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Experimental of Ballast Free System with Air-Injected Pressure Bubbles in Reducing Ship Resistance

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ABSTRACT

The discharge of ballast water may introduce and transport unwanted marine organisms to the discharging area. Marine Environment Protection Committee (MEPC) of IMO consider the action as hazard due to possibility of having negative impact on the receiving ecosystems. Many researchers have investigated possible solutions for management of ballast water to minimize the risks including the ballast free system. The concept of ballast free system is to replace the conventional ballast water management system to avoid the use of costly ballast water treatment system. However, application of ballast free system has created a new issue on ship hull resistance. The objectives of this research are to determine the effect of the system on LNG ship resistance and how the air-injected pressure bubbles affecting the ship resistance and overall system performance. To achieve the objectives, experimental tests in towing tank have been carried out at Froude number of 0.17 to 0.22 and air-injection pressure of 0.5bar, 1.0bar and 1.5bar. The application of ballast free system on the LNG ship has increased the total resistance at a range of 5% to 16%. However, air-injection to the system has reduced the total resistance by 29.8% and 8.9% in average for 0.5bar and 1.0bar injection pressure respectively. For 1.5bar injection pressure, the resistance at certain speeds is slightly increased by 1.34% in average. The optimum resistance reduction occurred at Froude number of 0.19 and 0.5bar air-injection pressure. The finding of the research can be served as a guideline for the modification of ballast tank configuration in experimental and numerical mode as a comparison to real ship conditions.

1. Introduction

Most of ships need adequate weight to submerge their propellers into the water so that they can safely operate by maintaining its stability, preventing from structural damage and providing good maneuverability with good efficiency that leads to optimisation in the fuel consumption. Sufficient

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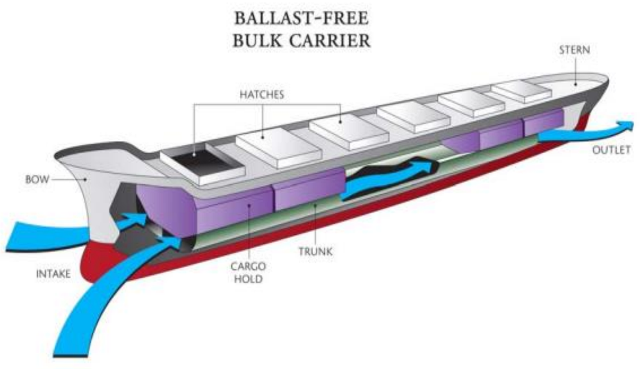
weight is required for the ship to replace the unloaded cargo weight using ballast system. For doing so, sea water is pumped in to fill in the provided ballast tanks.

However, taking water from one area and discharge it to other areas for ballast water can be likened as a transport of marine organisms. Mixing varies of marine organisms from varies areas causing the emergence of new environments that may alter and impact to the receiving ecosystems. As a solution, the water is treated during the ballasting and deballasting processes. The treatment consists of filtering large particles, ultra violet (UV) radiation, ballast water heating and chlorination of ballast water [1] . According to IMO [2], all ships shall remove and dispose the sediments from the ballast spaces during the exchanging process. Ballast water shall discharge 10 biota per cubic meter greater than or equal to 50 microns and less than 10 biota per milliliter between 10 microns to 50 microns in minimum dimension.

For reduction of ecosystem related problem and avoidance from use of costly ballast water treatment, a concept of Ballast Free Ship (BFS) Concept invented by Kotinis [3] as shown in Figure 1(a) and have been extended the research until 2011 [4-8]. Rather than pumping in water into ballast tanks in the double bottom and side tanks, longitudinal structural tunnels have been introduced throughout the ship length which allows water to flood in through a forward plenum and discharge out from an aft plenum. Total ballast free system, as demonstrated by the above authors, requires raising the double bottom height to sufficiently bodily sink the ship for full propeller submergence. Consequently, the ship depth needs to be increased to compensate for the loss of cargo space.

However, in 2012 the concept of ballast free ship suggested by Kotinis [3] and Parsons and Kotinis [4-8] was improved by Godey *et al.,* [9-10] as shown in Figure 1(b). In the concept, there are no plenum chambers and flow through elliptical pipes as longitudinal tanks are provided in placed of the conventional double bottom tanks throughout the length of the ship to reduce the buoyancy in ballast condition. These pipes equipped with valves at forward and aft ends of the ship which can be controlled. To ensure the loss of buoyancy, the valves are to be open to the sea during the ballast voyage and closed during the loaded departure with pipes emptied of ballast water. Introduction of elliptical pipes caused of ballast capacity reduction.



(a)

(b)

Fig. 1. The Ballast Free System by (a) Kotinis [3] and (b) Godey *et al.,* [10]

Other than that, in dealing with ballast water management solutions, there are three projects in which the concept of a ship with zero ballast water (NOBS) has been developed (GEF and IMO [11]): (i) Det Norse Veritas (DNV) – Volume Cargo Ship, (ii) Delft University of Technology (DUT) – Monomaran Hull, (iii) Daewoo Shipbuilding & Marine Management (DSME) – Solid Ballast Ship. The DNV concept is a tri-hull concept that provides a high level of stability, while the DUT concept indicates a monomaran hull by adopting a catamaran shape to the underside of a broad single hull.

When a ship operating in unloaded condition, its stability without use of ballast water requires adequate buoyancy. Both the DNV and DUT concepts achieved this by moving the displacement volume outward from the centerline and widening the ship's beam. In the case of DSME concept, the ballast water is replaced by 25 tonne solid ballast in standard containers so that, the conventional displacement hull is retained. However, this method applicable for container ships only.

Ballast free concept proposed by Kotinis [3] looks more promising compare to improved ballast free concept (Godey *et al.,* [9]) and no ballast ship (NOBS) concepts (GEF and IMO [11]) for LNG ship. Rather than changing hull form to obtain the required volume of ballast water to submerge the propeller, there is a need for the ballast free system is being coupled with the conventional ballast system (Hamid *et al.,* [12]). The system aims at utilizing the existing ballast spaces without increasing the double bottom height. By adopting ballast free ship concept in LNG ship, there are possibilities of technical implication (Kotinis, [3]) that need to be investigated.

Despite that, the research on ballast free concept by Kotinis [3] and Godey *et al*., [9]) found that the application of the concept to the ship will affect the total hull resistance that contribute the fuel penalty. The biggest contribution of increasing hull resistance is when the ballast water flow out through the outlet plenum at stern of ship that caused disruption of flow boundary layer around propeller. The possible solutions for ship resistance reduction need to be investigated if the ballast free concept is applied to the ship for ballast water management solution.

Over the last three decades, naval architects has faced the crucial part of research and development on reduction in ship resistance. Many drag-reducing techniques have been developed in order to control the turbulence to reduce the skin frictional drag of the ship navigation in water and the fluid transportation in pipes including compliant coatings, microgroover (or riblets), addictive injections (such as polymer, surfactant and micro-bubbles), active blowing or suction, electromagnetic excitation and acoustic excitation (Yaakob *et al*., [13]). The author claimed that drag reduction technology by micro-bubbles give more advantages such as easy operations, environmental friendships, low costs and high saving energy and it is able to achieve a drag reduction rate as high as 80%. According to Gunawan *et al.,* [14], instead of microbubbles, nanobubbles is more effective and able contributes up to 85% of skin friction reduction when bubbles injected to the flat plate. Skudarnov and Lin [15] and Lu *et al.,* [16] revealed that even a small reduction of the total drag can result in a significant fuel saving for both naval ships and commercial or shortened transit time.

However, there are factors that need to be considered that leads to influence of drag reduction. Bubble size is one of the major factors influencing frictional resistance (Kodama *et al.,* [17]). When bubbles are ejected through a porous plate or hole, bubble size is decided by the air flow rate and the main flow velocity and not by the size of the hole (Moriguchi and Kato [18] and Ceccio [19]). Based on the experiment by Sayyaadi and Nematollahi [20] on determination of optimum injection flow rate to achieve maximum bubble drag reduction in ships found that the drag reduction effect slows down at higher ship's speeds. This is because as the speed is high, the bubbles cannot stay in the boundary layer at low injection rates. However, more bubbles will remain in the boundary layer with higher injection rates thus, the drag is reduced. So it would be more efficient to use the bubble drag reduction method in low speed vessels as further power can be saved in this situation.

2. Ballast Free System with Air-Injected Pressure Bubbles of LNG Ship

Ballast free system is said to perform well when it manages to change the old (conventional) system within a specific time according to IMO requirement without any additional ship resistance penalty. Introduction of air injection system to ballast free system may increase the resistance when pressure used is not suitable with the system. Hence, selection and verification of the appropriate pressure with different diameter of the hose have to be performed accordingly as both affect the overall system performance.

Previous research on ballast free system by Kotinis [3] and Parsons and Kotinis [6] revealed that the system affects the ship resistance due to distraction on the stern ship boundary layer by the water coming out from the outlet plenum. Addressing such finding, the current research designed a ballast free system with a good performance of water flow through the longitudinal trunk and air-injected pressure bubble to reduce the hull resistance. It is believed so as the bubble reduces the skin friction by providing air layer on the hull surface. For selection of the plenum position, the research took into account the highlight given by Parsons and Kotinis [6] that aft plenum position significantly influences the ship resistance as compared to forward plenum.

The current study implemented the ballast free system with air injection concept on the existing LNG ship fitted with conventional ballast system as displayed in Figure 2. Two longitudinal structural tunnels are located on each side of the ship centerline to replace some of the conventional ballast tanks at the double bottom. These tunnels are extended longitudinally from bow to stern as a part of the ship structure. The inlet plenum which allows the sea water coming into the tunnels is located at the tip of the bulb. These tunnels which act as aqueducts to supply the sea water to the ballast tanks are of similar function of aqueduct on the conventional system. Meanwhile, the outlet plenums are set on the ship bottom at every end of the ballast tanks to avoid the increases of ship resistance.

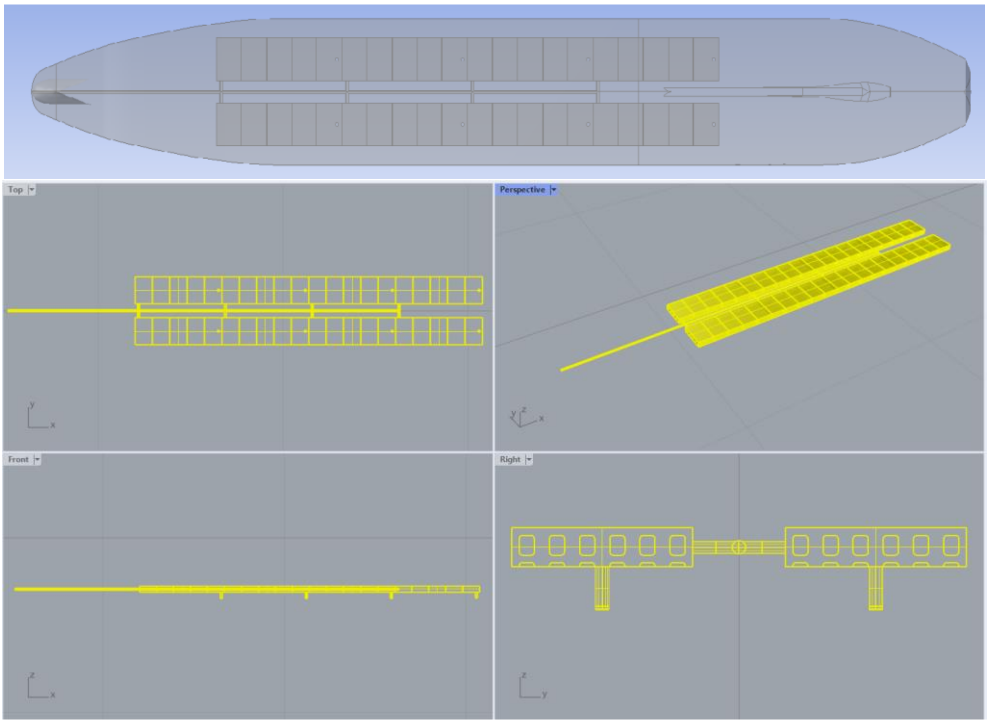


Fig. 2. LNG model and transverse framing system for each tank

When the ship operates in ballast condition, sea water is pumped into the aqueduct through the inlet plenum and the corresponding tanks are filled by opening the valves at the aqueduct. Afterwards, the sea water is discharged via outlet plenums. The process of filling the sea water into the tanks is powered by main ballast pumps which are connected to the ballast system line. After completing the process as a ballast free and ship operates in normal condition, all valves at the tunnels are closed for emptying process and main ballast pumps pump out the sea water inside the tunnels and ballast tanks.

The air-injection system connected to the compressor is installed at the outlet plenum as depicted in Figure 3. The position which is located above the water outlet at the mid height of the ballast tank is intentionally aimed to allow the injected bubbles to stay underneath the ship hull and results in reducing the ship resistance. Furthermore, the installation enables the increase of the ballast water flow out through the plenum hence minimize the time exchange between the inlet and outlet water and permits the system to always carry fresh ballast water.

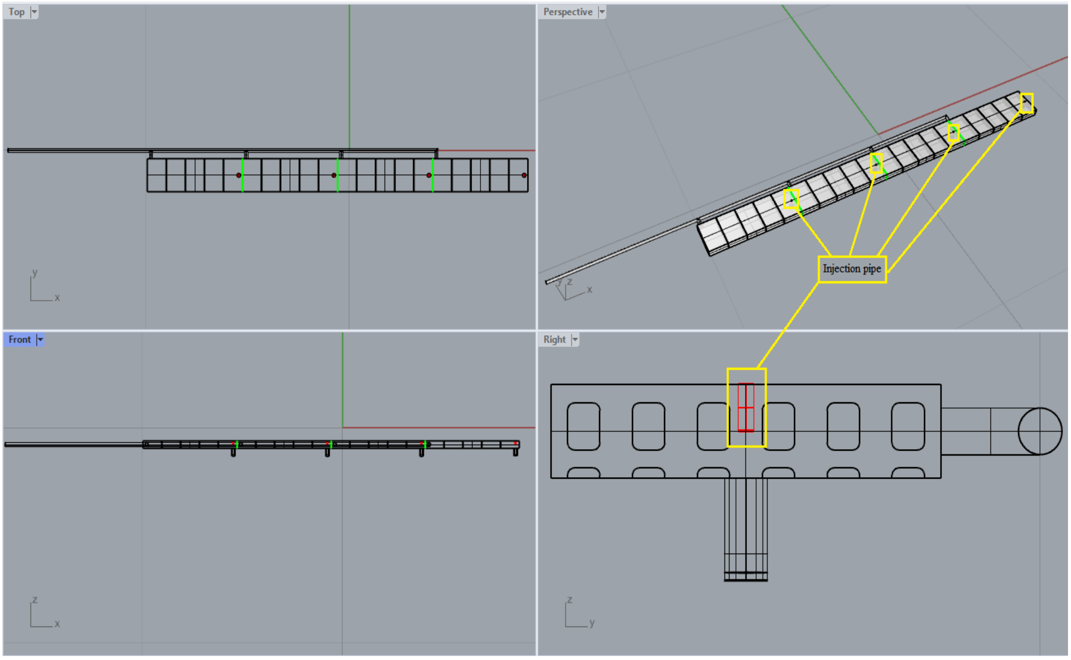


Fig. 3. LNG model with injection pipe for each tank at port side

3. Methodology

The study carried out the experimental model test in the towing tank of Marine Technology Centre (MTC), Universiti Teknologi Malaysia (UTM). Table 1 presents the specification of the towing tank where the facility is as shown in Figure 4.

Table 1
Specification of the towing tank in UTM Marine Technology Center

Parameter	Dimension
Length	120 m
Depth	2.5 m
Breadth	4 m

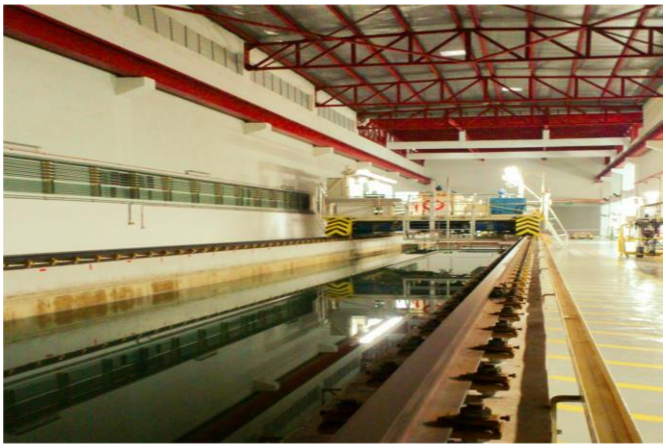


Fig. 4. Towing tank of UTM Marine Technology Center

The model used for this research is the Tenaga Class Liquefied Natural Gas (LNG) owned by the Malaysia International Shipping Corporation (MISC) Bhd. Table 2 shows the main particulars of the full scale and ship model identified as MTL 063 as depicted in Figure 5.

Table 2
Principal particulars of the Tenaga class LNG carrier (MTL 063)

Main Characteristics	Symbol	Full scale	Model (MTL 063)
Length overall [m]	L_{OA}	280.620	3.508
Length at waterline [m]	L_{WL}	268.414	3.355
Length between perpendiculars [m]	L_{PP}	266.000	3.325
Breadth at waterline [m]	B	41.600	0.520
Draught [m]	T	11.130	0.139
Normal ballast water draught [m]	T	9.755	0.122
Block coefficient	C_B	0.746	0.746
Water density [kg/m^3]	ρ	1025	1000
Water kinematic viscosity [m^2/s]	ν	1.19×10^{-6}	1.43×10^{-6}
Gravitational acceleration [m/s^2]	g	9.810	9.810
Scale factor	λ	1	80

Fig. 5. LNG model used for experiment (MTL 063)

The ballast free system examined in the study consists of four underneath plenums as illustrated in Figure 2. The centroid of the water outlet is placed approximately at waterline 0.5m corresponds to about 0.005m at model scale. Following the existing ship model of MTL 063, the ballast system studied is also modeled by 1/80 scale. However, the system is tested for one side region only due to some technical and financial limitations. Figure 6 displays the modeled system consists of four ballast tanks sized of 0.5125m x 0.147m x 0.0375m separated by cofferdam. Each tank is supported by four transverse framing systems which was prepared using plywood material and coated with spray layers to avoid water from seeping in as shown in Figure 7.

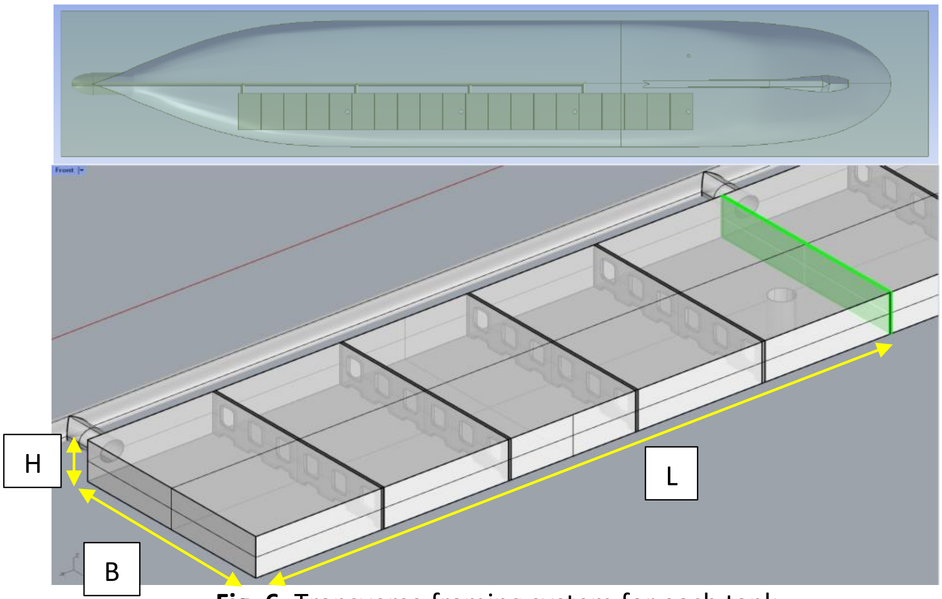


Fig. 6. Transverse framing system for each tank

Fig. 7. Framing system using plywood material

The ballast tank is modeled using wood and joined by applying high quality glue to prevent the water inside the tank to overflow when subjected to high pressure during the experiment. Each tank is equipped with water inlet and outlet at the side and end bottom of the tank respectively. The green pipe shown in Figure 8 is used to transfer the water from main inlet at the tip of the bulb to the tanks. The light blue pipe indicated in the figure is the T-connector to the pipes which function is to ensure the water filled into the tank equally.

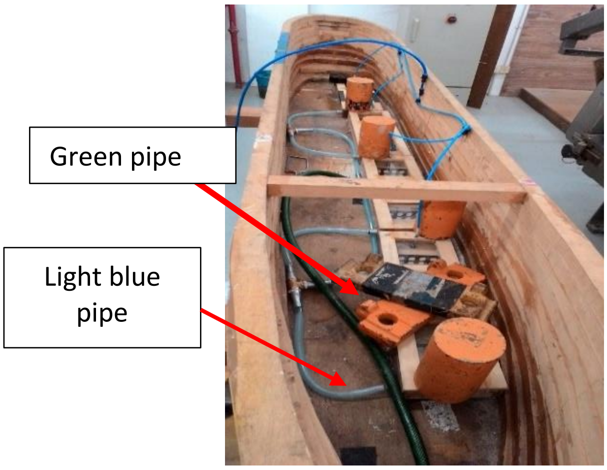


Fig.8. Arrangement of piping system in the ship model

The research determined the tested pressure conditions of the air injection system by referring to previous work of Jang *et al*., [21] due to similarity in the model geometries. The verification process allows the selection of the best hose diameter required to increase the ballast water flow rate at the outlet. A small tank shown in Figure 9 was used to manually measure the flow rate due to the absence of flowmeter in the MTC UTM facilities. The tank is sized of 1.18m x 0.9m x 0.69m (0.69m is original water height) and water flow rate is measured in one minute. Table 3 summarises the two hose diameter sizes used in the verification process and the measured flow rate obtained.

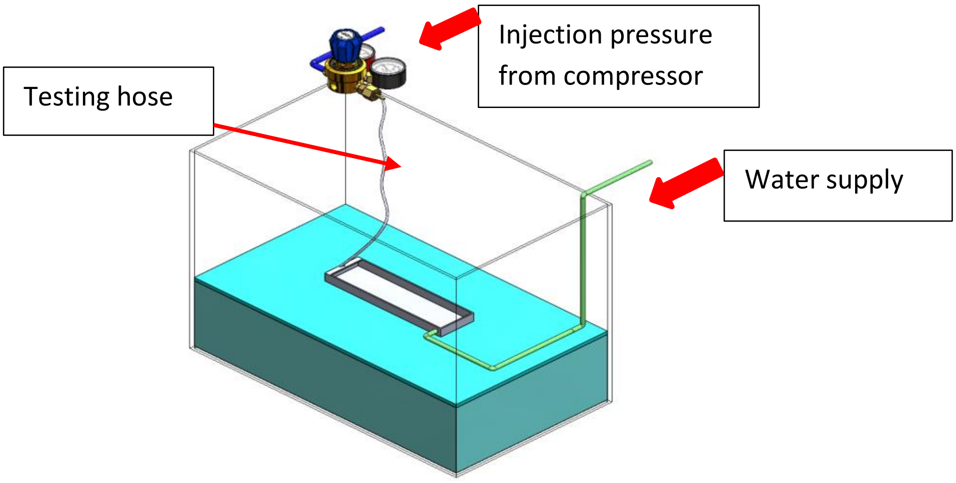


Fig. 9. Setup to measure the outlet flowrate to select the hose diameter

Table 3
Tested air injection pressures

Hose Diameter	Air injection Pressure (bar)	Additional water height when air pressure was injected, x (m)	Flowrate (m^3m^{-1})
0.6mm	0	0.06	0.049
	0.5	0.09	0.073
	1.0	0.07	0.057
	1.5	0.06	0.049
0.8mm	0	0.06	0.049
	0.5	0.06	0.049
	1.0	0.07	0.057
	1.5	0.09	0.073

According to Table 3, the highest flow rate is 0.073m^3m^{-1} obtained from 0.6mm and 0.8mm hose diameter at 0.5bar and 1.5bar air injection pressure respectively. This implies that flow rate increases accordingly as the increase in hose diameter and air injection pressure. Considering that higher air pressure requires more power, the research opted the smaller diameter hence lower injection pressure to save power.

Figure 10 displays the air compressor used in the experiment equipped with 0.6mm diameter nylon pipes. Figure 11 accordingly shows the test set up fitted with air filter pressure regulators and gas T-connectors connected to the compressor. The regulators which employ bar scale readings set and control the air injection pressure from the compressor while the gas T-connectors create equal air flow in each of the bottom air injectors and regulator setup. Since the ballast tank is only at port side, additional setup is required to balance the model from rolling and to maintain the model at ballast draft by putting the ballast weight at the starboard side.

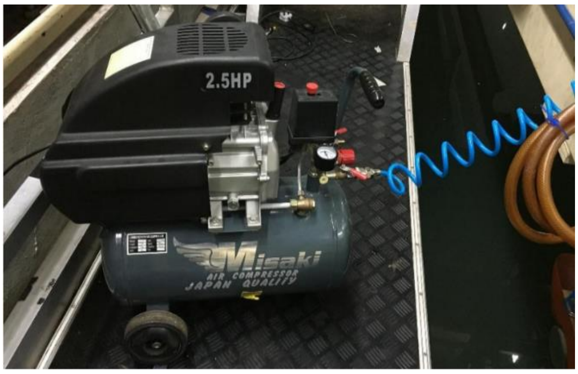


Fig. 10. Air compressor

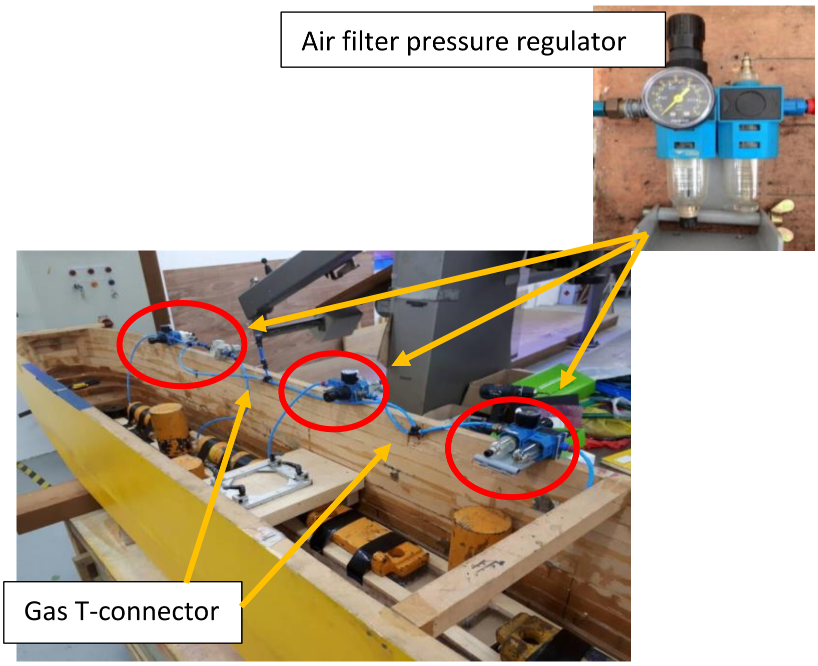


Fig. 11. Gas T-connector and air filter pressure regulators setup in the model

4. Results and Discussion

Resistance tests have been performed to investigate the impact of ballast free system with air-injected pressure bubble installation on an existing LNG carrier model of conventional ballast system. Experiments have been done for several times in calm water and ballast draft condition at Froude number range of 0.17 ≤ Fr ≤ 0.22. The percentage of relative increase for the total resistance from the bare hull, R_{BARE} is presented in Table 4. The total resistance curves of bare hull and ballast free system with and without air-injected pressure bubble from the experiment are shown in Figure 12.

Table 4
Total resistance of LNG model for each case and relative increase from bare hull

Fr	R_{BARE} [N]	R_{BFS} [N]	Relative increase (%)	$R_{BFS+0.5B}$ [N]	Relative increase (%)	$R_{BFS+1.0B}$ [N]	Relative increase (%)	$R_{BFS+1.5B}$ [N]	Relative increase (%)
0.17	4.70	5.16	9.76	4.25	-9.74	4.90	4.08	5.39	14.58
0.18	5.28	5.57	5.58	3.42	-35.22	4.53	-14.18	5.31	0.60
0.19	5.63	6.11	8.54	3.30	-41.39	4.90	-12.97	5.64	0.18
0.20	6.15	7.13	15.98	3.90	-36.56	5.78	-5.98	5.81	-5.49
0.21	6.94	7.98	14.90	4.80	-30.87	6.40	-7.82	7.00	0.82
0.22	8.15	9.17	12.55	6.11	-24.99	6.81	-16.39	7.93	-2.64
	Average		11.22		-29.79		-8.88		1.34

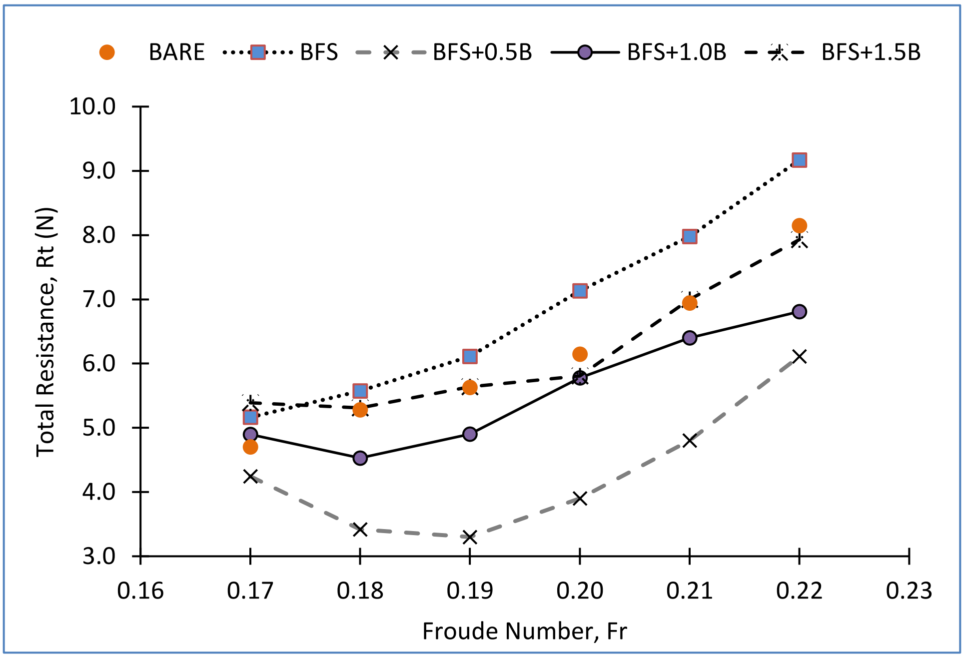


Fig. 12. Total resistance between bare hull and ballast free system with and without using air-injected pressure bubble method

As observed from the resistance curves, bare hull and hull equipped with ballast free system show the same trend of resistance where the values and speed increase accordingly at all time. Meanwhile, the hull with injected air pressure ballast free system create a fluctuate trend where resistance increases at low Froude number, decreases while approaching Froude number of 0.19 and afterwards increases accordingly. A distinct trend is shown by the hull fitted with 1.0bar injection pressure where resistance decrease a little later at Froude number of 0.2. The change in the resistance trend indicates the effect of the hull configuration due to modification of the ballast system on hull resistance.

As indicated by the figures, ballast free system offers no significant advantage on the total LNG hull resistance. Instead, the system increases the total resistance of the LNG model up to 11.22% in average. This situation also occurred in previous research by Kotinis [3], Parsons and Kotinis [6] and Godey *et al.,* [9] when ballast free concept is applied the ship model. In the study, the increases significantly up to 15.98% when the ship is at Froude number of 0.20. The increase in the resistance is predominately due to the drag generated from the additional wetted surface area of the ballast pipe and tank immersed in the water and the outlet opening at bottom of ship hull. Water flow in through the inlet and discharge at the outlet causes a distraction to the boundary layer around the ship hull and results in increase of the ship resistance. Meanwhile, the inlet opening at the bulbous bow normally causes a pressure relief and contributes to the reduction of drag (Parsons and Kotinis [6])

However, when the ballast free system is combined with air-injected pressure bubble, the results show decreasing trend in the total resistance. Lowering the air injection pressure results in lower total hull resistance. As recorded, the air injection by 0.5bar shows the highest resistance reduction at an average of 29.79% where Froude number of 0.19 corresponds to 19knots ship operating speed at full scale is the main contributor in this reduction. This 0.5bar air injection pressure is able to restrain the injected bubbles to stay underneath the ship hull, formed an air layer and reduces the hull friction hence promotes the ship resistance reduction.

At 1.5bar injection pressure, the resistance slightly increases from the bare hull by 1.34% due to excessive injection pressure bubble which decays the turbulent boundary layer, allowing a decrement in the drag reduction effects to occur. Furthermore, highly pressured air injection at 90^o angle at outlet plenum also causes an increase in ship resistance (Mostafa *et al.,* [22]). At an air injection pressure of 1.0bar, the resistance reduction is 8.88% in average. As Sayyaadi and Nematollahi [20] denoted that the air injection bubbles cannot stay in the boundary layer as the ship speed gets higher, the reduction implies that the bubble remains despite the high speed operation at Froude number of ≥0.2. Overall, the injection of air bubble counteracts the increase of total hull resistance indicated by ballast free system.

Comparing the overall ballast system configurations, the test result revealed that:

i. The increase of ship resistance in ballast free system is due to the drag generated by the immersion of the ballast pipe and the tank as well as the outlet opening, whilst
ii. The decrease of the resistance in ballast free system with air injected pressure bubble is due to the bubble layer formation which reduces the hull skin friction.

To study the phenomenon, two assumptions based on previous works by Sayyaadi and Nematollahi [20] and Godey *et al*., [10]) were made as follows. that:

i. The total resistance of the model (bare hull) consists of skin friction and residual resistance.
ii. The residual resistance remains constant for all system configurations (ballast free system with and without air-injected pressure bubble).

Based on assumption (i), the total resistance is defined as in Eq. (1).

$$\mathrm{R_T} = \mathrm{R_F} + \mathrm{R_R} \tag{1}$$

where $\mathrm{R_F}$ and $\mathrm{R_R}$ signify the frictional resistance and residual resistance respectively.

The non-dimensional form of the resistance is given by

$$C_T = C_F + C_R \tag{2}$$

where, C_T is the total drag coefficient, C_F is the skin friction coefficient and C_R is the residual resistance coefficient accordingly.

In the case of bare hull resistance, the skin friction coefficient C_F is defined using ITTC 1957 formula as follows.

$$C_F = \frac{0.075}{(\log R_n - 2)^2} \tag{3}$$

and

$$R_F = 0.5 \text{ x } C_F \text{ x } \rho \text{ x WSA x } U^2 \tag{4}$$

while,

$$R_n = \frac{U \text{ x } L}{\vartheta} \tag{5}$$

where, ρ is fluid density, WSA is wetted surface area of hull, U is fluid velocity, L is ship length and ϑ is kinematic viscosity of water.

Substituting Eq. (1) and Eq. (4), the residual resistance R_R is derived by

$$R_R = R_T - R_F \tag{6}$$

And

$$C_R = \frac{R_R}{0.5 \text{ x } \rho \text{ x WSA x } U^2} \tag{7}$$

Hence

$$C_T = \frac{R_T}{0.5 \text{ x } \rho \text{ x WSA x } U^2} \tag{8}$$

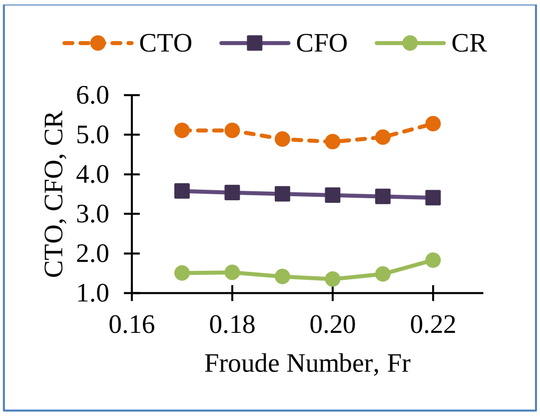
As per given assumption (ii), the total drag coefficient for bare hull has to be defined first using Eq. (8) prior to determining the skin friction coefficient for ballast free system with and without air-injected pressure bubble. Afterwards, the interpolation of R_T to C_T is carried out for bare hull and ballast free hull with and without air-injected pressure bubble where the C_F for both configuration is determined by subtracting C_T and C_R . The value of C_T and C_F from this interpolation is presented in Table 5 and accordingly depicted in Figure 13.

Table 5
The calculated C_T and C_F for bare hull using ITTC 1957 equations, the determined C_T using interpolation and C_F using minus operation of C_T and C_R for BFS and air-injected pressure

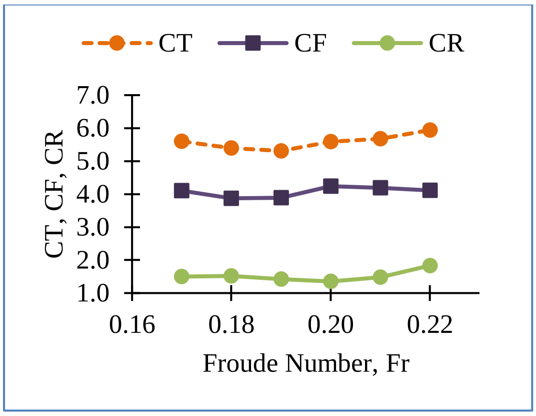
Fr	Bare Hull		BFS		BFS+0.5B		BFS+1.0B		BFS+1.5B		C_R
	CTO x10-3	CFO x10-3	CT x10-3	CF x10-3	CT x10-3	CF x10-3	CT x10-3	CF x10-3	CT x10-3	CF x10-3	(same for all cases) x10-3
0.17	5.11	3.58	5.60	4.10	4.61	3.10	5.31	3.81	5.85	4.35	1.50
0.18	5.11	3.54	5.39	3.87	3.31	1.79	4.39	2.86	5.14	3.62	1.52
0.19	4.89	3.50	5.31	3.89	2.87	1.45	4.26	2.84	4.90	3.48	1.42
0.20	4.82	3.47	5.59	4.24	3.06	1.71	4.53	3.18	4.56	3.20	1.35
0.21	4.94	3.44	5.67	4.19	3.41	1.93	4.55	3.07	4.98	3.50	1.48
0.22	5.28	3.41	5.94	4.11	3.96	2.13	4.41	2.58	5.14	3.31	1.83

As observed from the figures, C_F is generally inversely proportional to Froude number. The reduction in C_F values for bare hull is small but exceptionally high for ballast free system hull with 0.5 bar and 1.0bar air injection pressure respectively at Froude number of 0.17 and 0.18. The trend of C_F for all ballast free system hull with air injection pressure is similar such that C_F values are quite high at low Froude number. The trend is started to change upside down at Froude number of 0.20 for ballast free system hull with lower air injection pressure of 0.5bar and 1.0bar and Froude number of 0.21 for higher air injection pressure of 1.5bar.

The sudden change in the C_F trend at Froude number of 0.19 for ballast free system hull with lowest air injection pressure by 0.5bar indicates the significant impact of the air-injected pressure on the skin friction resistance. The bubbles created at such low pressure significantly promote the formation of air layer which reduce the skin friction and contribute to highest reduction in the total resistance. For the same system with higher air injection pressure by 0.1bar, the C_F value shows sudden drop after Froude number of 20. The trend indicates that injection of 1.0bar pressured air is advantageous when ship operates at higher speed.



(a)



(b)

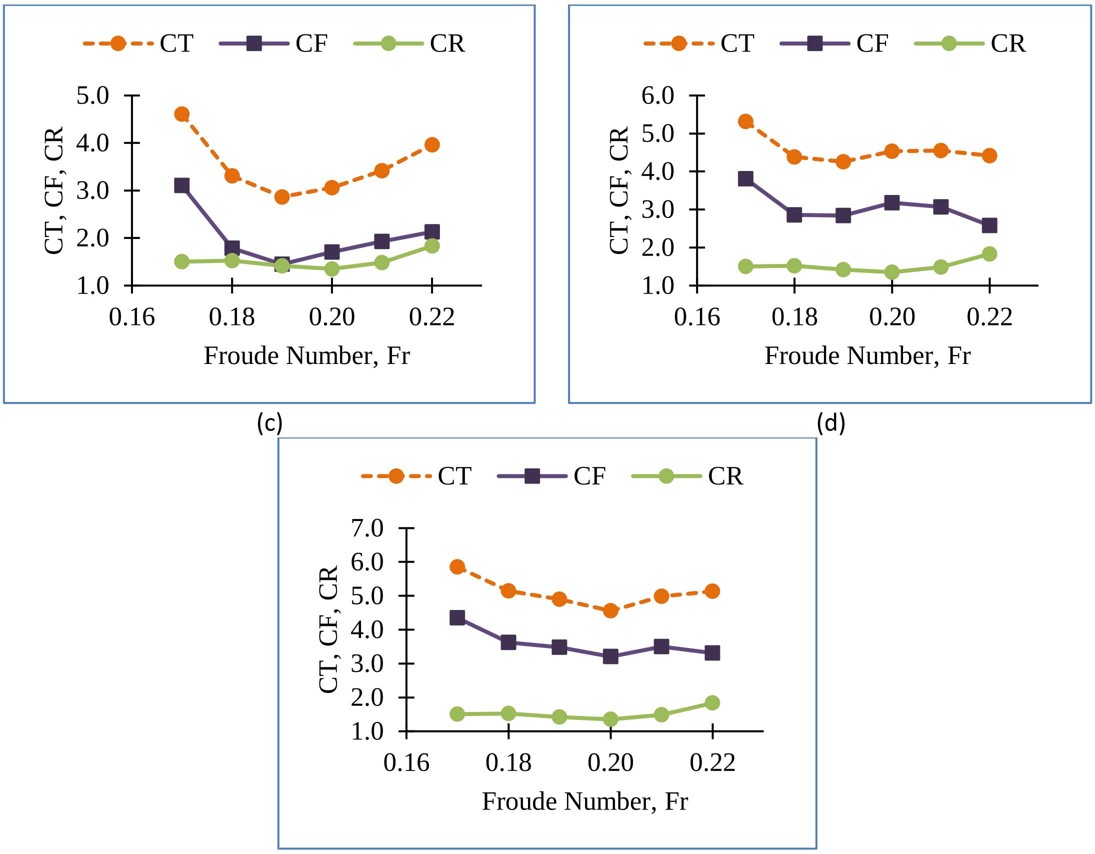


Fig. 13. The resistance coefficient curve of LNG for case (a) bare hull (b) BFS (c) BFS+0.5bar (d) BFS+1.0bar (e) BFS+1.5bar

4. Conclusions

The research is aimed at analyzing the LNG ship performance in various ballast system configurations comprise bare hull and hull with ballast free system and similar system with 3 levels air injection pressure. Whilst focus is on the ship resistance, highlights are given on the following details

i. The LNG hull fitted with ballast free system increases the total ship resistance as disclosed by Kotinis [3] and Godey *et al.*, [10]. The increase of total resistance is believed due to the increase in friction resistance which is originated from the additional wetted surface of the ballast tank and the pipes.
ii. The air-injection at outlet plenum produced an air layer under the LNG hull surface. This layer acts as a lubricant that reduces the interaction between the water and the hull surface which results in reducing the skin friction resistance. The selection of air injection pressure is very important in determining the optimum total resistance reduction. In this research, air-injection pressure at 0.5bar produced the highest resistance reduction at Froude number of 0.19 corresponds to 19knot of the full-scale ship.
iii. The air-injection pressure bubble method is successfully reduced the skin friction originally created by the ballast free system. It is hence deduced that ballast free system performs better system with air-injected pressure bubble method.

The experimental work in this research however has some limitations concerning the time to examine the effect of different air-injection pressure and test speed conditions. A considerable resistance data enables creation of some parametric equations for LNG ship fitted with air-injected ballast free system. As such, the presented work should promote further studies with more air-injection pressure and speed ranges to enhance the knowledge on the changing pattern of the ship resistance.

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References
[1] Armstrong, G., E. Brookes, R. Lankester, G. Reynolds, and J. Isbester. "Ballast system design for flow-through exchange of ballast water. Discussion." *Transactions-Institute of Marine Engineers (1988)* 109 (1997): 257-269.
[2] IMO, MEPC. "International Convention for the Control and Management of Ships' Ballast Water and Sediments." Paper presented at the BWM/CONF./36, 2004.
[3] Kotinis, Miltiadis D. *Development and investigation of the ballast-free ship concept*. University of Michigan, 2005.
[4] Parsons, M. G., and M. Kotinis. "Seaway-sized bulk carrier model for hydrodynamic optimization of ballast-free ship design." *Department of Naval Architecture and Marine Engineering. University of Michigan* (2006).
[5] Kotinis, M. and Parsons, M. G. "Hydrodynamic Optimization of the Ballast-Free Ship Concept." Transactions SNAME, 115 (2007): 50-67.
[6] Parsons, Michael G., and Miltiadis Kotinis. "Further Development and Optimization of the Ballast-Free Ship Design Concept." (2008).
[7] Parsons, M. G., and M. Kotinis. "Refinement of the Ballast-Free Ship Concept, Department of Naval Architecture and Marine Engineering." *University of Michigan* 2600 (2011): 48109-2145.
[8] Parsons, Michael G., and Miltiadis Kotinis. "Trim and Draft Control Capability of the Variable Buoyancy Ship." *Journal of Ship Production and Design* 27, no. 03 (2011): 118-126. https://doi.org/10.5957/jspd.2011.27.3.118
[9] Godey, Avinashm, S. C. Misra, and O. P. Sha. "Development of a Ballast Free Ship Design." *International Journal of Innovative Research and Development (ISSN 2278–0211)* 1, no. 10 (2012): 567-581.
[10] Godey, Avinash, S. C. Misra, and O. P. Sha. "CFD Analysis for a Ballast Free Ship Design." (2014).
[11] GEF, UNDP, and GP IMO. "Gesamp."Establishing Equivalency in the Performance Testing and Compliance Monitoring of Emerging Alternative Ballast Water Management Systems (EABWMS), A Technical Review (2011).
[12] Hamid, H. A., Kadir, N. H, Ahmad, M. Z., Abdul Mukti, M. A., Abd Malek, A. M., Priyanto, A. "The Concept of Hybrid Ballast Free System." *Proceedings of Asia-Pasific Workshop on Marine Hydrodynamics*. (2012): 559-564..
[13] Hashim, Azlina, O. B. Yaakob, K. K. Koh, Nasrudin Ismail, and Yasser M. Ahmed. "Review of micro-bubble ship resistance reduction methods and the mechanisms that affect the skin friction on drag reduction from 1999 to 2015." *Jurnal Teknologi* 74, no. 5 (2015). https://doi.org/10.11113/jt.v74.4650
[14] Gunawan, Gunawan, A. S. A. Utomo, and Yanuar Yanuar. "Investigation Skin Friction Reduction Using Nano Bubble Injection on Flat Plates." *Journal of Advanced Research in Micro and Nano Engineering* 1, no. 1 (2020): 15-23.
[15] Skudarnov, P. V., and C. X. Lin. "Density Ratio and Turbulence Intensity Effects in Microbubble Drag Reduction Phenomenon." In *Fluids Engineering Division Summer Meeting*, vol. 41987, pp. 17-22. 2005. https://doi.org/10.1115/FEDSM2005-77075
[16] Lu, J. C., A. Fernandez, and G. Tryggvason. "Drag reduction in a turbulent channel due to bubble injection." *Phys. Fluids* 17 (2005): 095102. https://doi.org/10.1063/1.2033547
[17] Kodama, Yoshiaki, Akira Kakugawa, Takahito Takahashi, and Hideki Kawashima. "Experimental study on microbubbles and their applicability to ships for skin friction reduction." *International Journal of Heat and Fluid Flow* 21, no. 5 (2000): 582-588. https://doi.org/10.1016/S0142-727X(00)00048-5
[18] Moriguchi, Yasuhiro, and Hiroharu Kato. "Influence of microbubble diameter and distribution on frictional resistance reduction." *Journal of marine science and technology* 7, no. 2 (2002): 79-85. https://doi.org/10.1007/s007730200015
[19] Ceccio, Steven L. "Friction drag reduction of external flows with bubble and gas injection." *Annual Review of Fluid Mechanics* 42 (2010): 183-203. https://doi.org/10.1146/annurev-fluid-121108-145504

[20] Sayyaadi, H., and M. Nematollahi. "Determination of optimum injection flow rate to achieve maximum micro bubble drag reduction in ships; an experimental approach." *Scientia iranica* 20, no. 3 (2013): 535-541.

[21] Jang, Jinho, Soon Ho Choi, Sung-Mok Ahn, Booki Kim, and Jong Soo Seo. "Experimental investigation of frictional resistance reduction with air layer on the hull bottom of a ship." *International Journal of Naval Architecture and Ocean Engineering* 6, no. 2 (2014): 363-379. https://doi.org/10.2478/IJNAOE-2013-0185

[22] Mostafa, Nabil H., Berge Djebedjian, Emad MS El-Said, and Magdy Abou Rayan. "Experimental and Numerical Study of Spoiler Effect on Ship Stability: Effect of Spoiler Inclination Angle." *CFD Letters* 1, no. 1 (2009): 29-42.