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CFD investigation of ALS technique on frictional drag reduction of bulk carrier

Simcenter STAR-CCM+ predicts drag reduction in ships

Executive summary

This white paper details a 2018 study on 3D numerical investigations into frictional drag reduction by injecting air bubbles below the hull using the Siemens Digital Industries Software tool Simcenter™ STAR-CCM+™ software. The study is for a 1:23 scaled model of 8,000 tons of deadweight (dwt) bulk carrier for two speeds and six air injection rates. Numerical investigations were carried out at a ship's cruising speed (10 knots), and the other based on the experimental results obtained with maximum drag reduction (6 knots).

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Abstract

Vehicles moving in water experience more frictional drag than vehicles on land or in the air as water viscosity is greater than air. Increasing fuel costs and looming emissions restrictions are driving shipowners to reduce ship resistance and reduce installed power. It is reported[1] that the fluid frictional drag accounts for as much as 60 percent of a cargo ship's total drag; that number jumps to approximately 80 percent for a tanker. As a result, there is strong demand to reduce fluid frictional drag.

Numerous technologies[2], such as the use of micromorphology-riblets, polymers, heating walls and vibrating flexible walls, partial cavity creation, antifouling and coatings and super-hydrophobic surface and air lubrication systems (ALS), have been studied and utilized to reduce the frictional drag of a surface. Two different drag reducing techniques have been observed in the past: bubble drag reduction (BDR) and ALS.

Experimental results based on BDR effected drag reduction by 30 percent, and results based on ALS effected a reduction of greater than 80 percent. It is concluded that[3, 4, 5] ALS has added advantages over other drag reducing technologies, such as being environmentally friendly, easy to operate, being low in cost and realizing high energy savings. It is also reported that ALS achieves 80 percent reduction in frictional drag, which can result in substantial fuel savings for commercial and naval ships.

Experimental investigation was carried out at the towing tank of the Department of Ocean Engineering, Indian Institute of Technology in Madras, India. The numerical investigation was conducted with the Simcenter STAR-CCM+ tool from Siemens Digital Industries Software to simulate air bubbles below the hull. It was used to create simulation control volume for the specific hull with 225 air injection holes using both 1 mm in diameter and 2 mm in diameter injection holes. The simulation's objective was to determine the effectiveness of both injection holes.

"Siemens granted us almost unlimited licenses of Simcenter STAR-CCM+ for this study," says Professor Sudhir Sindagi, Tolani Maritime Institute. "It's a tool that we employ throughout our educational enterprise, so there will be students who are more adept at applying it. The computational card that we hold in our hand is absolutely amazing."

"We have been heavy users of Simcenter STAR-CCM+ for over five years," says Dr. R. Vijayakumar, Department of Ocean Engineering, Indian Institute of Technology, Madras, India. "The software interface, meshing and postprocessing are well-conceived and intuitive, enabling students to quickly become adept at utilizing the code. Moreover, meshing, solution and postprocessing are integrated into the suite."

Investigation of alteration of flow parameters due to injection of air bubbles

The frictional drag of any body is given by the expression:

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

From the above expression, it can be concluded that to reduce the frictional drag, the coefficient of friction (C_F), density of liquid (ρ) flowing and the wetted surface area(s) must be reduced. As seen from previous experiments based on ALS, it is clear that[2] the ALS effect is due to the reduction of local effective viscosity and density of the fluid which might reduce the Reynolds stress. Other factors that can cause reduction in frictional drag include bubble stratification, near wall phase composition, reduction of turbulence intensity in the streamwise direction and prevention of the formation of span-wise vorticity near the wall.

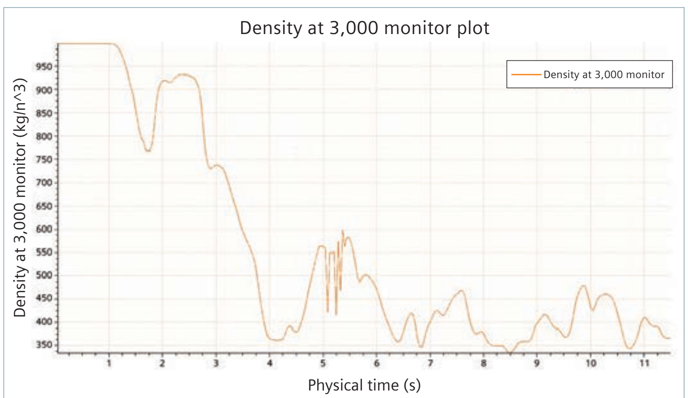

Figure 1

When air is injected into the boundary layer, an air-water mixture flow containing air bubbles and water can be formed. If the amount of injected air increases, air bubbles begin to coalesce into patches that continuously cover the surface, and a transitional air layer is formed where the patches coexist with air bubbles. If the flow rate of air is further increased, a continuous air layer is formed, reducing the direct contact of water with the surface. Formation of a continuous layer of air is desirable in reducing the density of fluid from water to air. As seen in figure 1, where the variation of density is plotted against time at a location of 3,000 mm from aft of the air injection point. From figure 1, it can be concluded that reduction in density is almost 55 percent, causing a reduction in frictional drag. The shear stress developed due to liquid viscosity can be estimated by using:

$$\tau_w = \mu \frac{du}{dy} - \rho U'V'$$

Here, μ is dynamic viscosity of liquid and the term $\rho U'V'$ is Reynolds stress.

Here, the term, $U' V' = - q\Lambda \frac{\partial u}{\partial y}$

Where, $q\Lambda$ is Eddy viscosity, $q2$ is turbulence energy and Λ is energy containing turbulent scale.

By substitution, we get:

$$\tau = (\mu + \rho q\Lambda) \frac{\partial u}{\partial y}$$

From the above expression, when air bubbles are present in the flow, the density of mixture decreases, and shear stress is reduced. The second term in the above equation is known as Reynolds stress, which reduces as the density (ρ) decreases. Similar observations have been made at the location 3,000 mm from the aft-most point of the ship for the variation in turbulent viscosity and dynamic viscosity due to the injection of air bubbles and are placed in figures 2 and 3. With the injection of bubbles below the hull, turbulent viscosity and dynamic viscosity at the localized area reduce the first term of the above expression. Similarly, as presented in figure 4, the other reason for the reduction in the frictional drag is the reduction in the turbulence dissipation rate due to the injection of bubbles. To conclude, the combined effect of density reduction, viscosity reduction, reduction in Reynolds stress and reduction in the turbulence dissipation rate causes the reduction in the frictional drag.

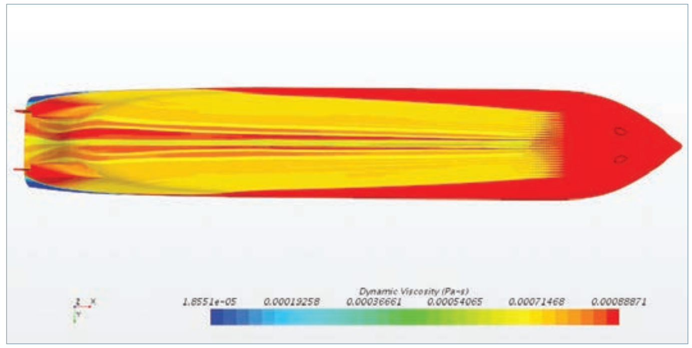

Figure 2

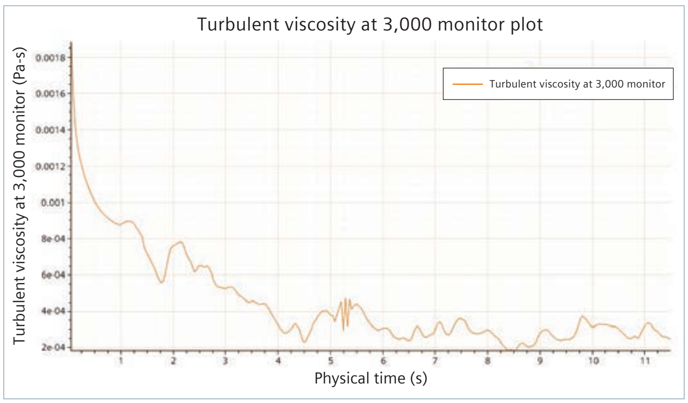

Figure 3

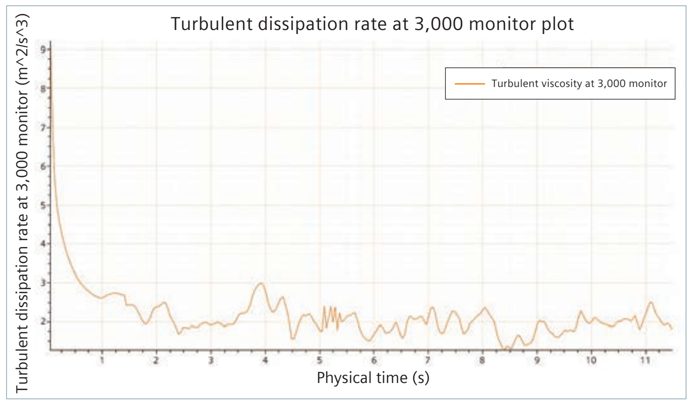

Figure 4

Study of different injection flow rates at 10 knots

Figures 5 and 6 describe the variation in the coefficient of friction (CF) values in longitudinal and transverse directions for two values of injection flow rate, 2.5 cubic feet per minute (CFM) and 1.5 CFM, respectively. CF does not remain constant, which depends on the formation of an air layer or the presence of bubbles (figure 7). Moreover, maximum reduction in the value of CF is at the centerline of the hull in contrast to the side of the hull, which is 300 mm from the centerline of the ship. With the increase in distance from the injection point in the longitudinal direction, the value of CF initially decreases due the formation of an air layer. As the distance increases, the CF value increases.

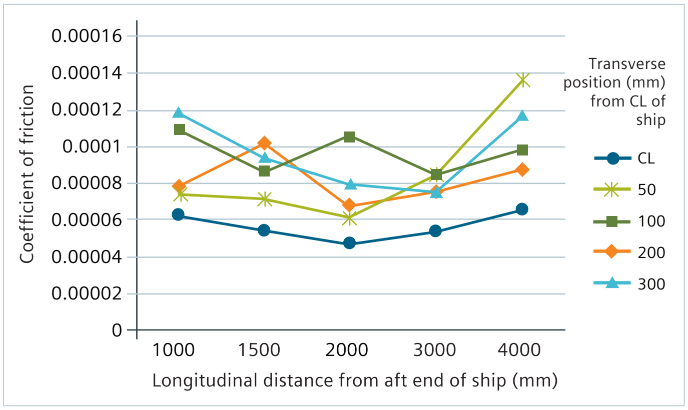

Figure 5

This reconfirms that the ALS effect reduces with the distance from the injection point in the longitudinal and the transverse direction. In past experiments conducted by various researchers[6, 7], it was found that at certain locations bubbles were escaping in the transverse direction. In this experiment, the hull was carefully selected with a flat bottom and it was found that bubbles did not escape until the aft-most end of the ship (figure 7). This was one of the reasons for the higher reduction value in

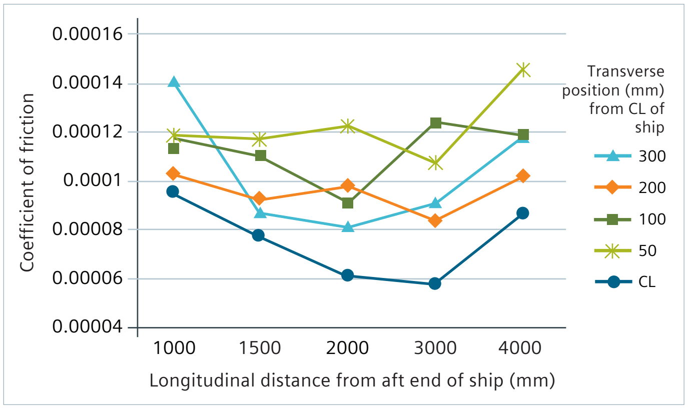

Figure 6

the total drag compared to previous experiments[6, 7] as bubbles covered the maximum area below the hull. Figure 7 also shows that as the longitudinal distance increases bubbles coalesce and form air pockets. This is the major reason for variation in CF values in longitudinal direction, as bubbles coalesce to form air pockets avoiding any contact of water with the surface and thus reducing the coefficient of friction. As seen in figure 7, coalescence depends on the ship's speed and air injection rate. At higher speeds, bubbles move separately

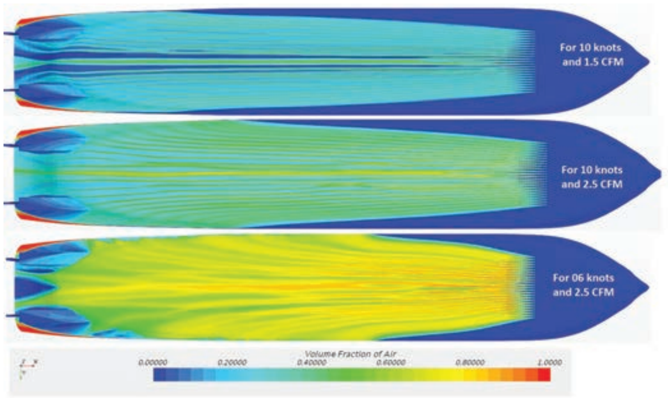

Figure 7

with less coalescence. At slower speeds, bubbles start coalescing with each other, forming an air layer completely displacing the water and giving maximum reduction in the frictional drag.

Variation of CF values in the longitudinal direction for different speeds at constant injection flow rates

An investigation on the effect of the ship's speed on ALS' effect in longitudinal direction for different air injection rates was carried out. From figures 8 and 9 it can be concluded that for air injection flow rates of 2.5 CFM and 1.5 CFM, the ALS effect is more for the ship's speed of 6 knots, giving the lowest values of coefficient of friction. As mentioned earlier, the reason for the maximum reduction at slower speeds is due to the formation of an air layer displacing water completely below the hull.

Variation of CF values in transverse direction for different speeds at constant injection flow rates

A similar investigation on the effect of the ship's speed on ALS' effect in transverse direction for different values of air injection rate also was conducted. From figures 10 and 11, it can be again concluded that ALS' effect is more for a ship's speed of 6 knots, also giving transverse direction the lowest coefficient friction values. Moreover, the effect of injection of air quickly diminishes in the transverse direction as there is no flow of air bubbles in the transverse direction.

To conclude, ALS' effect gradually decreases downstream and span wise because of the absence of bubbles.

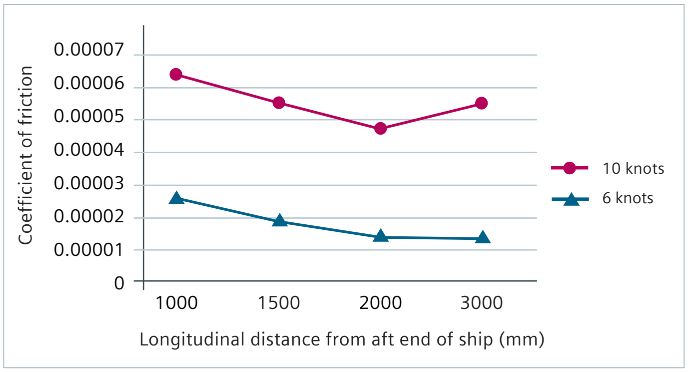

Figure 8

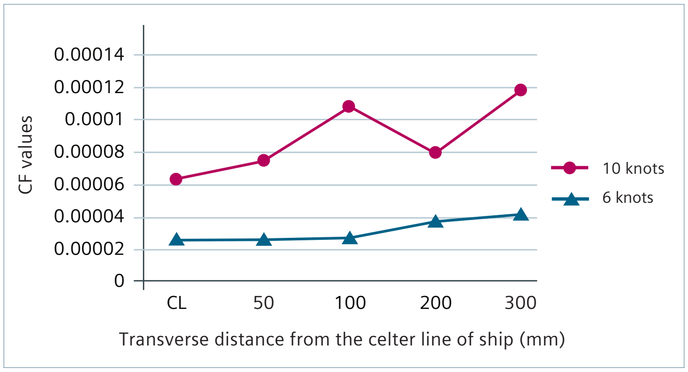

Figure 10

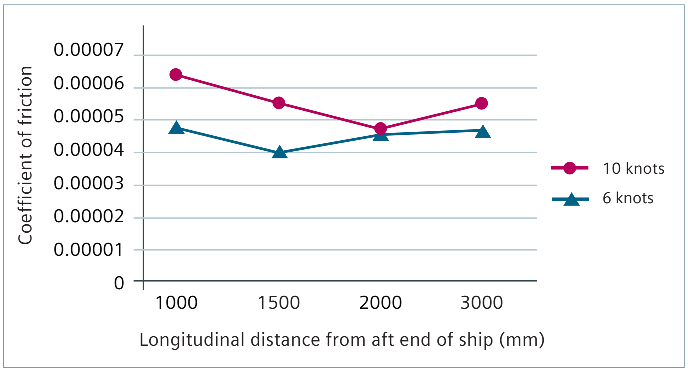

Figure 9

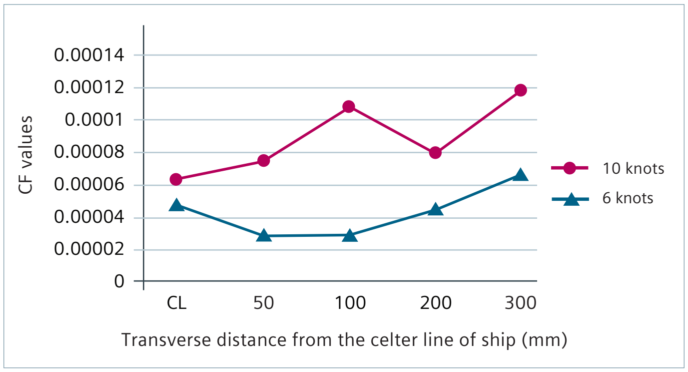

Figure 11

Comparison of flow parameters for different sized injection holes

In practical applications of the ALS technique, to reduce the power required to inject air bubbles the size of the injection holes should be larger. This section provides insight to the variation of flow parameters and the comparison of the reduction in the total ship drag for two different sized injection holes, one with 1 mm diameter injection holes and the other with 2 mm diameter injection holes. The investigation was carried out for two speeds of operation: 6 knots and 10 knots for four different injection rates.

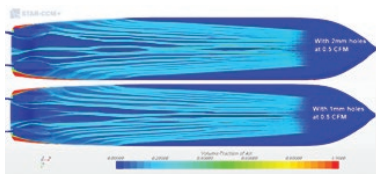

Figure 12

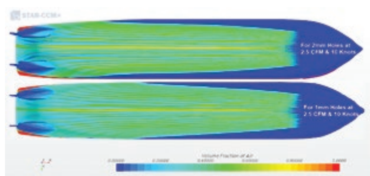

Figure 13

Figure 12 provides the comparison of volume fraction of air distributed below the hull for two sizes of holes with 2 mm and 1 mm diameter series of injection holes at 0.5 CFM at 6 knots. Figure 13 provides the comparison of volume fraction of air distributed below the hull for two sizes of holes with 2 mm and 1 mm diameter series of injection holes at 2.5 CFM at 10 knots. From the comparison, it can be concluded that there is no major difference in the distribution of volume fraction air below the hull except for a minor variation in the distribution at the aft of the ship, which is mostly due to the coalescence and breaking of bubbles.

Conclusion

3D numerical investigations into frictional drag reduction by injection of air bubbles were carried out using Simcenter STAR-CCM+ for a 1:23 scaled model of 8,000 tons DBC for two speeds and different air injection rates using different diameters of series of injection holes.

For the injection of air bubbles below the hull, two types of array of holes were used: one with 1 mm diameter holes and the second with 2 mm diameter holes. It was found that:

- The ALS effect is due to the alteration of local effective viscosity and density of the fluid which reduces the Reynolds stress and reduces the shear stress
- The ALS effect depends on both the ship's speed and the air injection flow rate, which decides the coalescence of bubbles and the formation of an air layer
- There is little variation in drag reduction values for different sized injection holes

"We have seen how CFD can inform the marine community in this particular area, and we are able to suggest some physics-based alternatives and provide physics-based explanations with regards to complex hydrodynamic flows," says Professor Sindagi.

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