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INVESTIGATION OF AIR LUBRICATION SYSTEM (ALS) ON DRAG REDUCTION OF SHIP

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For slow moving vessels, the frictional resistance accounts for as much as 80% of the total resistance, demanding for the reduction in it. The use of air as lubricant, known as ALS, to reduce the friction is an active research topic. In this study, experimental investigations into frictional drag reduction by microbubbles were carried out on a scaled model of Bulk Carrier for different ship speeds and injection flow rates. From the study, it is concluded that, for the cruising speed, the maximum reduction in the total drag of 24.8% was obtained at the injection flow rate of 2.5CFM.

KEY WORDS: Frictional Drag; Air Lubrication System; ALS; Advanced Ship technology; Green Technology; Hydrodynamics & CFD

INTRODUCTION

Marine transportation business is currently relied on researchers to develop drag reducing techniques addressing cost of shipping and environmental issues. It is stated that, for cargo ship, 60% of the total resistance is due to fluid friction and for tankers it is around 80%, demanding for the reduction in the frictional resistance. Numerous technologies (Sindagi, et al., 2016) have been studied and applied in reducing the frictional drag. Based on the study (Sindagi, et al., Apr-Jun 2018), (Sindagi, et al., Nov 2017), (Sindagi, et al., 2016), (Sindagi, et al., 2017) and (Sindagi, et al., 2018), it is concluded that, MBDR has additional advantages over other technologies, such as operation is quite easy, low operating costs and high energy savings and more importantly it is environmental friendly. The most noteworthy contribution regarding MBDR methodology was presented by (McCormick & Bhattacharyya, 1973) using hydrogen bubbles produced through electrolysis process. From then, numerous studies have been carried out on MBDR. As mentioned in the study (Yoshiaki , et al., 2000), reduction of frictional drag for ships has its own difficulties like higher value of Reynolds number and skin friction device such as riblets that scale up with friction velocity, becomes more problematic to apply, as size of the body increases. Moreover, problem of fouling in the sea environment makes application of methodologies more difficult. displacement ships such as Bulk Carriers, VLCC, ULCC, tankers and Cargo Ships, are well suited to this technique, as they are more or less in box shape with wide flat bottom causing injected bubbles at the bottom staying close to the hull bottom due to the action of buoyancy force (Yoshiaki , et al., n.d.). As the ship's speed increases, the wave making resistance component becomes larger and in turn frictional drag reduces, reducing the efficiency of MBDR technique. Therefore, MBDR is expected to be suited for slow moving vessels with Froude number varying from 0.05 to 0.15 (MARIN, 2011) and of course to vessels operating in shallow water, where in, reduction in pressure below the hull due to shallow water effect requires lesser energy for the injection (Sindagi, et al., 2016) & (Sindagi, et al., 2018). Based on the work on effect of MBDR in a rectangular channel (Sindagi, et al., 2018), it is concluded that, the most significant parameter in deciding the MBDR effect is the effective value of the Volume fraction at the point of analysis, which is influenced by both, the injection rate. In this study, experimental investigation into frictional drag reduction by injecting air below it was carried out for an 8000 Tonnes Deadweight Bulk Carrier for different speeds and for different air injection rates. For the injection of air bubbles, injector unit with bottom plate having array of holes with 2mm diameter has been used. 1:23 scaled model of the ship is constructed and is tested for the resistance of ship for both with and without injection of microbubbles in the towing tank. The experimental study was carried out for speed range of 4 knots to 12 knots in the interval of 1 knot and for each speed, effect of six different injection flow rates of 0.5 CFM to 3.0 CFM in the interval of 0.5 CFM was investigated.

EXPERIMENTAL SETUP

The experimental work for the current study has been carried out in a Towing tank of Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai, India. As it was confirmed that, ALS technique has maximum effect for ships with flat bottom. Hence, for the study, a suitable hull is selected, which suits to the investigation. Details of the selected hull are placed at Table 1. 1:23 scaled model of the ship is constructed and is tested for the resistance of ship for both; with and without injection of microbubbles in the towing tank

Table 1 Principal particulars of 8000 DWT Bulk Carrier

Particulars	Ship
L_{BP}	117.1m
Breadth	20m
Depth	7.2m
Draft	4.8m
Speed	10 knots

Displacement	10164 tonnes

The most commonly used method to generate microbubbles is by making use of Porous material, in which air is injected into the flow through the porous medium. (Yoshiaki , et al., 2000) pointed out following problems in using porous plate

- Non-uniform distribution of size and number of microbubbles
- The pressure loss is very much significant.

In order to solve above problems, plate with array of holes was used by (Yoshiaki , et al., 2000). For the current study, array of holes is used for the injection purpose. As shown in the Figure 1, air compressor is used initially to compress the air, which is then fed into an air injector unit consisting of air chamber through a valve to control the flow rate of air and then through the flow meter to measure the flow rate. The air chamber has 225 holes of 2mm diameter made into its bottom plate. The Air chamber is mounted into the wooden model of ship in such way that, the bottom of air chamber is flush mounted with bottom of the model. Compressor sizing was carried out initially based on the operating conditions. Kalki Vayu Digital Air Flow meter has been used for the measurement of air injection flow rate.

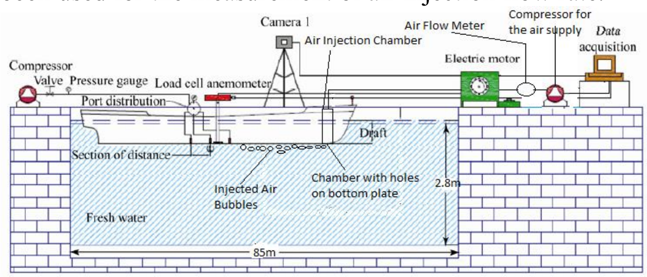

Figure 1 Details of Experimental Setup

For the visualization of flow and movement of air bubbles below the hull, bottom of the model is cut at three longitudinal locations, which is then replaced with 9mm thick acrylic sheets. Special care has been taken to avoid any leakage into the model along with proper stiffening of acrylic sheets with longitudinal and transverse framing as shown in the Figure 2.

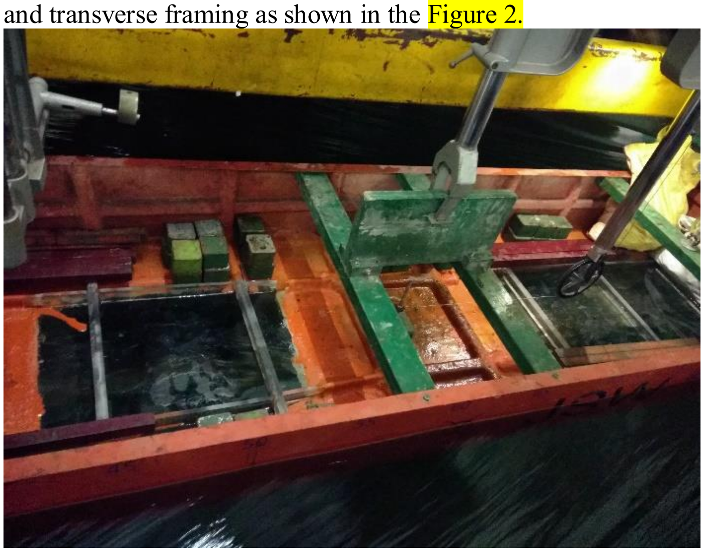

Figure 2 Acrylic sheets placed for the visualization of flow

50kg Load cell has been used for the measurement of total resistance of the model. The flow meter, Load cell and control valve have been initially calibrated for the accuracy of the measurement. The experimental investigation was carried out for speed range of 4 knots to 12 knots in the interval of 1 knot and for each speed, effect of six different injection flow rates of 0.5 CFM (Cubic Feet per Minute) to 3.0 CFM in the interval of 0.5 CFM was investigated.

RESULTS AND DISCUSSION

Towing tank results without the injection of microbubbles

Initially the hull was towed without the injection of air bubbles for the speed range of 2 knots to 12 knots in the interval of 1 knots. ITTC – Recommended Procedures (ITTC – Recommended Procedures, 1999) for conducting model test have been strictly followed. Total resistance of the model has been noted without the injection of air bubbles below the hull. Prohaska's method (Prohaska, 1996) which is based on Hughes method (Hughes, 1954), has been utilized to determine the value of form factor. Details of experimental parameters are placed at Table 2. Results obtained for the total resistance of ship without the injection of air bubbles are placed at **Figure 3**.

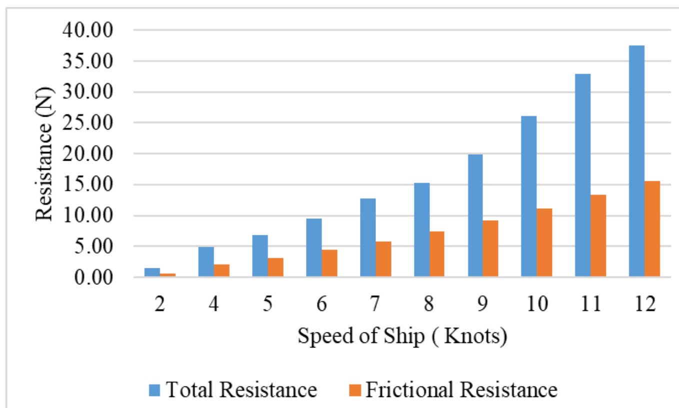

Figure 3 Towing tank results without the injection of microbubbles

Table 2 Range of Ship and model speeds for the model testing

Ship's Speed (Knots)	Froude Number
2	0.03
4	0.06
5	0.08
6	0.09
7	0.11
8	0.12
9	0.14
10	0.15

11	0.17
12	0.18

Towing tank results with the injection of microbubbles

An exhaustive review on past research work carried out on the experimental and numerical investigation of MBDR methodology by (Sindagi, et al., Apr-Jun 2018) & (Sindagi, et al., 2018) revealed that, frictional drag of any body is given by the equation

$$R_F = C_F \frac{1}{2} \rho S V^2$$

To reduce the frictional resistance, one can reduce the value of C_F and/or density of liquid flowing and/or the wetted surface area. As seen from previous experiments based on ALS, combined effect of reduction in density and wetted surface area along with reduction in C_F due to alteration of flow properties and modification of turbulent momentum transport due the causes considerable reduction in frictional drag. When air or gas is injected below the plate into the boundary layer, mixture of air or gas bubbles and water is formed (Jinho, et al., 2014). Figure 4 shows different mechanisms of air lubrication techniques (Mäkiharju, et al., 2012). In Micro Bubble Drag Reduction (MBDR) air or gas is injected, using a slot, porous medium or a perforated plate. In this case, size of Bubbles generated will be very small as compared to boundary layer thickness. This causes reduction in the density of liquid flowing along with alteration of the turbulent momentum transport. If the air injection flow rate is increased, air bubbles start coalescing with other, forming patches that cover the surface. If the injection rate of air is injected further, transition from a bubbly flow to a Transitional Air Layer occurs, where in a Transitional air layer is formed covering more area below the body (Elbing, et al., 2008). As the injection rate is increased further, a continuous air or gas layer is formed covering entire surface, known is Fully developed air layer reducing the wetted surface area. This in turn causes considerable reduction in frictional drag which reaches to almost 80%.

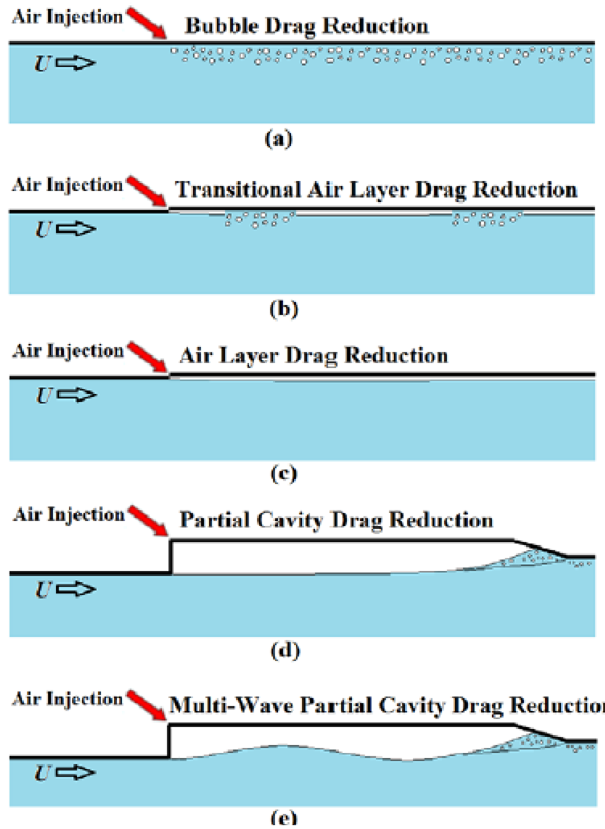

Figure 4 Different MBDR techniques used to reduce frictional drag (Mäkiharju, et al., 2012) & (Jinho, et al., 2014).

The present study is carried out to analyze the effect of different air injection flow rate and ship's speed on the reduction in frictional drag and total drag of ship. Figure 5 to Figure 10 shows results obtained from the experimental investigation. As seen from the Figure 5, showing the variation of reduction in the frictional and total drag of ship for the constant injection flow rate of 0.5 CFM. From the Figure 5 one can conclude that, maximum reduction of 27.9% in the total drag is obtained at a ship's speed of 7 knots. At this speed, 43.6% reduction in the frictional drag is obtained. At the cruising speed of 10 knots for which the ship is designed, the reduction in the total drag and frictional drag is found to be 17.8% and 29.7% respectively. For all other speeds, reduction in the drag of the ship was found to be dipping. In fact, for the speed of 12 knots, it can be seen that, reduction is found to be negative in nature. It is a well-known fact that, at higher speeds, the percentage of wave making resistance is higher as compared to the frictional drag and as MBDR reduces only frictional drag and probably it might increase the wave making resistance also, causing increment in the total drag. Moreover, reduction in the total drag is found to be more at slower speeds as compared to at higher speeds.

Figure 5 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 0.5 CFM

For the higher injection flow rate of 1.0 CFM, shown in the Figure 6, in general, the reduction in the total drag and frictional drag is found to be more as compared to the reduction at the injection flow rate of 0.5 CFM. The maximum reduction in the total drag and frictional drag of 37.8% & 58.3% respectively is found at a speed of 5 knots. Even at the speed of 7 knots the reduction of 34.2% is found and at cruising speed of 10 knots 17.3% reduction is obtained.

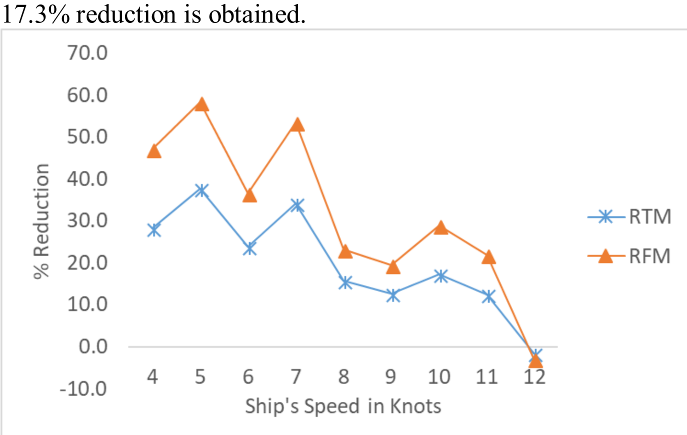

Figure 6 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 1.0 CFM

For the injection flow rate of 1.5 CFM shown in Figure 7, one can conclude that, the speed at which maximum reduction in the total drag is found; is the same speed at which maximum reduction in the frictional drag is obtained. Maximum reduction of 36.3% is obtained at a speed of 4 knots and at cruising speed of 10 knots, the reduction of 18.1% is obtained.

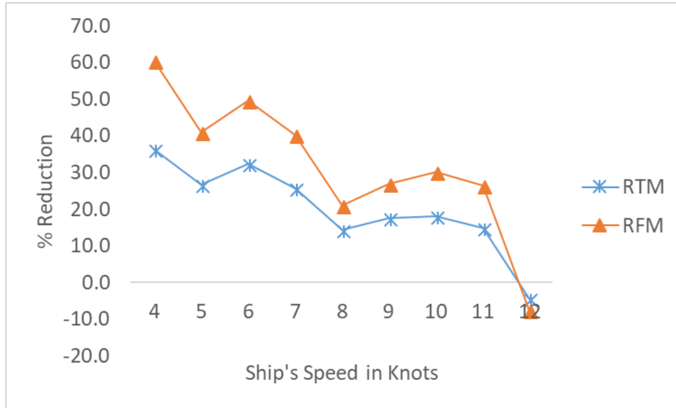

Figure 7 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 1.5 CFM

For the injection flow rate of 2.0 CFM as shown in the Figure 8, interesting observation is made at a speed of 12 knots, wherein, the reduction in the total drag is obtained. Moreover, at a speed of 11 knots, the reduction is found to be 24.8%. Maximum reduction of 32.8% is obtained at a speed of 6 knots and at cruising speed of 10 knots, the reduction of 19.4% is obtained.

Figure 8 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 2.0 CFM

For the injection flow rate of 2.5 CFM as shown in the Figure 9, maximum reduction of 35.4% is obtained at a speed of 6 knots and at cruising speed of 10 knots, the reduction of 22.4% is obtained. Moreover, at a speed of 11 knots, the reduction is found to be 25.4%.

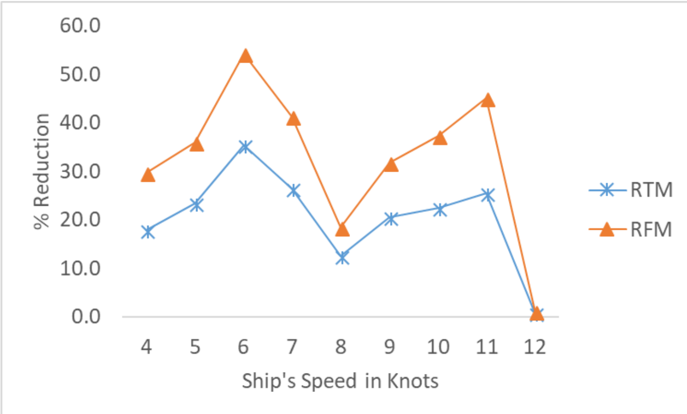

Figure 9 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 2.5 CFM

For the maximum injection flow rate of 3.0 CFM as shown in the Figure 10, maximum reduction in the total drag and frictional drag of 43.8% and 67.2% respectively is obtained at a speed of 6 knots and at cruising speed of 10 knots, the reduction of 21% is obtained.

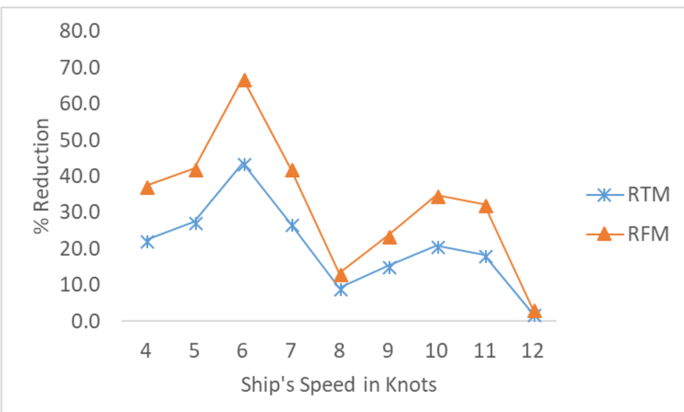

Figure 10 Comparison of Percentage Reduction in Total resistance and frictional resistance of ship for Injection rate of 3.0 CFM

From the above study, it can be concluded that, maximum reduction in the total drag and frictional drag of 43.8% and 67.2% respectively is obtained at a speed of 6 knots at the injection flow rate of 3.0 CFM. If one considers the cruising speed, the maximum reduction of 24.8% was obtained at the injection flow rate of 2.5CFM. Moreover, as mentioned earlier, in most of the cases of injection flow rates, the maximum reduction is obtained at slower speeds, wherein, the percentage contribution and reduction of frictional drag is higher. Experimental results obtained are in line to the results obtained by (Madavan, et al., 24 Aug 1984), (Madavan, et al., 1983), (Shen, et al., 2006) (Winkel, et al., 2004), (KATO & KODAMA, 2003) (Kato, et al., 1998), (Yoshiaki , et al., 2000), (Takahashi, et al., 2001), (Foeth, n.d.) and (Kodama, et al., 2004).

Distribution of microbubbles below the hull

The intuition says that, the bubble size is one of the major factor which influences the MBDR effect. Actually, the bubble size depends upon the interaction of injected air or gas flow with the local structure of flow. It is predicted that, no MBDR effect can be obtained with bubble size greater than certain value (Kato, et al., 1998). (Shen, et al., 2006) conducted the nitrogen injection test and concluded that, smaller size of bubbles produced similar drag reduction and drag reduction effect depends on the volumetric flow rate of air and the static pressure in the boundary layer and does not depend on the size of bubbles. (Shen, et al., 2006) & (Winkel, et al., 2004) mentioned the importance of bubble size in terms of the ratio given as below

$$d^+ = \frac{d_b}{l_v}$$

It is also mentioned that; the buffer region of flow extends from $5y^+$ to $30y^+$.

$$y^+ = \frac{y}{l_v}$$

Where y is the normal distance from the wall or plate. This is the region where higher value of Reynolds stress is developed along with high momentum transfer. If the size of injected bubbles in the buffer region are smaller than to a viscous wall unit (l_v) then the density of water reduces, otherwise, if the size of bubbles is much greater than or equivalent to $30l_v$, then it may not be possible for bubbles to modify the fluid momentum exchange in the buffer region. The local void fraction was measured in an experiment by (Kawashima, et al., n.d.) & (Takahashi, et al., 2001). Typical observations were made, which are in line to observations made by (Madavan, et al., 1985). MBDR technique can be easily applied to full-scale ships by reducing the amount of injected air, in turn, improving the efficiency of MBDR effect. To do this, one needs to carry out the full-scale tests on ship's hull. The full-scale experiment was carried out in the Pacific Ocean, off Tokyo Bay. From the experiment, it is concluded that, the injected air bubbles did not stay in the internal area of the boundary layer and did not spread over the hull but flowed like chimney smoke. Also, the air injection rate was not maximum when the best result was obtained. (Takahashi, et al., 2001) conducted MBDR experiments for 50m long flat plate in the in 400m long towing tank. Objective was to understand the streamwise persistence of MBDR effect. It was observed that, distance of point of observation from the injection point is the most significant parameter, and that the thickness of boundary layer has slight effect on the MBDR. (Kodama, et al., 2004) carried out similar models tests on a 22m long plate with width of 1m. (Sanders, et al., 2006) conducted experiment, where in, the degree of coalescence of bubbles and their sizes were varied with the streamwise distance from the injection point for different flow speed. It is observed that, the bubbles coalesce to form intermittent or continuous air layer at slower speeds and discrete bubbles were formed at higher speeds.

By considering all these results, it is concluded that, microbubbles are very effective in reducing skin friction, if they can be concentrated in the inner region of the boundary layer, close to the wall. In line to these observations made, variation of bubbles size, their coalescence and breaking and formation of air layer is observed in the current experiment through the cut sections at three different longitudinal locations. Typical observation made at speeds of 6 knots and 8 knots at constant injection flow rate of 1.0 CFM are placed at, Figure 11 ad Figure 12 respectively. As seen from these figures, with the increase in the speed of the ship, it is found that, bubbles were separating/splitting with each other. At slower speeds, these bubbles found to be coalescing with each other forming an Air Layer, giving maximum reduction in the frictional as well as total drag of the ship. The reason for the formation of air layer could be, as the flow speed and also the migration speed of bubbles was low, maximum time was available for the coalescence of bubbles. At higher speeds, as bubbles were breaking/splitting/separating from each other, the reduction in the drag was found to be lesser as compared to slower speeds. Moreover, at higher speeds, bubble size was found to be smaller as compared to slower speeds. With increase in the longitudinal distance from the injection point, bubbles were found to be coalescing irrespective of speed of ship. Here observations made from experiments are in line to observations made from previous experimental and numerical results.

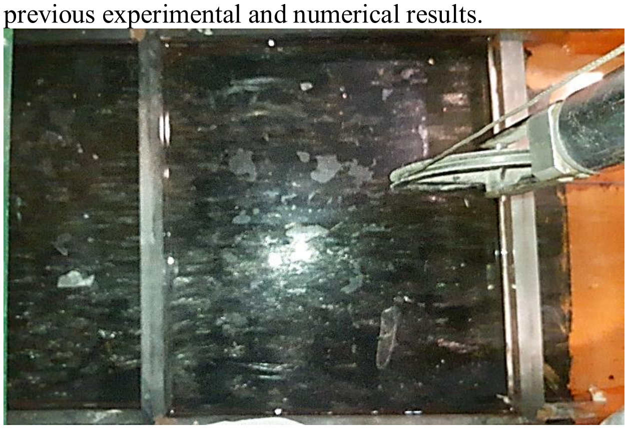

Figure 11 Distribution of bubbles below the hull at a speed of 6 knots and air injection rate of 1.0 CFM

In the past experiments conducted by various researchers (Fukuda, et al., 2000) & (Yoshiaki , et al., 2000), it was found that, at certain locations, bubbles were escaping in the transverse direction. However, as, for this experiment, as the hull was carefully selected with flat bottom, it was found that, bubbles did not escape till the aft most end of the ship. This was one of the reason for higher value of reduction in the total drag as compared to previous experiments conducted (Fukuda, et al., 2000) & (Yoshiaki , et al., 2000).

Figure 12 Distribution of bubbles below the hull at a speed of 8 knots and air injection rate of 1.0 CFM

CONCLUSIONS

In this study, experimental investigations into frictional drag reduction by microbubbles were carried out for an 1:23 scaled model of Bulk Carrier for different speeds and for different air injection rates using series of injection holes of 2mm diameter. Following inferences can be made from the experimental investigation carried out:

- Maximum reduction in the total drag and frictional drag of 43.8% and 67.2% respectively is obtained at a speed of 6 knots at the injection flow rate of 3.0 CFM.
- For the cruising speed of 10 knots, for which the ship is designed, the maximum reduction in the total drag of 24.8% was obtained at the injection flow rate of 2.5CFM.
- MBDR effect was found for the speed range of Froude numbers between 0.04 and 0.17 as against the speed range of Froude numbers between 0.05 and 0.15 predicted by (MARIN, 2011).

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