that the power required for bubble release is saved by installing the hydrofoil when the following condition is satisfied:

$$ C_P B \alpha > A \approx \frac{L}{h_b} C_D \sin \theta, $$

where $L$, $h_b$, and $\theta$ are the chord length of the hydrofoil, the air bubble-mixed layer thickness, and the angle of attack, respectively. The theory indicates that a hydrofoil with a high $C_P/C_D$ ratio should be used to obtain high net power saving performance, which is the reason why we use hydrofoils rather than bluff bodies.

We should also note that Eq. (8) gives another critical velocity $U_c$ at which the system reaches the power-free condition, $W = 0$. This critical velocity is derived as below, and is always faster than the previous kind of critical velocity $U_c$.

$$ U_c = \sqrt{\frac{2 g H}{C_P} \left( \frac{A}{B C_D} - \frac{L}{h_b} C_D \right) \sin \theta}. $$

As an example, if we consider a NACA 65-410 hydrofoil (where $C_P = 1.50$, $C_D = 0.015$ at $\theta = 10^\circ$) under conditions of $H = 2-5$ m, $\alpha = 5\%$, $L = 50$ mm, and $h_b = 20$ mm, then $U_c = 5.3-8.5$ m/s. This simple estimate shows that both high-speed marine vehicles and moderate-speed marine vehicles can save the net power required for air release by installing the hydrofoil device.

### 3. Performance tests and scaling for total drag reduction by a hydrofoil device

In the previous section, we presented theory with regard to the air entrainment principle of the hydrofoil device. Here, we describe laboratory experiments to examine the process of bubble generation and its role in reducing the frictional drag of the downstream horizontal flat wall.

#### 3.1. Hydrofoil device bubble generation process

Fig. 3 shows towing experiments on bubble generation by a moving hydrofoil close to an air–water interface. After the atmospheric air is entrained by the negative pressure, instability takes place on the air–water interface so that smooth interface naturally transits to turbulent state as seen by the dark area in the photograph. The transition occurs because of wave-breaking, i.e. upstream water which is accelerated by the hydrofoil’s curvature to be faster than the gravitational wave propagation velocity dashes into the slow downstream water region. The wave breaking threshold is given by the wave steepness (the height/length ratio of a wave) and it was found to be approximately 0.1 (Kumagai et al., 2010, 2011a, 2011b). Beyond this threshold, small bubbles are naturally ventilated into a thin layer just beneath the original gas–liquid interface, and this phenomenon supports continuous but active release of small bubbles for the downstream region close to the wall. It is worth noting that this threshold is not a specific finding only for the WAIP system, but is known as a general trend of deep water wave-breaking mechanism reported such as in ocean wave breaking (Peregrine, 1983; Toffoli et al., 2010).

Small bubble generation observed behind the hydrofoil is interpreted as energy conversion from the wave energy to turbulent kinetic energy. Since the wave energy is produced by the rapid deflection of water flow above the hydrofoil, the design of the hydrofoil should be optimized to promote the wave-breaking. In its downstream, bubbles of various sizes are potentially generated because of a broad spectrum in wave number coming out on the turbulent interface. Among them, large bubbles are un-survivable in strong shear so that only small bubbles occupy the downstream turbulent boundary layer. The maximum survivable bubble size is scalable with the following Weber number $W_e$, which describes
the bubble deformability due to shear against surface tension:

$$W_{e} = \frac{\rho U^2 d}{\sigma} = \frac{\rho d}{\sigma} \left( \frac{dU}{dy} \right)^2 \approx \frac{\rho d^3 U^2}{\sigma \delta^2},$$

where $\sigma$, $dU/dy$, and $\delta$ are the surface tension of the bubble, the shear rate around the bubble, and the turbulent boundary layer thickness, respectively. If we assume that the critical Weber number at which the bubbles break up is of the order of 10, the size of the air bubbles for a cruising speed $U=5–10 \text{ m/s}$ is expected to be around 200 to 300 $\mu\text{m}$.

### 3.2. Measurement of drag reduction by the hydrofoil device

The amount of drag reduction provided by the small bubbles depends on the void fraction, the bubble size, the flow conditions, and the position where the bubbles are generated. The internal fluid mechanics of bubble-base drag reduction contains a long and complex story as one of the authors recently reported in a review paper (Murai, 2014). We are not going into such physics hidden in bubbly two-phase turbulent boundary layer in the present paper, but we here examine for engineering purpose how much the small bubbles generated by our hydrofoil device reduce the drag of a flat plate downstream. Our experiments were carried out in a circulating water channel as its look is shown in Fig. 4. The flow velocity of the circulating water ($V$) was set at 5.6 m/s, considering the typical cruising velocity of ships. In the test section, four kinds of measurement instruments are setup as listed in Table 1. The experimental model ship was designed to focus on the WAIP performance test, and it consists of four parts as shown by A, B, C, and D in Fig. 5. The total drag force acting on parts B and C ($D_t$) was measured by a single load cell. In parallel, the drag force acting on part B was separately measured by another load cell ($D_o$). Hence the drag force acting on the flat acrylic plate of 2.6 m long ($D_b$) was given by

$$D_b = D_t - D_o.$$  

### Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Instrument</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow velocity</td>
<td>Pitot tube</td>
<td>$3.0 \text{ mm H}_2\text{O}$</td>
</tr>
<tr>
<td></td>
<td>Differential pressure cell</td>
<td>Capacity: $0.2 \text{ kgf/cm}^2$</td>
</tr>
<tr>
<td></td>
<td>Propeller type velocity meter</td>
<td>Propeller Dia.: 3 mm, Max. velocity: $2.0 \text{ m/s}$, nonlinearity: $\pm 2.0% \text{ F.S.}$</td>
</tr>
<tr>
<td>Induced air volume</td>
<td>Load cell (strain gauge type)</td>
<td>Rated load: 500 N, nonlinearity: $\pm 0.1% \text{ F.S.}$</td>
</tr>
<tr>
<td>Drag on box of 2.6 m long</td>
<td>Load cell (strain gauge type)</td>
<td>Rated load: 100 N, nonlinearity: $\pm 0.3% \text{ F.S.}$</td>
</tr>
<tr>
<td>Drag on box of 0.25 m long</td>
<td>Tube</td>
<td>$3.0 \text{ mm H}_2\text{O}$</td>
</tr>
<tr>
<td>Static pressure</td>
<td>Differential pressure cell</td>
<td>Capacity: $0.1 \text{ kgf/cm}^2$</td>
</tr>
</tbody>
</table>

Fig. 4. (a) Circulating water channel (West Japan Fluid Engineering Laboratory Co. Ltd.); (b) microbubbles generated by the hydrofoil device.

Fig. 5. Schematic diagram of the experimental set-up: Top view (upper), side view (lower), and front view (bottom right).
The volume flow rate of air entrainment by the hydrofoil \( Q \) was also monitored using a propeller-type flow meter attached to the AIP (air induction pipe). The hydrofoil that we employed in the device was an NACA 653-618 hydrofoil, which was attached to the bottom of the AIP. This position is hereafter denoted as origin, \( x_0 = 0 \) to evaluate the streamwise persistence of drag reduction. We examined three angles of attack: \( \theta = 12^\circ, 16^\circ, \) and \( 20^\circ \) together with the drag force measurement for a bare plate \( \Delta D_0 \) as a reference (i.e. the case without a hydrofoil).

Table 2 summarizes our experimental results. Here, the increase in drag force caused by the attachment of the hydrofoil, \( \Delta D_{\text{ho}} \) is

\[
\Delta D_{\text{ho}} = D_{\text{ho}}(\text{hydrofoil}) - D_{\text{ho}}(\text{bare plate}),
\]

where \( D_{\text{ho}}(\text{hydrofoil}) \) and \( D_{\text{ho}}(\text{bare plate}) \) are the drag forces with and without the hydrofoil, respectively. \( \Delta R_{2.6m} \) is the drag reduction for the flat plate (part C) caused by the air bubbles that were generated by the hydrofoils:

\[
\Delta R_{2.6m} = D_{\text{ho}}(\text{hydrofoil}) - D_{\text{ho}}(\text{bare plate}).
\]

As shown in Table 2, we confirmed that the drag reduction (\( \Delta R < 0 \)) on the flat plate of part C was caused by the air bubbles generated by the hydrofoil device. From the specifications of two load cells applied for Eqs. (13) and (14), measurement uncertainty for \( \Delta D_0 \) is estimated to be 0.7%, and that for \( \Delta R_{2.6m} \) is 1.2%.

### 3.3. Estimation of total drag forces for a full-size ship

In the previous section, some readers may have supposed that attachment of the hydrofoil causes increased drag because the magnitude of \( \Delta R \) is smaller than that of \( \Delta D_0 \). However, the 2.6 m flat plate (part C; from \( x = 2.216 \) m to 4.816 m) considered in the previous experiment corresponds only to a small part of the real ship’s hull which is typically longer than 10 m. In this section, we describe the total drag force \( F_{\text{total}} \) that acts on a long flat plate for application to full-size ships.

For practical use, we simply express the total drag force \( F_{\text{total}} \) that is acting on a flat plate with length \( L \) by use of local friction factors with and without the air bubbles, represented by \( C_f \) and \( C_{f_{\text{ho}}} \), respectively:

\[
F_{\text{total}} = D_{\text{ho}} - \int_0^L \frac{1}{2} \rho V^2 C_{f_{\text{ho}}}(1 - \frac{C_f}{C_{f_{\text{ho}}}}) B_h \ dx.
\]

Here, \( B_h \) is the horizontal width of the bubble-mixed layer. The second term on the right hand side of Eq. (15) can be rewritten using \( \Delta R_{2.6m} \) as follows:

\[
\Delta R_{\text{total}} = -\int_0^{2.216} \frac{1}{2} \rho V^2 C_{f_{\text{ho}}}(1 - \frac{C_f}{C_{f_{\text{ho}}}}) B_h \ dx + \Delta R_{2.6m}
\]

\[
-\int_{2.216}^{4.816} \frac{1}{2} \rho V^2 C_{f_{\text{ho}}}(1 - \frac{C_f}{C_{f_{\text{ho}}}}) B_h \ dx,
\]

where

\[
\Delta R_{2.6m} = -\int_{2.216}^{4.816} \frac{1}{2} \rho V^2 C_{f_{\text{ho}}}(1 - \frac{C_f}{C_{f_{\text{ho}}}}) B_h \ dx. \quad (17)
\]

Although the magnitude of \( \Delta R_{2.6m} \) is smaller than that of \( \Delta D_0 \) in the previous experiments (Table 2), the total drag reduction due to the air bubbles \( \Delta R_{\text{total}} \) overcomes the increase in drag caused by the hydrofoil attachment (\( \Delta D_0 \)) if the plate length \( L \) is sufficiently

\[\text{Table 3}\]

<table>
<thead>
<tr>
<th>Gas-volume flow rate Q (l/min)</th>
<th>Impact distance ( a ) (m)</th>
<th>Approach distance ( b ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.7</td>
<td>2.9</td>
</tr>
<tr>
<td>200</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>300</td>
<td>2.0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

**Fig. 6.** Local skin friction ratio \( (C_f/C_{f_{\text{ho}}}) \) as a function of distance \( x \). The plots are made from IHI experimental data (Watanabe et al., 1998). The fitting curves were obtained by regression analysis (see text).

**Fig. 7.** Drag reduction produced on a flat plate by a hydrofoil device, \( \Delta R_t = \Delta R_{\text{total}} \) as a function of distance \( x \) from the trailing edge of the WAIP.

### Table 2

Experimental results on the effect of hydrofoils on drag forces.

<table>
<thead>
<tr>
<th>Type</th>
<th>Attack angle (deg)</th>
<th>( V ) (m/s)</th>
<th>( D_0 ) (kgf)</th>
<th>( D_{\text{ho}} ) (kgf)</th>
<th>( \Delta D_0 ) (kgf)</th>
<th>( \Delta R_{2.6m} ) (kgf)</th>
<th>( P_1 ) (mAQ)</th>
<th>( V_{\text{avg}} ) (m/s)</th>
<th>( Q ) (m³/mi.)</th>
<th>( X_c ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare plate</td>
<td>12</td>
<td>5.6</td>
<td>20.9</td>
<td>13.1</td>
<td>7.5</td>
<td>1.1</td>
<td>0.04</td>
<td>0.110</td>
<td>0.035</td>
<td>8.5</td>
</tr>
<tr>
<td>NACA12</td>
<td>16</td>
<td>5.6</td>
<td>21.5</td>
<td>17.0</td>
<td>4.9</td>
<td>1.1</td>
<td>0.04</td>
<td>0.140</td>
<td>0.044</td>
<td>11</td>
</tr>
<tr>
<td>NACA16</td>
<td>20</td>
<td>5.6</td>
<td>22.6</td>
<td>16.6</td>
<td>4.8</td>
<td>1.2</td>
<td>0.04</td>
<td>0.135</td>
<td>0.042</td>
<td>12</td>
</tr>
</tbody>
</table>
large. Here, we define the compensation distance $X_c$ as the distance where $\Delta D_a = \Delta R_{\text{total}}$. To apply our device to a real ship, we should use a hydrofoil with a shorter $X_c$. The experimental results indicate that “NACA12” (i.e. the NACA 65–618 with the angle of attack $\theta = 12^\circ$) is the best hydrofoil for reduction of the drag of ships in the tested range ($X_c = 8.5$ m, Table 2).

3.4. Estimation of local skin friction ratio and total drag reduction by a hydrofoil device

To estimate $\Delta R_{\text{total}}$ for full-scale ships, it is necessary to know the local friction factor $C_f/C_p$ as a function of the distance from the air release point, $x$. We referred to experimental drag reduction results for a long, slender ship model ($L = 40$ m, $B = 0.6$ m) in a towing tank (Watanabe et al., 1998). The calibration curves of $C_f/C_p$ as a function of $x$ are obtained using the following equation:

$$
\left( \frac{C_f}{C_p} \right) = 1 - \frac{a}{x + b}
$$

where $a$ and $b$ are constants determined by curve fitting based on a least-squares regression (Fig. 6, Table 3). Because these constants have length dimensions, we call the approach distance, respectively. The approach distance $b$ seems to be independent of the gas volume flow rate $Q$, whereas the impact distance $a$ depends on $Q$. If we assume that $a = 0$ when $Q = 0$, then we obtain the following empirical equation:

$$
a = (3.96 \times 10^2)Q.
$$

Note that the impact distance $a$ and the gas volume flow rate $Q$ are given by the units of m and m$^3$/s, respectively.

If we apply the relationship of Eq. (19) to the gas volume flow rate realized in a hydrofoil when using the experimental constraints of the partial drag reduction $\Delta R_{\text{part}}$ (Eq. (17)), the total drag reduction provided by the hydrofoil device, $\Delta R_{\text{total}}$, as a function of $x$ is obtained from Eq. (16). Fig. 7 shows $\Delta R_{\text{total}}$ when we use the local skin friction formula derived by Schlichting (1979):

$$
C_f = [2\log_{10}(Re_x) - 0.65]^{-2.3}.
$$

The Reynolds number $Re_x$ is defined as

$$
Re_x = \frac{Vx}{\nu}.
$$

where $\nu$ is the kinematic viscosity of the fluid (water at 15 °C). For a long flat plate, while the local drag reduction ratio decreases with increasing $x$ because of bubble diffusion, the total drag reduction integrated in the streamwise direction increases with increasing $x$.

3.5. Air bubble release method for drag reduction

To reduce the drag on a ship’s hull at 15–20 knot, the injection of small bubbles ($< 0.5$ mm) into the turbulent boundary layer is desirable, because only an adequate supply of these small bubbles can markedly reduce the turbulent momentum transfer, i.e., the skin friction of the wall. Although the mechanism of the drag reduction produced by such small bubbles remains an open question academically, the current common understanding from historical experimental observations is that the injection of these small bubbles into the turbulent region causes reduction of the Reynolds shear stress (Kitagawa et al., 2005). This implies that the ideal condition is to have the highest bubble number density at the peak Reynolds shear stress position, which is located between the viscous sublayer and the buffer layer of the turbulent boundary layer (Murai, 2014). Additionally, small bubbles tend to be accumulated naturally into the turbulent shear layer, as reported in previous studies of bubbly two-phase jets and also for hydrofoil (Ohashi et al., 1990). To be precise, small bubbles tend to remain in a high-enstrophy region where the second invariant of the velocity gradient tensor has a negative value (Kitagawa et al., 2001). In the flow beneath a moving ship, this region corresponds to the layer with the most active turbulent eddies, and thus the small bubbles remain for a long period inside the turbulent boundary layer and resist the turbulent diffusion effect.

For provision of a supply of these small bubbles to the turbulent boundary layer, the method of air injection is highly important. Fig. 8 shows an illustrative comparison how the present WAIP system should be operated. When the ship's draught is shallow (<5 m), the hydrofoil works as a self-priming pump, as discussed in Section 2. As a result, the small air bubbles are released near the ship’s hull by the hydrofoil device. For larger vessels with deeper draughts (>5 m), the pressure reduction by the hydrofoil is insufficient and a moderate air pressure rise is required to maintain bubble generation. In this case, the air–water interface should be placed between the AIP outlet and the top surface of the hydrofoil (Fig. 8a). Otherwise, for example, if we use blowers with high air volume flow rates, the upper surface of the hydrofoil would be covered with air cavities (Fig. 8b), and it would no longer be able to work as an air inducer using the pressure lowering effect of the hydrofoil. On this condition, the hydrofoil’s own drag would be highly increased because of different phase (gas/liquid) between the top and the bottom surfaces. Further increases in the air-volume flow rate using blowers would leave the hydrofoil completely isolated from the ambient water flow (Fig. 8c), and only large bubbles would be produced outside the boundary layer. Moreover, the hydrofoils would work as a resistance of the air injection by blowers. We must avoid such situations, which are simply a waste of bubble generation energy. Therefore the pressure regulator from the air reservoir of the compressor, instead of the blower, is necessary for the WAIP system to control the position of the air–water interface above the hydrofoil.
4. Applications to various ships

In the previous sections, our semi-theoretical estimations have predicted that significant drag reduction can be obtained by the installation of hydrofoil devices (i.e. WAIPs) on a long flat plate. Here, we report the actual application of these devices to four ships. The specifications and examination conditions of these sea trials are briefly summarized in Table 4. Basically the same WAIP systems (Fig. 1) were installed on all the four kinds of ships. However, we should note that each examination was conducted in different operation schemes due to various restrictions in sea trials. As inevitable fact, our data to be shown hereafter involve various uncontrollable factors such as data-sampling method allowed in each ship and meteorological variances. Therefore, consequent drag reduction performance was evaluated upon largely fluctuating nature. In this section, we will review each of the sea trials with describing the examination scheme in detail so that how the WAIP system worked on actual sea is demonstrated.

4.1. Adventure 2

In December 2002, we installed two hydrofoils beneath a small fishing boat Adventure 2 (Fig. 9a) as historically the first feasibility test of the WAIP system. Two WAIPs were located in-line to the main stream and the downstream one was activated. The flow conditions beneath the ship were monitored through a window located downstream of the WAIPs (Fig. 9b). As the ship's speed increased, the atmospheric air was entrained into the seawater as we expected, and the generation of small bubbles was confirmed at the downstream as it look white cloud in the window (see Fig. 9c).

Fig. 9d shows the fuel consumption rate as a function of the ship's speed. The power saving effect depends on the ship's speed, and a fuel saving of about 4% was provided by the device when the ship's speed was approximately 29 knot. The amount of drag reduction was modest because we installed only two WAIPs in order to evaluate the sensitivity of the WAIP-to-drag reduction performance. Supplementation on the examination scheme is given below.

The comparison of fuel consumption rate between “with WAIP” and “without WAIP” for Adventure 2 was conducted in a few hours (from 10AM to 2PM) of a single day. It was a fine day with calm wind (wind speed < 5 m/s) without sudden climate change, judged suitable for testing. The route for the examination was 10-sea mile round-trips in Imari Bay, Nagasaki, Japan at five different log speeds. Inside this bay, local maximum seawater current was estimated to be 1.0 m/s. Each single plot of the fuel consumption rate in Fig. 9 is the time averaged value for 10 min. Since the ship hull was made of FRP, we mounted resin-made hydrofoils which were easily removable in a short working time for returning to the original flat surface by capping the air induction pipes. This allowed us to measure the differential fuel consumption rate provided by WAIP's function appropriately. Thus, the drag increment due to the protrusive hydrofoil was excluded in the case of "without WAIP" in Fig. 9(g). In combination of the above-mentioned conditions, the measurement uncertainty of fuel consumption rate due to fluctuating seawater current is estimated to be 2.8%, and that due to wind is 1.8%. Therefore, total measurement uncertainty is estimated to be 3.3%. This value is not small enough to the measured fuel saving ratio about 4%, and we thereby declare that the significance of measurement result is not fully guaranteed. This is simply reasoned by only a single operation of the WAIP system which covers the ship with bubbles at less than 10% of the total wet-surface of the hull as shown in Fig. 9(b). Adventure 2 is positioned as our first feasibility study and this led to the application to larger ships to investigate the more integral performance of the WAIP system as described below.

4.2. Santander Ferry 1

The second sea trial was for a ferry boat of 28.8 m-long, named Santander Ferry 1 (Fig. 10a). Ten WAIPs were installed on the ship's hull (Fig. 10b) and the ship cruised at approximately 12 knot. We conducted the WAIP performance tests twice for the ferry in September 2004 and February 2005. The location of both sea trials was the route between Santander (Cebu Island) and Duma- guete (Negros Island) in Philippine, and these tests were carried out during commercial use with boarding of passengers. From the first test in September 2004, we confirmed about 10% of fuel saving in gross average, and based on it we proceeded to the second test in February 2005 which was carried out with recording various parameters.

Table 5 shows experimental results of the second test. The WAIP operation conditions were classified to four cases as shown in the rows. “All closed” means that all the air induction pipes (AIP) were closed by valves so that bubble injection stops. “No.1” and “No.2” mean the valve conditions for front four WAIPs and rear six WAIPs, respectively. Fuel consumption rate over 500 s was recorded as the

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4. Applications to various ships

In the previous sections, our semi-theoretical estimations have predicted that significant drag reduction can be obtained by the installation of hydrofoil devices (i.e. WAIPs) on a long flat plate. Here, we report the actual application of these devices to four ships. The specifications and examination conditions of these sea trials are briefly summarized in Table 4. Basically the same WAIP systems (Fig. 1) were installed on all the four kinds of ships. However, we should note that each examination was conducted in different operation schemes due to various restrictions in sea trials. As inevitable fact, our data to be shown hereafter involve various uncontrollable factors such as data-sampling method allowed in each ship and meteorological variances. Therefore, consequent drag reduction performance was evaluated upon largely fluctuating nature. In this section, we will review each of the sea trials with describing the examination scheme in detail so that how the WAIP system worked on actual sea is demonstrated.

4.1. Adventure 2

In December 2002, we installed two hydrofoils beneath a small fishing boat Adventure 2 (Fig. 9a) as historically the first feasibility test of the WAIP system. Two WAIPs were located in-line to the main stream and the downstream one was activated. The flow conditions beneath the ship were monitored through a window located downstream of the WAIPs (Fig. 9b). As the ship's speed increased, the atmospheric air was entrained into the seawater as we expected, and the generation of small bubbles was confirmed at the downstream as it look white cloud in the window (see Fig. 9c).

Fig. 9d shows the fuel consumption rate as a function of the ship's speed. The power saving effect depends on the ship's speed, and a fuel saving of about 4% was provided by the device when the ship's speed was approximately 29 knot. The amount of drag reduction was modest because we installed only two WAIPs in order to evaluate the sensitivity of the WAIP-to-drag reduction performance. Supplementation on the examination scheme is given below.

The comparison of fuel consumption rate between “with WAIP” and “without WAIP” for Adventure 2 was conducted in a few hours (from 10AM to 2PM) of a single day. It was a fine day with calm wind (wind speed < 5 m/s) without sudden climate change, judged suitable for testing. The route for the examination was 10-sea mile round-trips in Imari Bay, Nagasaki, Japan at five different log speeds. Inside this bay, local maximum seawater current was estimated to be 1.0 m/s. Each single plot of the fuel consumption rate in Fig. 9 is the time averaged value for 10 min. Since the ship hull was made of FRP, we mounted resin-made hydrofoils which were easily removable in a short working time for returning to the original flat surface by capping the air induction pipes. This allowed us to measure the differential fuel consumption rate provided by WAIP's function appropriately. Thus, the drag increment due to the protrusive hydrofoil was excluded in the case of "without WAIP" in Fig. 9(g). In combination of the above-mentioned conditions, the measurement uncertainty of fuel consumption rate due to fluctuating seawater current is estimated to be 2.8%, and that due to wind is 1.8%. Therefore, total measurement uncertainty is estimated to be 3.3%. This value is not small enough to the measured fuel saving ratio about 4%, and we thereby declare that the significance of measurement result is not fully guaranteed. This is simply reasoned by only a single operation of the WAIP system which covers the ship with bubbles at less than 10% of the total wet-surface of the hull as shown in Fig. 9(b). Adventure 2 is positioned as our first feasibility study and this led to the application to larger ships to investigate the more integral performance of the WAIP system as described below.

4.2. Santander Ferry 1

The second sea trial was for a ferry boat of 28.8 m-long, named Santander Ferry 1 (Fig. 10a). Ten WAIPs were installed on the ship's hull (Fig. 10b) and the ship cruised at approximately 12 knot. We conducted the WAIP performance tests twice for the ferry in September 2004 and February 2005. The location of both sea trials was the route between Santander (Cebu Island) and Duma-guete (Negros Island) in Philippine, and these tests were carried out during commercial use with boarding of passengers. From the first test in September 2004, we confirmed about 10% of fuel saving in gross average, and based on it we proceeded to the second test in February 2005 which was carried out with recording various parameters.

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ferry cruised a periodical round trip “Go” and “Back” four times a day. Since there was a large variation in the fuel consumption rate because of change in the number of passengers and so on, we show the weight-corrected fuel consumption rate in the table. Furthermore, the influence of speed difference has been corrected to obtain the comparable values that are shown on the bottom line of the table. From this, we confirmed 16% reduction in the fuel consumption rate as all the ten WAIPs were activated (16% = 100 × (91.0 – 76.5)/91.0). The data in the case “No.1 only open” corresponds to 21% reduction, and implies that bubble injection from the front part of the ship is more effective. However, the authors still suspect that this value is too large to believe. The measurement uncertainty of fuel flow rate, total weight, and ship speed are estimated to be less than 3%. In contrast, fuel consumption dependence on sea and wind states would be more effective. To clarify this issue in the success of a single-day sea trial, we advanced to the next sea trial spending more than 100 days for guaranteeing statistics reliability as reported next.

4.3. New Ferry Misaki

As the third application of the WAIP system, we chose a 68 m-long cargo, called New Ferry Misaki. Fig. 11 shows a photograph of the ship, and it cruises at about 18 knot on sea. Since New Ferry Misaki is much larger than previous test cases, we installed 34 WAIPs. Another feature is that we introduced compressors to assist the WAIP system because of the deep draught. As explained in Section 3.5, the additional pressure should be adjusted not to
lose the original performance of the hydrofoil. The pressure rise adopted to AIP was 41 kPa using pressure adjusting valves, which corresponds to hydrostatic pressure of 4 m. This adjustment helps the water surface in the AIP with reaching the region above the hydrofoil. New Ferry Misaki has been navigating in the route called Shimo-Gotou Route; Nagasaki New Port–Fukue–Naru–Wakamatsu–sima. She has made one round trip a day with single refueling. Weather and wave condition were not recorded but at least she was operated under commercially operable states for shipping service. She cruised 77 days without air injection to be without WAIP, and 148 days with WAIP operation. The fuel consumption rate for her engine has been reported to the authors from chief engineer’s log book. It is noted that the total fuel consumption is about 15 to 20% larger than that for main engine because of ship-interior uses. It is irrelevant to drag reduction phenomenon and was not considered.

Table 5
Fuel consumption rate of Santander Ferry.

<table>
<thead>
<tr>
<th>Santander Ferry WAIP operation conditions</th>
<th>Starboard side engine</th>
<th>All closed</th>
<th>No.2 only open</th>
<th>No.1 only open</th>
<th>All open</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Go Back</td>
<td>Go Back</td>
<td>Go Back</td>
<td>Go Back</td>
<td></td>
</tr>
<tr>
<td>Elapsed time [s]</td>
<td>550 534</td>
<td>537 513</td>
<td>545 517</td>
<td>517 543</td>
<td></td>
</tr>
<tr>
<td>Fuel remained on board</td>
<td>1.566 1.501</td>
<td>1.436 1.371</td>
<td>1.306 1.241</td>
<td>1.176 1.111</td>
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<tr>
<td>Persons including passengers</td>
<td>2.210 2.730</td>
<td>3.510 1.755</td>
<td>1.495 1.950</td>
<td>1.600 2.340</td>
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<tr>
<td>Fuel consumption rate [l/h]</td>
<td>101.1 80.5</td>
<td>79.6 72.6</td>
<td>72.2 66.4</td>
<td>77.2 70.9</td>
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<tr>
<td>Weight corrected with 3.776 [t]</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Fuel consumption rate [l/h]</td>
<td>80.9 80.6</td>
<td>72.1</td>
<td>71.5 66.0</td>
<td>76.5 70.7</td>
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<tr>
<td>Averaged fuel con. rate [l/h]</td>
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</table>

Fig. 11. New Ferry Misaki (68.0 m (Lpp), 12.3 m (Bmd), 8.95 m (Dmd), 3.2 m (draft), 4076 ps (power)). (Courtesy of Hirofumi Morieda).
average daily fuel consumption decreases to 3733 with a standard deviation of 191 l/day (5.1% to the average). The true average daily fuel consumption decreases to 3733 with a standard deviation of 191 l/day (5.1% to the average). The true average daily fuel consumption decreases to 3733 with a standard deviation of 191 l/day (5.1% to the average).

TABLE 6
Main engine fuel consumption of New Ferry Misaki without WAIP.

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5. Conclusions

We developed a device to be used as an air-bubble generator for drag reduction ships; the device consists of an air induction pipe (AIP) and an angled hydrofoil, and is called the winged air induction pipe, or WAIP. Air bubbles are released from the induction pipe outlet into the turbulent boundary of ship hull via the negative pressure produced above the hydrofoil beneath the AIP. In this paper, the theoretical principle of air entrainment by this device was described and its performance was confirmed by a series of laboratory experiments. A simple theoretical analysis for critical velocity at which air bubbles start to release was in good agreement to the observation in a towing tank experiment. To estimate the net drag reduction obtained by installing a single WAIP system, a circulating water channel experiment was carried out. From semi-empirical scaling, a compensation distance at which drag reduction exceeds the drag increment due to hydrofoil’s own drag has been estimated to be less than 10 m at typical cruising speed.

Four kinds of full-scale tests were carried out to demonstrate the feasibility of the WAIP system while individual tests were conducted in different schemes owing to various restrictions in their sea trials. For a small fishing boat Adventure 2, single WAIP operation earned 4% of fuel saving but it was not fully guaranteed as we consider fluctuating nature in sea states. A passenger ferry Santander Ferry employed 10 WAIPs and obtained 16% of fuel saving for four round trips a day. In order to obtain higher statistic reliability in long operation, we advanced to 148-day sea trials using a long cargo New Ferry Misaki where 34 WAIPs were installed. She obtained 9% reduction in main engine fuel oil consumption in her commercial shipping service, by which fuel oil of 55,204 l was saved in 148 servicing days. In the case of
a long hold cargo Filia Ariea, 34 WAIPs out of a total of 52 were under water, and a net power saving of about 10% was achieved. As we experienced in large vessels with deeper draughts, the WAIP requires the assistance of an air compressor since the negative pressure provided above the hydrofoil fails in insufficient for realizing natural ventilation (see Eq. (2)). To the contrary, surplus air supply from blowers into air induction pipe alters the two-phase flow structure around the hydrofoil to totally lose the hydrofoil performance. For satisfactory operation of the WAIP system in ships with deeper draughts, future
studies will be conducted on (1) the optimization of the hydrofoils (e.g., the attachment of flaps, and hydrofoils suitable for two-phase flow) to enhance the hydrofoil’s air entrainment performance, (2) appropriate operation of the air compressors to assist the device, and (3) investigation of their relevance to the downstream physics of the drag reduction.

Acknowledgments

The authors would like to thank Dr. Yuji Tasaka and Dr. Yoshihiko Oishi for their contributions to the WAIP project. This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) of Japan (Grant no. 08 B 36002) and by JSPS KAKENHI (Grant no. 24236033).

References