HULL RESISTANCE AND AIR-INJECTED BALLAST FREE SYSTEM PERFORMANCE FOR LIQUIFIED NATURAL GAS SHIP

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

School of Mechanical Engineering
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Universiti Teknologi Malaysia

AUGUST 2022

DEDICATION

Bismillahirrahmanirrahim

To my beloved parents, to my caring husband, my precious Aqil Qayyum and my beautiful twins Durrani Syafia and Durrah Surfyna.

ACKNOWLEDGEMENT

All praises to Allah and His blessing for the completion of this thesis. I thank God for all the opportunities, trials and strength that have been showered on me to finish writing the thesis. I experienced so much during this process, not only from the academic aspect but also from the aspect of personality. My humblest gratitude to the holy Prophet Muhammad (Peace be upon him) whose way of life has been a continuous guidance for me.

I am extremely thankful to my supervisor Prof. Dr. Adi Maimun B. Hj. Abdul Malik for his noble guidance, support with full positive encouragement and enthusiasm to finish this thesis. I am grateful to my co-supervisor Dr. Arifah Binti Ali and Prof. Ir. Dr. Ab Saman B. Abd Kader for their valuable suggestions, ever encouraging and motivating guidance. In particular, I greatly acknowledge the support and encouragement from my previous supervisor Prof. Madya Dr. Mohd Zamani bin Ahmad. It has been a great pleasure and honour to have these experts as my supervisor and co-supervisor.

Very special thanks to technical staffs of UTM Marine Technology Centre; Mr Azlan bin Arip, Mr Ismail bin Abdul Syukor and teams who give their best during assisting my experimental works.

Most importantly, my deepest gratitude and grateful goes to all my family; my dearest father and mother, my sisters, my brother especially Md Amirul bin Kadir and my beloved husband for their unconditional, unequivocal, and loving support.

I offer my special thanks to Admin Staff in the School of Mechanical Engineering for their help and support in the administrative works. I also would like to extend my thanks to other lecturers, colleagues and friends.

May God shower the above cited personalities with success and honour in their life and I thank all of you wholeheartedly.

ABSTRACT

Ballast water discharge may introduce and transport unwanted marine organisms to the discharging area. The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) considers ballast water hazardous due to possibly have a negative impact on the receiving ecosystems. Many researchers have investigated possible solutions for the management of ballast water to minimize the risks, including the ballast-free system. However, the application of the ballast-free system has created a new issue on the hull resistance. Many techniques have been developed in order to reduce the frictional resistance of ship navigation. The need to have an advanced Liquefied Natural Gas (LNG) ship with environmentally friendly and low fuel consumption has brought to the application of an LNG ship with an air-injection ballast-free system. This research aims to determine the effect of resistance on the LNG ship which has been fitted with ballast-free system and to evaluate how the air-injected pressured bubbles reduce ship resistance and improve the system performance. Firstly, the total hull resistance of the LNG model with a one-sided system was determined by simulation using ANSYS CFX and validated by laboratory experiment. Secondly, the resistance of the two-sided system was generated using ANSYS CFX. The experiment and simulation were limited to Froude number Fr=0.17 to Fr=0.22 at the ballast draft. The total resistance in the model's scale was extrapolated to the ship's scale according to the International Towing Tank Conference (ITTC – 1957) equations. From the extrapolated result, the LNG hull with the ballast-free system has increased the total bare hull resistance by 7.58% and 23.71% for one-sided and two-sided systems, respectively. The increment of resistance is due to the additional wetted surface area of the ballast tanks and pipes. Meanwhile, the 0.5 bar air injection shows the optimum resistance reduction compared to the other air injection pressures. The 0.5 bar air injection has reduced the total bare hull resistance by 20.17% and 24.67% for one-sided and two-sided systems, respectively. The reduction of resistance from the two systems is due to more area on the hull's bottom surface has been surrounded by air bubbles. Thus, these findings can be a guideline for the estimation of power calculation and future improvement from the current works.

ABSTRAK

Pembuangan air balast mungkin mendatangkan dan memindahkan organisma marin yang tidak diinginkan ke kawasan pembuangan. Jawatankuasa Perlindungan Persekitaran Marin (MEPC) di bawah Organisasi Maritim Antarabangsa (IMO) menganggap air balast berbahaya kerana ia mungkin berimpak negatif kepada ekosistem penerima. Banyak penyelidikan dalam pengurusan air balast telah dijalankan bagi meminimumkan risikonya, termasuk sistem bebas balast. Namun, penggunaan sistem bebas balast menimbulkan masalah baru pada rintangan kapal. Banyak teknik telah dikembangkan untuk mengurangkan rintangan geseran dalam pelayaran kapal. Keperluan untuk memiliki kapal Gas Asli Cecair (LNG) yang mesra alam dan menjimatkan kos penggunaan bahan api telah membawa kepada aplikasi kapal LNG yang dilengkapi dengan sistem bebas balast suntikan udara. Tujuan kajian ini adalah untuk menentukan kesan rintangan pada kapal LNG yang dipasang sistem bebas balast dan mengkaji bagaimana peranan gelembung udara bertekanan yang disuntik dapat mengurangkan rintangan kapal serta meningkatkan prestasi sistem. Pertama, jumlah rintangan model kapal LNG bagi sistem satu-sisi ditentukan oleh simulasi dengan menggunakan ANSYS CFX dan disahkan melalui eksperimen. Kedua, rintangan model bagi system dua-sisi dihasilkan dengan menggunakan ANSYS CFX. Eksperimen dan simulasi dihadkan pada nombor Froude Fr=0.17 hingga Fr=0.22 pada draf balast. Jumlah rintangan dalam skala model diekstrapolasi kepada skala kapal mengikut persamaan Persidangan Tangki Tunda Antarabangsa (ITTC – 1957). Dari keputusan yang diektrapolasi, kapal LNG dengan sistem bebas balast telah meningkatkan jumlah rintangan badan kapal licin sebanyak 7.58% dan 23.71% bagi sistem satu-sisi dan sistem dua-sisi masing-masing. Kenaikan rintangan adalah disebabkan oleh pertambahan luas permukaan basah tangki balast dan paip. Sementara itu, suntikan udara 0.5 bar menunjukkan pengurangan rintangan optimum berbanding tekanan suntikan udara yang lain. Suntikan udara 0.5 bar telah mengurangkan rintangan badan kapal licin sebanyak 20.17% dan 24.67% bagi sistem satu-sisi dan sistem dua-sisi masing-masing. Pengurangan rintangan tersebut disebabkan oleh lebih banyak permukaan bawah badan kapal telah dilitupi oleh gelembung udara. Dengan demikian, hasil kajian ini boleh dijadikan garis panduan untuk anggaran pengiraan kuasa dan penambahbaikan masa hadapan daripada kerja-kerja semasa.

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LIST OF ABBREVIATIONS

BFS	-	Ballast free system
NOBS	-	Zero ballast water
IMO	-	International Maritime Organization
NIS	-	Nonindigenous species
DNS	-	Direct Numerical Simulation
CFD	-	Computational Fluid Dynamic
LNG	-	Liquified Natural Gas
SST	-	Shear Stress Transport Turbulence Model
WSA	-	Wetted surface area
RANS	-	Reynolds Navier-Stokes
VOF	-	Volume of Fluid
ITTC	-	International Towing Tank Conference
MISC	-	Malaysia International Shipping Corporation
MTC	-	Marine Technology Center
D.A.A.S	-	Data Acquisition and Analysis System

LIST OF SYMBOLS

B	-	Breadth of a ship at waterline
ρ	-	Density of water
T	-	Draught of ship
T_B		Normal ballast water draught
Re_m	-	Reynold Number of water
U		fluid velocity
Fr	-	Froude Number
g	-	Gravitational acceleration
Cb	-	Ship block coefficient
L_{OA}	-	Length overall of ship
L_{WL}	-	Length at waterline of ship
L_{PP}	-	Length between perpendiculars of ship
v	-	Water kinematic velocity
μ	-	Water dynamic viscosity
S	-	Wetted surface area
λ	-	Wavelength/scale factor
L	-	Length of one compartment of ballast tank model
D	-	Depth of one compartment of ballast tank model
H	-	Height of one compartment of ballast tank model
H_{water}	-	Water height
R_{Tm}	-	Total resistance of model
R_{Fm}	-	Friction resistance of the model
R_{Rm}	-	Residuary resistance of the model
V	-	Model velocity
C_{Tm}	-	Total resistance coefficient of the model
C_{Fm}	-	Friction resistance coefficient of the model
C_{Rm}	-	Residual resistance coefficient of the model
k	-	Turbulence kinetic energy
ω	-	Specific dissipation rate
Γ_k , Γ_ω	-	The effective diffusivity of k and ω

$\bar{G}_k$, G_ω	-	The generation of turbulence kinetic energy due to mean velocity gradients and the generation of *ω*
Y_k , Y_ω	-	The dissipation of *k* and *ω* due to turbulence
D_ω	-	The cross-diffusion term
S_k , S_ω	-	The user-defined source terms
p_x , p_y , p_z	-	Partial derivatives of pressure component
u_t , v_t , w_t	-	Partial derivative of velocity per rate time
u_x , u_y , u_z	-	Partial derivative of velocity *u* at components axis
v_x , v_y , v_z	-	Partial derivative of velocity *v* at components axis
w_x , w_y , w_z	-	Partial derivative of velocity *w* at components axis
f_i	-	Acceleration due to the volumetric force

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Most ships, such as cargo and liquid containers need adequate weight to submerge their propellers into the water so that they can safely operate by maintaining its stability, preventing structural damage and to provide good maneuverability with good efficiency that leading to affect fuel consumption of the ship. Sufficient weight is required for the ship to replace the weight that has been discharged in port. Thus, sea water will be pumped in through the valve into the ballast tank to stabilize the ship.

However, taking water from one area and discharging it to other areas can be likened to the transport of marine organisms to discharging areas. Mixing various marine organisms from various areas causes the emergence of new environments that may alter and impact the receiving ecosystems. As a solution, the water should be treated during the process of ballast water being pumped into the ship. Ballast water treatment consists of filtering large particles, ultraviolet (UV) radiation, ballast water heating, and chlorination of ballast water (Armstrong, 1997). According to IMO (2004), all ships shall remove and dispose of sediments from ballast spaces during exchanging process. Ballast water shall discharge 10 biotas per cubic meter greater than or equal to 50 microns and discharge fewer than 10 biotas per milliliter between 10 microns to 50 microns in minimum dimension.

In conjunction with the need to reduce ecosystem-related problems and avoid costly ballast water treatment, a Ballast Free Ship (BFS) Concept for bulk carriers was invented by Kotinis (2005) and extended by the research by Kotinis and Parsons until 2011. 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, allowing water to flood through a forward plenum and discharge out from an aft plenum. As demonstrated by the above authors, the total ballast free system 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. The ballast-free concept is suitable for large container vessel because this type of ship significantly uses ballast water to replace the weight that has been discharged at the port.

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 (GESAMP Reports – 2011): (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 monomer hull by adopting a catamaran shape to the underside of a single broad hull. When a ship operates in unloaded condition, its stability without 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 the 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 is applicable to cargo ships only.

Meanwhile, Arai *et al.* (2010) has introduced a series of converted conventional ballast tanks that submerged to provide enough draught in the ballast condition and then continuously discharged at normal speed to ensure efficient exchange without the need uses of pumps. The concept can be fitted to existing conventional ballast ships as well as new installations for new ship builds. The seawater enters each ballast compartment through an inlet near the ship's centreline and then discharges through two valves positioned at the aft end compartment port and starboard. The position is to maximize the water pressure differential to drive and increase the water flushing process as the ship moves forward. However, the water inlet and outlet under the hull affect the pressure resistance.

In 2012, the concept of ballast free ship suggested by Kotinis and Parsons was improved by Godey *et al*. In the concept, there are no plenum chambers and flow through elliptical pipes as longitudinal tanks are provided in place of the conventional double bottom tanks throughout the length of the crude oil tanker to reduce the buoyancy in ballast condition. These pipes are equipped with valves at the 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. The introduction of elliptical pipes caused ballast capacity reduction.

The ballast free concept proposed by Kotinis (2005) and Arai *et al.* (2010) looks more promising compared to the improved ballast free concept (Godey *et al.,* 2012) and no ballast ship (NOBS) concepts (GESAMP Reports – 2011) for advance 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.,* 2012). The system aims at utilizing the existing ballast spaces without increasing the double bottom height. By adopting the ballast free ship concept in the development of advanced LNG ships, there are possibilities of technical implications (Kotinis, 2005) that need to be investigated.

Despite that, the research on ballast free concept by Kotinis (2005) and Godey *et al.* (2012) found that applying the concept to the ship will affect the total hull resistance that contributes to the fuel penalty. The contribution of increasing hull resistance is when the ballast water flows out through the outlet plenum at the stern of the ship that causing disruption of the flow boundary layer around propeller and additional wetted surface area that caused an increase in frictional resistance. Meanwhile, the increase in resistance in Arai *et al.* (2010) concept is due to positioning the water inlet and outlet as an appendage under hull. 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 have faced the crucial part of research and development on reduction in ship resistance. Many techniques have been developed in order to reduce the frictional skin drag of the ship navigation in water and the fluid transportation in pipes, including compliant coatings, microgroover (or riblets), addictive injections (such as surfactant, polymer, and micro-bubbles), active blowing or suction, electromagnetic excitation and acoustic excitation (Janssen *et al.*, 1984 and Xu *et al.*, 2002). The authors claimed that drag reduction technology by micro-bubbles gives more advantages such as easy operations, environmentally friendly, low costs, and high saving energy, and it is able to achieve a drag reduction rate as high as 80%. Skudamov *et al.* (2005) and Lu *et al.* (2005) revealed that even a small reduction of the total drag could result in a significant fuel saving for both naval ships and commercial or shortened transit time.

The need to have an advanced LNG ship with environmentally friendly and save on fuel consumption cost has brought to the discussion the application of LNG ship fitted with an air-injection ballast free system. However, factors need to be considered when the injected pressure bubbles method is applied to the system. According to Kodama *et al.* (2000), when dealing with the bubbles injection method for drag reduction, bubble size is one of the major factors influencing frictional resistance. When bubbles are ejected through a porous plate or hole, bubble size is decided by the airflow rate and the main flow velocity and not by the size of the hole (Moriguchi and Kato, 2002 and Ceccio, 2010). Based on the experiment by Sayaadi and Nematollahi (2013) on the determination of optimum injection flow rate to achieve maximum bubble drag reduction in ships, the drag reduction effect slows down at a higher injection flow rate. In addition, a higher injection flow rate also produced higher bubbles number that influenced the turbulence boundary layer. Therefore, the air-injected bubble configuration should be analysed accordingly to ensure the effectiveness of producing acceptable resistance properties in various speed conditions.

1.2 Problem Statement

Discussion on the ballast free system concept to overcome the effect on the ecosystem has led to an increase in ship resistance due to the introduction of inlet/outlet (Kotinis, 2005 and Arai *et al.*, 2010) and additional wetted surface area (Godey *et al.*, 2012). Currently, there are no proposed ballast free concepts that reduce total hull resistance. Hence, this needs to be solved in view of better ballast free system concept during operation. Considering the injection bubbles method reduces the resistance (Sayaadi and Nematollahi, 2013, Lyu *et al*., 2014), the current ballast free system concept needs to be improved based on the concept using a hypothesis that ballast free systems have a better performance than air-injected pressure bubbles.

The development of the concept of an air injection ballast free system needs to consider several factors to produce a concept that is efficient in ship's operation and able to protect the ecosystem. The previous research on the ballast free system by Kotinis (2005) and Godey *et al*. (2012) highlighted that the opening of the inlet at the bow region helps relieve and reduce the wave height that reduces pressure resistance. Meanwhile, the outlet at the stern region will disturb the pressure contour on the hull. Hence, appropriate inlet and outlet locations should be developed to avoid increased resistance when a ballast free system is implemented.

In the development of an air injection system, the system configuration, including the amount of injection pressure, should be analysed as varied characteristics from different air injection pressure influence the hull resistance due to the difference in generated flow velocity around the hull. Other than that, different injection pressure produces difference bubble size and bubble number, which also influences the hull resistance (Kawamura *et al*., 2004) and discharge water flowrate for the ballast free system.

The contributing factors to the resistance of the LNG with ballast free system and LNG with air injected ballast free system should be analysed, and the pressure distribution and generated wave analysis should be performed to determine the effect of air injection and ballast free system on the LNG resistance components. Besides that, the performance of the water flow in the ballast tank should be analysed to determine the system's effectiveness.

One of the concerns toward further improvement of the ballast free system concept with the air injection bubble method to actual ship is the fact that the energy required to supply air bubbles using conventional bubble generators is quite significant. The extrapolation of the hull resistance to actual ship scale is needed for further research application in power calculation, which will provide information to optimize the air injected ballast free system concept and lead to further improvement.

1.3 Research Questions

The research was conducted based on the following research question:

(a) What are the factors that contribute to the LNG hull resistance fitted with ballast free system?

(b) How does the air-injected pressure configuration affect the ballast free LNG hull resistance components?

(c) How to determine reduction of hull resistance by using air-injected ballast free system to the LNG vessels?

1.4 Research Objectives

The study aimed to analyse the LNG performance which considers the configuration of the air-injected ballast free system fitted to the hull. The objectives of the research were outlined as follows:

(a) To determine the total hull resistance of the LNG fitted with and without air-injected ballast free system.

(b) To determine the contributing factors of the LNG hull resistance fitted with ballast free system.

(c) To evaluate the role of the air injection pressure to the ballast free system and the LNG resistance components.

(d) To extrapolate the hull resistance in actual ship's scale.

1.5 Research Scopes

The research is focused on the LNG hull performance in resistance and the role of air-injected pressure to the ballast free system and the LNG resistance components. The scope of the research was outlined as follows:

(a) The research was performed by utilizing the LNG carrier model available in Marine Technology Centre, UTM and a part of UTM Research Grant, Flagship, to develop a ballast free system for advanced LNG ships. Because the model always carries a lot of ballast water to accommodate the weight being transferred, it was suitable to implement a ballast free system into it.

(b) The study was limited to the hydrodynamics studies, including flow characteristics studies around the hull and the air-injected ballast free system.

(c) The analysis was performed in deep water at the designed speed and at fully ballast draught in calm water conditions. The designed speed of the LNG ship is 19 knots. Hence, the range of the speed used in the research between 17 knots to 22 knots is equivalent to 0.17 to 0.22 of the Froude number.

(d) The computational method used the Computational Fluid Dynamic of ANSYS CFX solver to simulate the case problem and the laboratory experimental method used a towing tank to validate the simulation results.

(e) The analysis focused on the resistance of the LNG ship with and without ballast free system. Then, the resistance was analyzed when the air was injected into the ballast free system.

1.6 Significance of Research

Significance of the research lies in the concept that are convenient for ship development and reliable experimental modelling and computer simulation programming hence superior over the existing concepts.

The significances of the research are as follows:

i) The concept of Air-Injected Ballast Free System for LNG ship

a. the proposed concept is environmentally friendly and save on fuel consumption cost where it can reduce the total hull resistance with the presence of the air bubbles.

ii) The experimental modelling and computational simulation

a. The findings are important to database and has a significant contribution particularly related to the application of air injection pressure to the ballast water free system that may be used by other researcher for further research.

1.7 Thesis Outline

The thesis consists of five chapters focusing on the topics below.

Chapter 1 - Introduction of the research consists of the research's background, problem statement, research questions and objectives, and scopes of the research.

Chapter 2 - Literature Review provides the review of the past research whose topics are significant for understanding the research details and the research methodology and possess the knowledge for discussing the research result and findings. The chapter reviews ballast free system performance and characteristics, ship hull resistance, the theory of bubble characteristics that reduced hull resistance, and the tool used to determine resistance.

Chapter 3 – Research Methodology describes all the methods chosen for the research work towards achieving the research objectives. This chapter explained the basic theory and mathematical formulation of computational fluid dynamic simulation for the purposes of validation resistance tests. Besides that, the methodology to obtain the force distribution of total hull resistance using ANSYS CFX and the derived equation of the computational model for fluid dynamic simulation were explained. Resistance test by experiment also was described in this chapter.

Chapter 4 – Presented and elaborated the resistance components result of the LNG bare hull and hull fitted with air-injected ballast-free system in deep water at ballast draft and designed speed. The results comprised the experiment data and simulation results at the varying parameter of air-injected pressure. This chapter also presented discussed the simulation result of air-injected ballast free system characteristics.

Chapter 5 – Concludes the current research, and valuable recommendations are provided for future works.

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