STUDY OF REAL-TIME FUEL CONSUMPTION MODEL FOR LARGE BULK CARRIER

Ailong Fan[1,2,3], **Xinping Yan[1,2]**, **Richard Bucknall[3]**, **Qizhi Yin[1]**, and **Rui Song[3]**

[1]School of Energy and Power Engineering, Wuhan University of Technology, 1178 Heping Avenue, Wuhan 430063, China
[2]National Engineering Research Center for Water Transport Safety, MOST, 1178 Heping Avenue, Wuhan 430063, China
[3] Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

ABSTRACT

With a 53,000-ton coastal bulk carrier as the selected ship, modelling and simulating of the ship real-time fuel consumption are carried out. Firstly, the on-board data collection system is introduced as well as the operational features of the selected ship. Then, based on the interaction relation of the hull-engine-propeller, the real-time fuel consumption model of the selected ship is developed using empirical formulas. Lastly, this model is simulated on the MATLAB/Simulink considering the impact of the random environmental factors, like, wind and wave. Comparison analysis between the simulated results and the actual measured data is also carried out. The results indicate that the measured fuel consumption and speed shows a high degree of dispersion due to the changeable working condition of the ship and the uncertainty existing in the on-board data monitoring system; the developed model has a good accuracy in predicting real-time fuel consumption. This research could help the ship manager to assess the likely fuel consumption level under different ocean environment.

Keywords: Low carbon shipping, bulk carrier, fuel consumption, modelling and simulating, and on-board data collection

1. INTRODUCTION

In recent years, with the aggravation of the global warming, climate change has attracted increasing global attention and concerns. It is known that the shipping industry is responsible for transporting more than 80% of international trade, the greenhouse gas (GHG) emissions within the shipping industry represents 2.6% of the world's total emissions of CO2 for the year 2012 (Smith etc. 2014).

Currently, emission-reduction within the shipping industry has become the consensus with relevant GHG mitigation regulations are becoming increasingly stringent. A list of regulations for curbing GHG emissions from international ships have been proposed by the International Maritime Organization (IMO), like the mandatory energy efficiency regulations of ships, in which the energy efficiency design index (EEDI) and the energy efficiency operational indicator (EEOI) has been proposed as the key performance indicator (KPI) evaluating the CO2 emission efficiency of ships (MEPC, 2011).

On the other hand, the global shipping market has been in recession in the recent decade, which can be reflected in the overall lowering of the Baltic Dry Index (BDI). The struggling market presents the shipping companies with difficulties, making cost reduction and efficiency improvement priorities within the industry. There is a statistic showing that the ship's fuel cost accounts for the 50% of the total cost of running the shipping company. Reducing the fuel cost has become one of the most effective methods in improving the competitiveness of the companies (Banawan, 2013).

In general, energy saving and emission reduction within the shipping industry is not only the need to fulfill the requirements of international emission reduction regulations, but also becomes the effective methods to improve the companies' economic benefit.

In this paper, a 53,000-ton, Chinese coastal bulk carrier is selected as the research vessel and a real-time fuel consumption model of the ship is developed and simulated with consideration of environmental factors.

Coastal areas are China's economically developed, densely populated areas. Many large ports and terminals are situated along the coastal areas. According to the 2030 China Shipping Development Outlook report, the total size of China's coastal fleet in 2030 will reach more than 150 million tons, will be more than the current rose more than 60% (PCPCL, 2015). At present, most of the coastal ships are using marine heavy oil as fuel, making the ships' emissions more harmful than the average diesel engine. Therefore, the air pollution of ships and ports can bring huge public health risks and environmental impacts to the economic and social development of coastal areas. As a consequence, it is of significance to study of energy saving and emission reduction for coastal ships.

2. OPERATIONAL FEATURES OF THE BULK CARRIER
2.1 ON-BOARD DATA COLLECTION

A 50,000-ton Handymax bulk carrier is selected as the research ship. This ship has the features of large in the capacity, short in the service age, high in the degree of automation, convenient in the on-board data collection. These features make it easy to study the on-board data monitoring and analyse the fuel consumption. Figure 1 is the outside photo the ship and Table 1 is the main ship parameters.

Figure 1 Coastal bulk carrier

Table 1 Main ship parameters

Length	190 m	Breadth	32.26 m
Main engine	Man B&W 6S50MC	Fuel type	IFO 380
Rated power	9480kW	Rated speed	127 rpm
GWT	53,000 tons	Scantling draft	12.5 m
Shipping line	North and south of China's coastal area		

To get the experimental data, many data collection sensors are installed on the selected ship

(1) Fuel oil monitor: to collect the data of real-time fuel consumption of the ship.
(2) Shaft power meter: to collect the real-time power and revolution speed of the tail shaft
(3) Weather instrument: to collect the wind speed and direction, water depth.
(4) Speed log: to collect the ship speed over ground and water (water velocity).
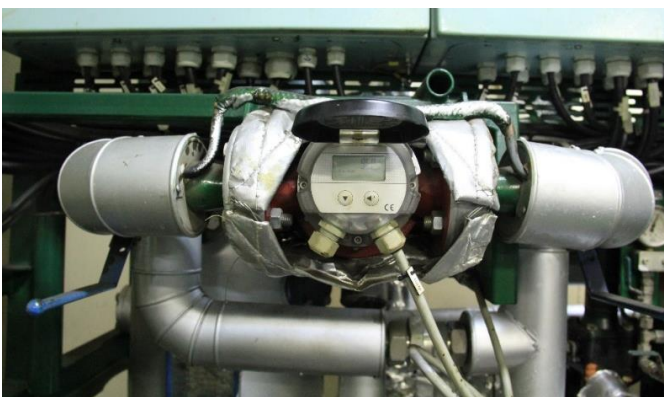
These sensors are shown by following Figure 2-Figure 6.

Figure 2 Fuel monitor

Figure 3 Shaft power meter

| Figure 4 Wind monitor | Figure 5 Fathometer | Figure 6 Speed log |

2.2 SAILING LINE AND OPERATIONAL FEATURES

The selected ship is a coastal coal-transporting carrier and usually sails between China's northern coal ports to the southern electricity generation plants. Using its AIS data, its sailing line can be depicted as shown in Figure 7.
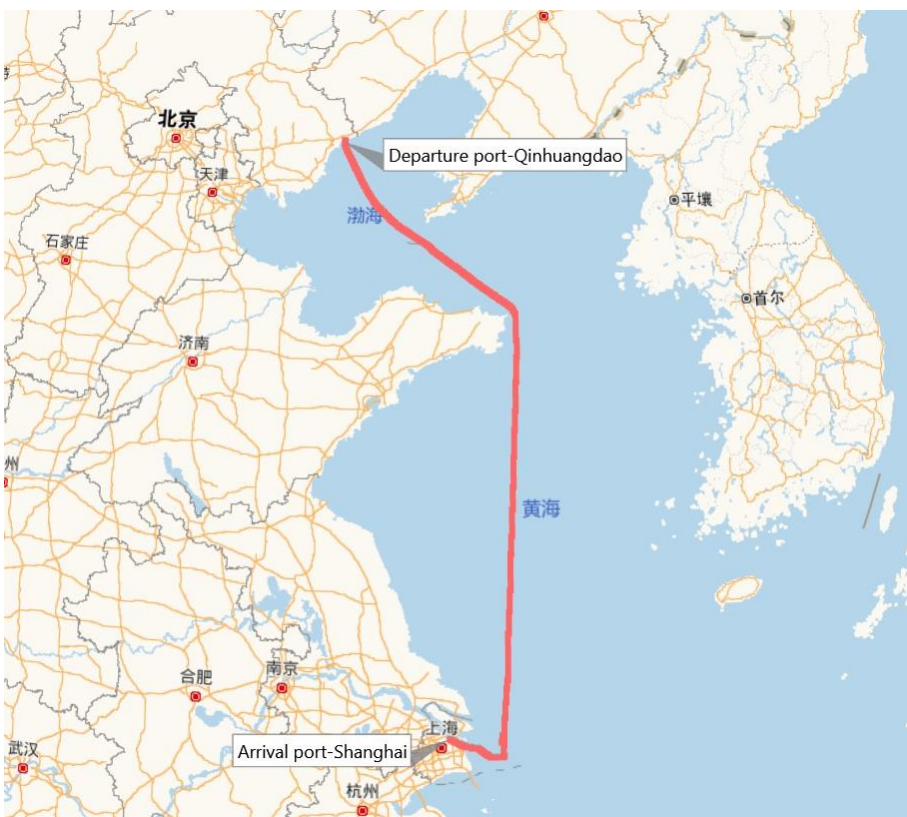

Figure 7 Sailing line

China's coastal sailing line is rather fixed due to the routing system required by the maritime administration. Therefore, there is no space for the route planning to save energy along the coastal line.

However, it is estimated that the sailing time is only made up of 40% of the total voyage time, which means that the selected ship has a large potential to decrease its service speed to be more energy efficient.

3. MODELLING OF SHIP REAL-TIME FUEL CONSUMPTION

Ship fuel consumption is an important parameter indicating the economy of the main engine as well as the energy efficiency level of the whole ship, while the real-time fuel consumption is more important in terms of showing the dynamics of the engine.

Ship propulsion system is essentially an energy transformation system composed of the hull-engine-propeller.

(1) The hull generates the resistance R due to the water friction, pressure difference, wave, and other environmental load.

(2) The propeller is the power demanding side. It receives the power P_E from the main engine through the transmission of the shafting systems.

(3) The main engine is the power supplying side. It generates the required power P_B through burning a certain amount of fuel $MEfc$.

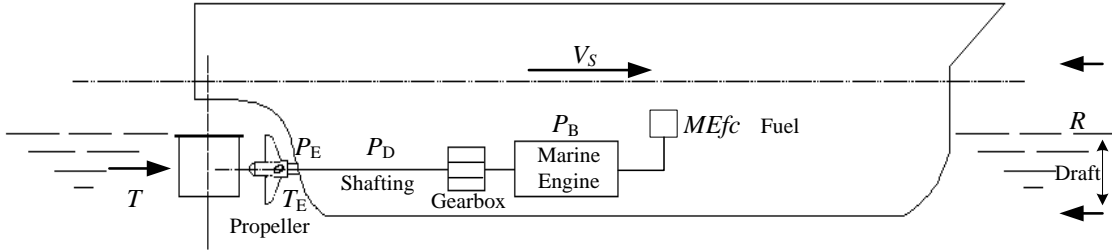Their interaction relation is simplified and depicted in Figure 8.

Figure 8 Schematic diagram of the hull-engine-propeller system

According to this interaction relation, the real-time fuel consumption model can be developed on the basis of the ship resistance model and main engine power model. These parameters are all instantaneous variables.

3.1 SHIP RESISTANCE MODEL

According to the theory of ship resistance (Larsson, 2010), ship total resistance R is mainly made up of the resistance in calm water R_0 and the additional resistance ΔR .

$$R = R_0 + \Delta R = R_F + R_{PV} + R_W + \Delta R \tag{1}$$

Where the resistance in calm water R_0 consists of frictional resistance R_F , viscous pressure resistance R_{PV} and additional resistance in wave R_W ; the additional resistance ΔR is made up of many parts, like the wind load, wave load, appendage resistance, etc.

In this paper, the resistance in calm water R_0 is calculated using the Holtrop-Mennen method (Holtrop,1982).

$$R_0 = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \tag{2}$$

Where R_F indicates frictional resistance; $1 + k_1$ indicates form factor describing the viscous resistance of the hull form in relation to R_F ; R_{APP} indicates resistance of appendages; R_W indicates wave-making and wave-breaking resistance; R_B indicates additional pressure resistance of the bulbous bow near the water surface; R_{TR} indicates additional pressure resistance of immersed transom stern; R_A indicates model-ship correlation resistance.

It is known that ship resistance is proportional to its draft. In this paper, the scantling draft is taken for example, the resistance in still water is obtained, as shown in Figure 9. The X-axis is the ship speed over water and the Y-axis is the ship resistance in still water. With regard to the selected ship, the scantling draft is the service full loading condition when the fore and after draft is 12.5m.
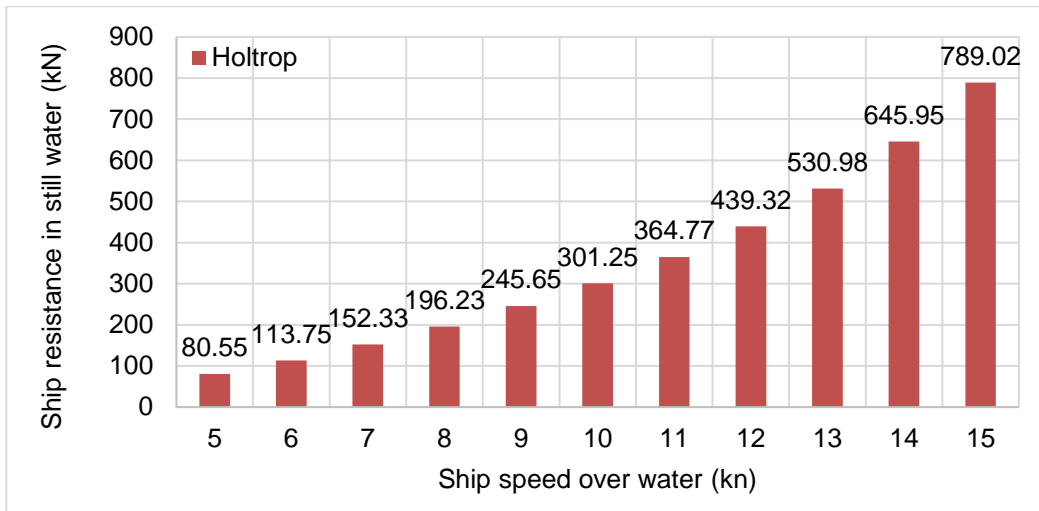
Figure 9 Ship resistance in still water

The natural environmental factors are believed to have a certain impact on ship's resistance (Sun, 2013; Fan, 2017). In this paper, the wind and wave load would be considered.

The wind resistance can be calculated by (MAN, 2011; Andersen 2013)

$$\Delta R_A = C_X \cdot \frac{1}{2} \rho_A V_A^2 A_T \tag{3}$$

where C_X is the wind force coefficient; ρ_A is the density of the air; V_A is the relative wind speed and A_T is the transverse projected area above waterline.

The additional resistance in wave can be calculated by (Kreitner 1939; ITTC, 2005)

$$\Delta R_{AW} = 0.64 \xi_W^2 B^2 C_B \rho g / L \tag{4}$$

where ξ_W is the wave height; B is the ship width; C_B is the block coefficient; ρg is the sea water specific gravity; L is the ship length.

Regarding these two expressions, the relative wind speed V_A and wave height ξ_W are both associated with the natural true wind, which is usually scaled by Beaufort number (*BN*). Therefore, V_A and ξ_W would be represented by a common variable *BN* in the simulation.

Using these expression, the wind resistance and the additional resistance in wave of the selected ship in scantling draft can be got, as shown in Figure 10 and Figure 11.
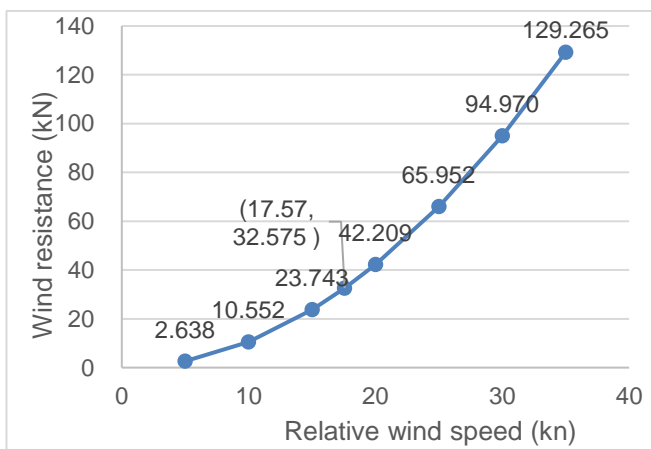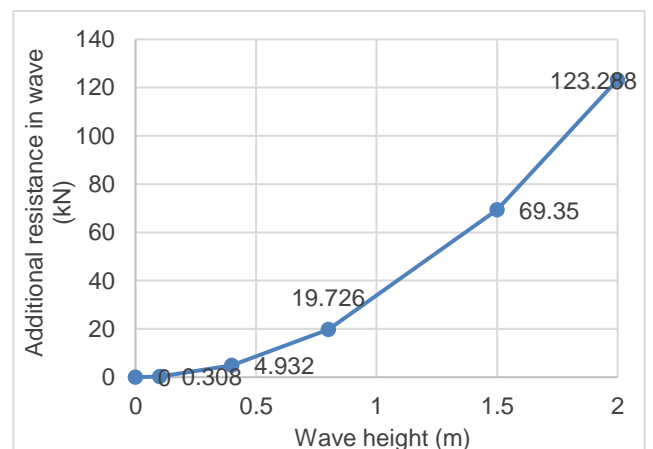

Figure 10 Wind resistance

Figure 11 Additional resistance in wave

3.2 MAIN ENGINE POWER MODEL

According to the interaction relation between the hull-propeller-engine, the delivered power of the main engine is determined by the ship's resistance. Through a complex deduction, the delivered power of the main engine P_B can be represented by (Fan, 2017)

$$P_B = \frac{2\pi\rho D^5 n^3 K_Q}{\eta_S \eta_G \eta_R} \qquad (5)$$

Where K_Q is the torque coefficient; ρ is the water density; n is the shaft revolution speed; D is the propeller diameter; η_S indicates shaft transfer efficiency; η_G indicates gearbox efficiency; η_R indicates relative rotation efficiency.

The open water characteristic curves are needed to calculate the torque coefficient K_Q. For the selected ship, the number of propeller blades $Z = 4$, the blade area ratio $A_E / A_O = 0.53$, the pitch ratio $P/D = 0.74$. The open water characteristic of the propeller (MAU4-53, $P/D = 0.74$) can be obtained through the interpolation to the propeller atlas, as shown in Figure 12.
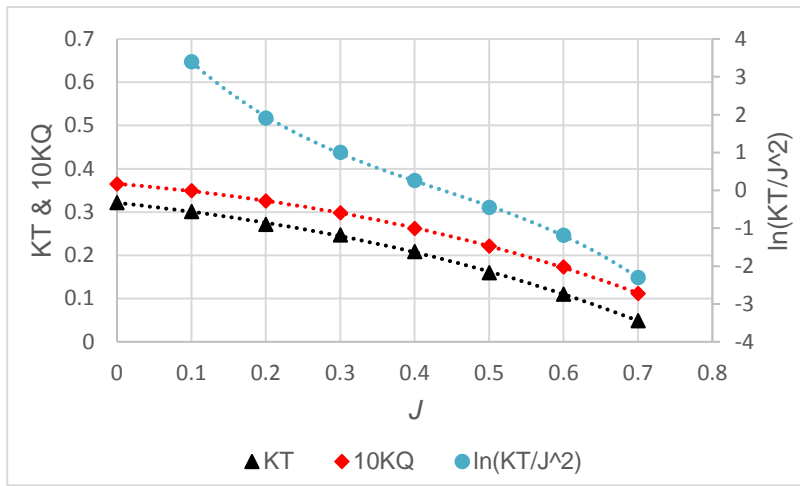

Figure 12 Propeller open water characteristic curves

3.3 MAIN ENGINE FUEL CONSUMPTION MODEL

The main fuel-consuming equipment on-board are the main engine, auxiliary engine, boiler, emergency generator, and incinerator. Among them, the top three consume the most of the fuel. According to the statistic issued by the China Classification Society (CCS), their percentage is 74.8%, 16.6%, and 8.4% respectively (CCS, 2014).

For the selected ship, only the main engine and auxiliary engine are in work while the ship is at sea. The fuel consumption of the ship can be represented by

$$fc = MEfc + AEfc = P_B \cdot SFOC \cdot (1 + LF) \qquad (6)$$

Where:

The fuel consumption of the main engine $MEfc$ is dependent on the propulsion load of the ship; normally $MEfc = P_B \cdot SFOC$, where P_B indicates the delivered power of the main engine, $SFOC$ indicates the specific fuel oil consumption of the main engine, which can be obtained from the characteristic curve of the main engine, Man B&W 6S50MC.

The fuel consumption of the auxiliary engine is believed to be proportional to that of the main engine, thus $AEfc = MEfc \cdot LF$, where LF indicates the load factor.

4. MODEL SIMULATION

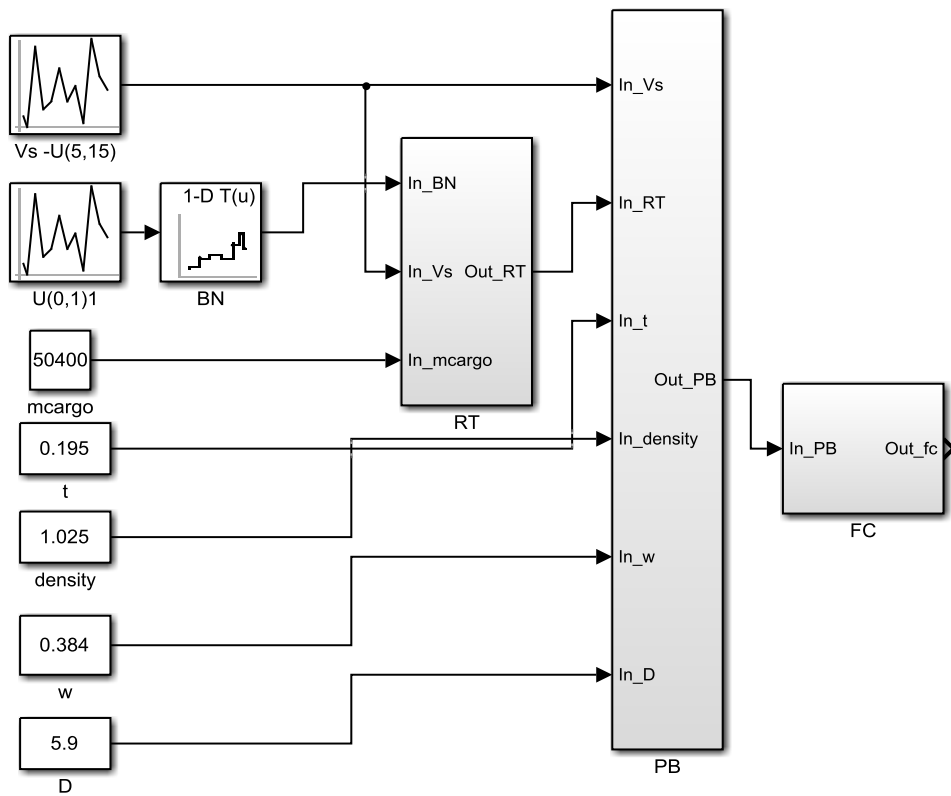The above-mentioned models are simulated on the MATLAB/Simulink, as shown in Figure 13.

Figure 13 Simulation of the ship real-time fuel consumption

Based on this simulation model, the calculation of the real-time fuel consumption is achieved through the following procedures:

(1) Generation of the input parameters, like the ship speed over water V_S, the Beaufort number *BN*, and the amount of cargo m_{cargo} corresponding to the scantling draft. As the wind is an environmental variable with a high degree of uncertainty and randomness, in this paper, it is regarded as a random variable. The random number *BN* is generated from its probability distribution, which is obtained from the actual measurement data of wind speed in accordance with Beaufort wind scale (Barua, 2005). Ship speed over water V_S is regarded as stochastic variable that obeys a uniform distribution within the range of (5, 15) (kn);

(2) Calculation of the ship total resistance R_T, including ship resistance in still water, wind resistance and additional resistance in wave;

(3) Calculation of the propeller advance coefficient J under the corresponding ship speed, as well as the torque coefficient K_Q and revolution speed n;

(4) Calculation of the power P_B of the main engine;

(5) Calculation of the specific fuel oil consumption $SFOC$, the real-time fuel consumption $MEfc$ of the main engine, then the real-time fuel consumption of the ship fc.

5. RESULTS AND VERIFICATION

The on-board measured data is used to investigate the Beaufort wind scale distribution features, as shown in Figure 14, and then a corresponding *BN* random data is generated.
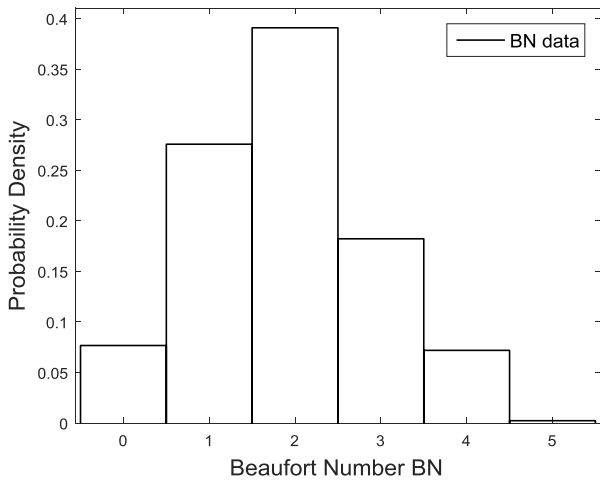
Figure 14 Beaufort wind scale distribution of the selected data

According to the simulation procedures, the ship fuel consumption can be calculated under different circumstance.
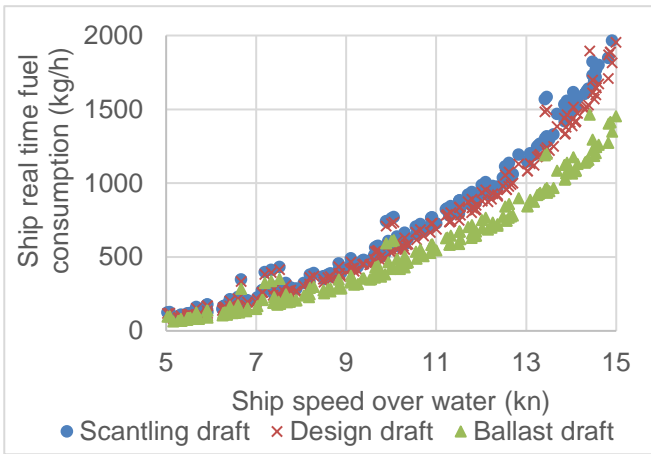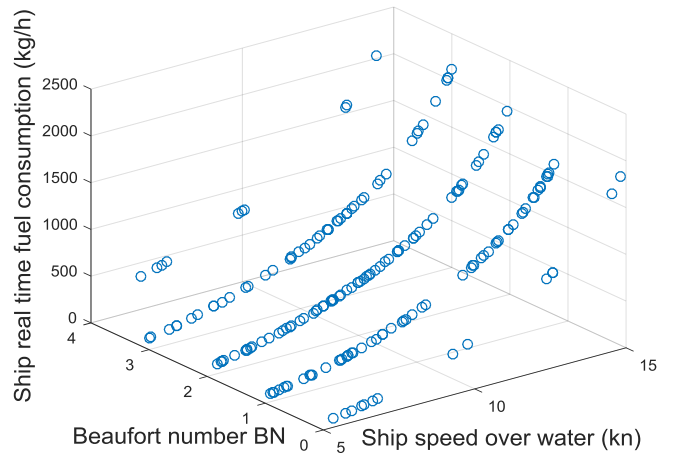

Figure 15 Ship fuel consumption for 3 draft

Figure 16 Ship fuel consumption for different speed and *BN*

$$y = 0.0021x^3 - 0.2432x^2 + 19.914x - 470.91$$
$$R^2 = 0.9993$$

$$y = 0.0007x^3 + 0.0297x^2 + 2.8414x - 19.359$$
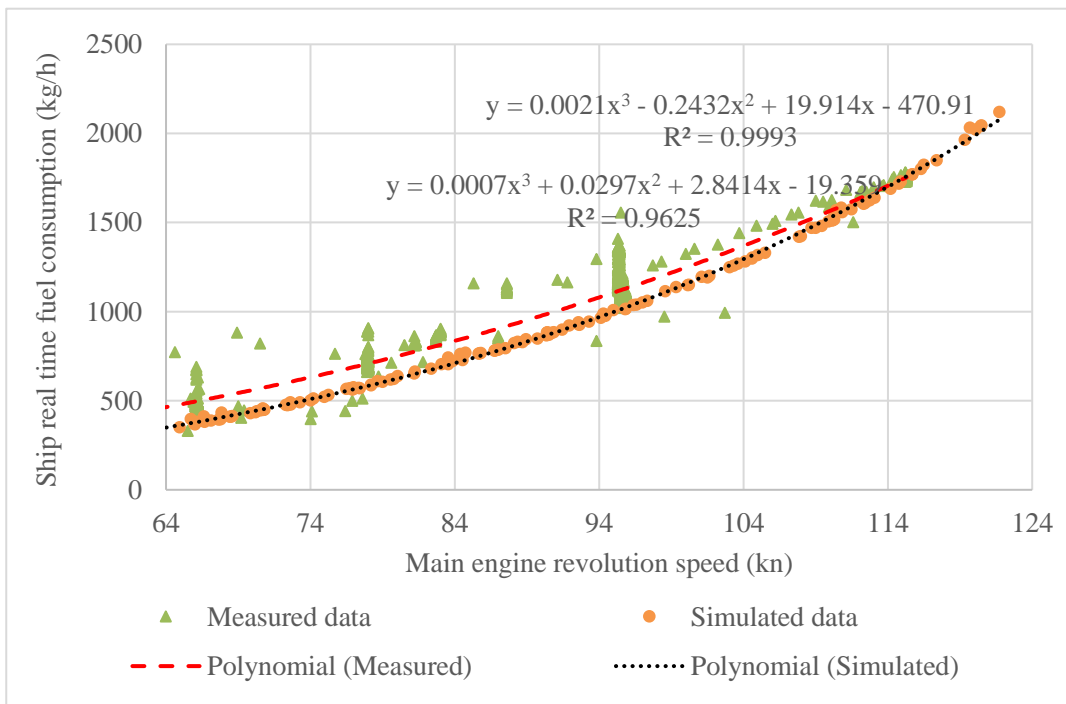$$R^2 = 0.9625$$

Figure 17 Comparison between measured and simulated data

In Figure 15, the X-axis is the ship speed over water, the Y-axis is the ship real-time fuel consumption. In Figure 16, the X-axis is the ship speed over water, the Y-axis is the Beaufort number, and Z-axis is the ship real-time fuel consumption. In Figure 17, the X-axis is the main engine revolution speed, and the Y-axis is the ship real-time fuel consumption. The orange scatters are the simulated results, and the green scatters are the actual measurement data.

It can be seen from Figure 17 that the measured data (green) shows a discrete distribution. There is no one-to-one correspondence between measured ship fuel consumption and revolution speed. Specifically, even at the same revolution speed, the ship fuel consumption can be different. The main reasons for the discrete distribution could be:

(1) Changeable working conditions of the ship. In the actual sailing, the operating conditions of the ship will change from time to time, such as sea conditions, weather, waterway scale, fouling and rudder movement, all of which could result in change of ship resistance; as a result, the ship fuel consumption would change accordingly.

(2) Uncertainty of on-board monitoring system. Due to the impact of sensor measurement accuracy, poor on-board environment and human errors, there are some uncertainties in the on-board monitoring data, which inevitably leads to the production of some singular data or noisy data.

Regarding the simulated data (orange) in Figure 17, it also shows a discrete distribution because the input environmental parameter, *BN*, is regarded as a random variable. The more discrete of the input parameter, the more discrete of the output fuel consumption.

It can be concluded from Figure 15-Figure 17 that the relationship between the fuel consumption, the ship speed (or main engine revolution speed) and the environmental variable can be presented like this:

(1) The ship speed is the main influencing factor of the ship fuel consumption. The growth rate of the ship fuel consumption is increasing with the increasing speed.

(2) The ship draft and the environmental variable, like wind and wave, also has impact on the ship fuel consumption.

(3) Affected by the changeable working conditions of the ship and uncertainty of the monitoring system, the output value of the ship fuel consumption shows discrete and is an interval value.

To evaluate the model accuracy, the measured and simulated data in Figure 17 are respectively regressed. Correspondingly, the red and black regression curves are obtained as well as the regression equation and R^2 value. Then select several revolution speeds, values of the two regression equations are calculated. Their differences are calculated to evaluate the accuracy of the model. The result shows that the model accuracy is good especially aiming at the high revolution speed. For the commonly used speed range (76, 116) rpm, the average difference of the two regression equations is around 6.04%.

6. CONCLUSIONS

A real-time fuel consumption model for a 53,000-ton bulk carrier is developed. Actual data is collected on the selected ship using the information monitoring sensors. The measured real-time data is used to verify the model. Although the both data show a certain degree of dispersion, their overall growth characteristic is very identical. Their regressive differences are further calculated and show the developed model has a good accuracy in predicting real-time fuel consumption. The developed model can be used to predict ship fuel consumption under different ship drafts, speed and sea states. The model can be the basis for the evaluation of the ship energy efficiency and for the study of energy efficiency improvement methods.

ACKNOWLEDGEMENTS

REFERENCES

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., ... & Raucci, C. (2014). 'Third IMO GHG study 2014'.International Maritime Organization (IMO), London, http://www. iadc. org/wp-content/uploads/2014/02/MEPC-67-6-INF3-2014-Final-Report-complete. pdf.

Marine Environment Protection Committee. (2011). 'Report of the marine environment protection committee on its sixty-second session'. London: Marine Environment Protection Committee.

Banawan, A. A., Mosleh, M., & Seddiek, I. S. (2013). 'Prediction of the fuel saving and emissions reduction by decreasing speed of a catamaran'. Journal of Marine Engineering & Technology, 12(3), 40-48.

People' s Communications Publishing Company Limited. (2015) 'China 's shipping development outlook 2030'.

Larsson, L., & Raven, H. C. (2010). 'The principles of naval architecture series: Ship resistance and flow'. Society of Naval Architects and Marine Engineers (SNAME).

Holtrop, J., & Mennen, G. G. (1982). 'An approximate power prediction method'.

Sun, X., Yan, X., Wu, B., & Song, X. (2013). 'Analysis of the operational energy efficiency for inland river ships'. Transportation Research Part D: Transport and Environment, 22, 34-39.

Fan, A., Yan, X., Yin, Q., Sun, X., & Zhang, D. (2017). 'Clustering of the inland waterway navigational environment and its effects on ship energy consumption'. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 231(1), 57-69.

Diesel, M. A. N. (2011). 'Turbo. Basic Principles of Ship Propulsion', MAN Diesel & Turbo, Copenhagen.

Andersen, I. M. V. (2013). 'Wind loads on post-panamax container ship'.Ocean Engineering, 58, 115-134.

Kreitner, J. (1939). 'Heave, Pitch and Resistance of Ships in a Seaway'.Transactions of the Royal Institute of Naval Architects,'London, 87.

ITTC. (2005), 'Full scale measurements – Speed and power trials – Analysis of speed/power trial data', Recommendations of the 24th Int. Towing Tank Conf., Edinburgh

Ailong, F., Xinping, Y., & Qizhi, Y. (2017). 'Modeling and Analysis of Ship Energy Efficiency Operational Indicator Based on the Monte Carlo Method'. Naval Engineers Journal, 129(1), 87-98.

China Classification Society. (2014) 'Ship Energy Consumption Distribution and Energy Conservation Guide'.

Barua, D. K. (2005). 'Beaufort Wind Scale'. In Encyclopedia of Coastal Science (pp. 186-186). Springer Netherlands.