Analysis of the operational ship energy efficiency considering navigation environmental impacts

Yupeng Yuan[1, 2], Zhixiong Li [3, 4], Reza Malekian[5], Xinping Yan[1, 2]

[1] Reliability Engineering Institute, School of Energy and Power Engineering; Key Laboratory of Marine Power Engineering & Technology, (Ministry of Transport), Wuhan University of Technology, Wuhan 430063, China; ypyuan@whut.edu.cn (Yuan); lzx___520@163.com (Yan)

[2] National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan, China

[3] School of Manufacturing & Mechanical Engineering, University of New South Wales, Sydney 2200, Australia; zhixiong.li@ieee.org

[4] School of Mechatronic Engineering, China University of Mining & Technology, Xuzhou 221110, China; zhixiong.li@ieee.org

[5] Department of Electrical, Electronic& Computer Engineering, University of Pretoria, Pretoria 0002, South Africa; reza.malekian@ieee.org

* Correspondence: ypyuan@whut.edu.cn (Yuan); zhixiong.li@ieee.org (Li)

Abstract:

In this study, a remote collecting system for ship operation energy efficiency was designed by using a tourist ship. According to measured data, the navigation environment factors of the ship were analyzed statistically. The gray correlation analysis was used to study the correlation degree among wind, water depth, water velocity and ship operation energy efficiency. On this basis, the Wuhan-Nanjing section of Yangtze River (upstream and downstream) was selected to analyze the law of wind speed effect on the energy efficiency of ship operation. The data analysis demonstrates that in different navigation environments, the ship energy efficiency can be significantly improved by optimizing the main engine speed.

Keywords: tourist ship, navigation environment, main engine speed, ship energy efficiency

1.Introduction

In the past decades, due to accelerated industrialization and dramatic increase of global population, human beings have produced huge amount of carbon dioxide and gaseous pollutants. The global environment has changed greatly. The climate change problem caused by greenhouse gases has become a hot topic in international community and aroused wide concern. It has been listed as the No. 1 problem among the top ten global environment problems. As a major perpetrator of greenhouse gas emission, the shipping industry is bearing increasing pressure. To control the ship CO_2 emission, International Maritime Organization (IMO) has established a strict baseline of CO_2 emission. Meanwhile, as the fuel price keeps climbing, shipping companies are continuously developing measures to reduce unitary fuel consumption and increase ship energy efficiency (Bijlsma, 2008; Kevin, 2014).

The mandatory greenhouse gas emission reduction measure for international traveling ships, Supplementary Provision VI of MARPOL, was passed at the 62th session of Marine Environment Protection Committee (MEPC) in July 2011, in which new supplementary provisions of ship energy efficiency was annexed. This is the first industry-wide, mandatory global greenhouse gas emission regulation(Marine Environment Protection Committee, 2011). The newly annexed Chapter 4 requires that all new ships of 400 gross tonnages or more mandatorily execute the new ship energy efficiency design index (EEDI) and all ships mandatorily execute the ship energy efficiency management plan (SEEMP). Among them, SEEMP provides shipping companies with ship operation energy efficiency index as a surveillance tool, in order to help ship operators measure the level of ship energy efficiency and the effectiveness of energy saving strategies.

Recent studies on ship energy conservation mainly focused on new ships, including the use of alternative fuels (such as bio-diesel, compressed natural gas (CNG)/liquid natural gas (LNG), dual fuel(combination of diesel and CNG), electricity or hydrogen), advanced high-efficiency propulsion systems (such as hybrid electric ship propulsions), energy saving devices, advanced low-resistance ship design and new vessel design, etc (Department for international development, 2011; Paulides andDjukic et al, 2015). On the other hand, for the huge amount of seagoing vessels, operation optimization and energy efficiency management measures can reduce ship fuel consumption and improve the ship operation energy efficiency. Within Europe the project-Modernisation of Vessels for Inland waterway freight Transport was executed, which focused on exploring and determining viable retrofit solutions for existing inland ships in order to improve environmental and economic performance. The research of energy efficiency of the ship was carried out from two aspects: design of new ships and ship operation (http://cordis.europa.eu/result/rcn/163291_en.html).

In terms of ship operation management, there have been numerous new technologies and measures for fuel cost and emission reduction so far, which include speed optimization, route optimization, operations management and scheduling, optimization of the ship's draft, etc(Christiansen and Fagerholt *et al*, 2004; Chen and Yan et al, 2014; Delitala and Gallino*et al*, 2010; Kontovas, 2014; Lin and Fang, 2013; Psaraftis and Kontovas, 2013; Takashima and Mezaoui *et al*, 2009; Wang and Alharbi*et al*, 2014; Xie and Wang *et al*, 2000; Yan and Sun *et al*, 2015). Among them, speed optimization is an effective measure for improving ship energy efficiency, which has been widely studied in the past few years. The studies of Psaraftis (2013) and Lindstad *et al* (2011). proved that by reducing speed only, the CO_2 emission can be reduced by 19% at zero cost. Norstad (2011) focused on the navigation planning of fishing boats, and pointed out the drawbacks of traditional speed control mode. According to the third power relation between oil consumption and speed ($g=Kv^3$, where g is oil consumption; K is constant and v is ship speed), a staged variable decision speed optimization method was proposed. Jeppesen Marine Corp., America, released "voyage and vessel optimization system" (VVOS) software, based on which Ballou (2008) calculated CO_2 emission and pointed out that ship oil consumption could be greatly reduced by optimizing routes, choosing suitable speed and integrating multiple measures. Gershanik (2008) and Chang (2014) pointed out the irrationality of the predefined service speed in current ship contracts. They also proposed relevant method and model of speed optimization, which have great significance for improving ship energy efficiency. By establishing a maximum interest equation, Corbett *et al*.(2009) estimated the most economic speed to lower emission and demonstrated the feasibility of emission reduction by taking advantage of the tax rate. Ronen *et al*.(2011) constructed a cost model and designed a simple program to reduce the annual operating cost of a route by optimizing the ship speed and ship number. Data analysis in this study showed that operating at the speed of the lowest cost significantly increases the ship energy efficiency. Sun *et al*.(2013) focused on inland ships and discussed the relation between EEOI and ship speed. The EEOI under different working conditions was calculated and analyzed according to experimental data. Results showed that ship speed had major impact on the EEOI of inland ships.

Previous studies mainly focused on ship speed optimization. Reducing speed is an important way to decrease oil consumption; however too low speed inevitably prolongs ship voyage time and lowers the combustion efficiency of main engines, which results in more oil consumption per unit distance. Moreover, the energy efficiency level of a marine power system does not only depend on the working condition of the main engine and cargo status, but also on the changes of navigation environment. For maritime vessels, the main considerations include wave, surge, wind and stream; while for inland ships, the current directions are different for upstream and downstream voyage. These factors periodically affect the resistance of ships, thereby affecting the main engine power and energy efficiency level (Malekian, 2015; Jin, 2016; Xin, 2016) of inland ships at a certain speed. Therefore, optimization of speed under particular navigation condition becomes the focus in the study of increasing ship energy efficiency. This plays a key role in guiding economic ship voyage.

The management of inland ships is extensive and their energy consumption is high. Targeting these problems, our study focuses on the characteristics of inland ships and inland shipping. Here a ship of the most important inland river, Yangtze River, was chosen as the research object. According to the energy efficiency management requirements of IMO, we fully considered the effects of navigation environment and analyzed the energy efficiency problem of inland ships. The rest of the paper is organized as follows: the assessment method of ship operation energy efficiency is introduced in Section 2; the energy efficiency monitoring system for the object ship is discussed in Section 3; statistical analysis for navigation environment factors is presented in Section 4; the law of the navigation environment effect, especially wind speed, on ship operation energy efficiency is analyzed in Section 5; Section 6 summarizes the paper.

2. Evaluation method of ship operation energy efficiency

Compared with the EEDI of newly built ships, the operation energy efficiency index indicates the energy efficiency level of operating ships in a more objective manner. In July 2009, the 59th session of MEPC was held at the headquarters of IMO, and the new resolution "Ship energy efficiency operational indicator (EEOI)voluntary application guidelines" was passed (International Maritime Organization, 2009). According to this resolution, the CO_2 emission index of ships is defined as follows:

$$EEOI = \frac{\sum_j FC_j \times C_{carbon}}{m_{cargo} \times D} \tag{1}$$

where

- J represents fuel category;
- FC_j is the total fuel consumption of the ship in the voyage;
- C_{carbon} is the carbon content of the fuel used;
- m_{cargo} is the cargo capacity;
- D stands for the mileage of the ship in a single voyage (the real voyage distance of the ship in transportation, measured by *n*Mile or *km*).

Since the main power diesel engine is the main oil consuming equipment, here we only analyzed the oil consumption of the main engine as an example. The calculation equation for EEOI is established according to the configuration of the object ship:

$$\begin{aligned} EEOI &= \frac{\sum_j FC_j \times C_{carbon}}{m_{cargo} \times D} = \frac{C_{carbon}}{n_{passenger}} \times \frac{(FC_l + FC_r) \times 60 \times 0.8}{V_s \times 1.852} \\ &= K \times 25.92 \times \frac{FC_l + FC_r}{V_s} \end{aligned} \tag{2}$$

where

- $n_{passenger}$ is the number of crew members;
- FC_l and FC_r are the oil consumption of the left engine and the right engine, respectively (*L/min*);
- V_s is the ship speed (*kn*);

If we assume $\frac{C_{carbon}}{n_{passenger}} = K$, the parameter K remains largely unchanged for the selected tourist ship. Then, EEOI can be expressed as a value linearly correlated to K and is used to measure the ship operation energy efficiency in this study.

3. Ship energy efficiency monitoring system

In this study, a tourist ship of a shipping company from Chongqing was selected as the study object (see Figure 1), and data acquisition was performed on the ship for data analysis and model verification. Tourist ships, with long voyage distances, are widely used as one of the representative ship types on Yangtze River. The ship space is relatively large, which meets the requirements of equipment installation. Moreover, the operation of them is hardly affected by shipping market, which makes them suitable for long-term continuous data acquisition. The main parameters of the ship are as follows:

Fig. 1. Tourist ship on the Yangtze River

Table 1. The main parameters of the ship

Ship length, L=80m	Ship width, B=14.8m
Designed velocity, V=28km/h	Ship gross tonnage, GT=4587t
Main engine rated power 960kW×2	Main engine rated speed, n=750r/min
Propeller blade number, Z=4	Propeller diameter, D=1.74m
Pitch ratio, P/D=0.793	Blade area ratio, AE/AO=0.7

Following the principle of reliability, stability and security (Gong, 2016; Wang, 2016), we designed a dynamic data acquisition system for energy efficiency measurement. This system has fully considered the character of the object ship and the navigation environment (Ye, 2015; Prinsloo, 2016) of the voyage segment, and met the requirement of further analysis.

The system framework is shown in Fig. 2.

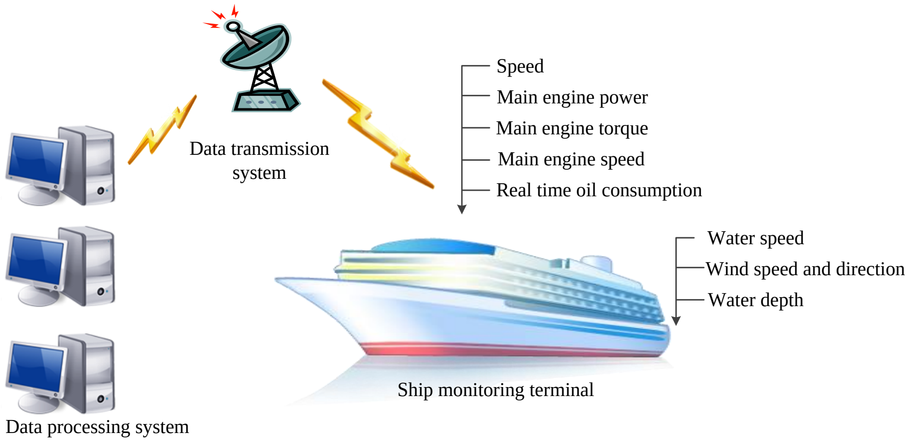
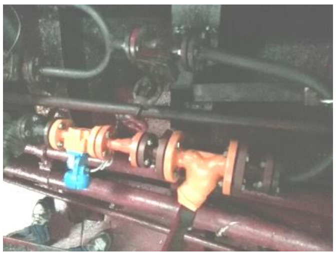


Fig. 2. Framework of data acquisition system for energy efficiency measurement

The whole system contains three parts, namely, ship monitoring terminal, data transmission system, and data processing system.

We used GPS, a shaft power meter and a diesel engine oil consumption meter to collect the working state information related to ship operation energy efficiency, including speed, power, torque, and oil consumption, etc. Wind speed and direction sensor, current speed sensor and depth finder were also used to collect the navigation environment information. Then the data collected by the sensors were packed and sent to GPRS terminal. The oil consumption data and navigation environment data were sent to the river bank terminal. The synthetic information service platform of the river bank terminal processed and analyzed the data for users. The sensors installed in the data acquisition system for energy efficiency measurement are shown in Fig. 3.



Oil consumption meter

Main engine torque and speed measurement device

Ultrasonic doppler flow meter

Anemometer and dogvane

Depth finder

GPS

Fig. 3. Sensors of data acquisition system

Table.2 Detailed information of data acquisition equipments

Equipment name	Model	Unit	Equipment accuracy
Oil consumption meter	NV~OVAL	*L/min*	0.5 grade
Shaft power meter	TQ201H-T	*r/min*	±0.1%
Depth finder	DS606-1	*m*	0.1 *m*
Water speed sensor	LSH10-1	*m/s*	1 *cm/s*
Wind speed sensor	LVFSZ-31	*m/s*	0.1 *m/s*
Wind direction sensor	LVFXZ-32	(°)	1°
GPS	XZ003-USB	*m*	3.0 *m*

From the above data acquisition platform, data of the object ship were collected multiple times in 2014. The whole voyage covered typical valleys of Yangtze River, including upstream, midstream, downstream, and the three gorges reservoir area, etc. The meteorological, hydrological and waterway conditions of the voyage segments were universal and the data collected were sufficient to meet the requirements of analysis. Some of the raw data are shown in Table 3.

Table 3 Part of the raw data (Apr. 16th, 2014)

Time	Wind speed($m \cdot s^{-1}$)	Water depth (m)	Longitude (°)	Latitude (°)	Water speed($m \cdot s^{-1}$)	Voyage speed (kn)	Oil consumption ($L \cdot min^{-1}$)
11:44:50	11.3	9.9	115.465	29.858	1.01	12.2	3.63
11:45:20	11.3	10.2	115.466	29.856	1.24	14.0	3.7
11:45:50	13.3	10.2	115.468	29.855	1.01	12.2	3.7
11:46:20	13.3	9.6	115.469	29.854	1.01	12.9	3.7
11:46:50	11.5	9.3	115.470	29.852	1.51	13.7	3.7
11:47:20	13.4	9.1	115.472	29.851	1.51	12.7	3.7

11:47:50	13.4	9.0	115.473	29.850	1.51	12.8	3.69
11:48:20	13.4	9.8	115.475	29.848	1.29	13.3	3.69
11:48:50	10.3	8.5	115.476	29.847	1.01	12.0	3.69
11:49:14	10.3	9.0	115.477	29.846	1.01	12.5	3.69
…	…	…	…	…	…	…	…

4. Statistical analysis on the characteristics of navigation environmental factors

The calibration of wind direction was performed during dogvane installation. The directions of the wind around the ship are defined as follows: 70° for portside wind, 160° for bow-windward (or headwind), 250° for starboard wind and 340° for stern-windward (or downwind). The frequency distribution of the wind direction is shown in Fig. 5.

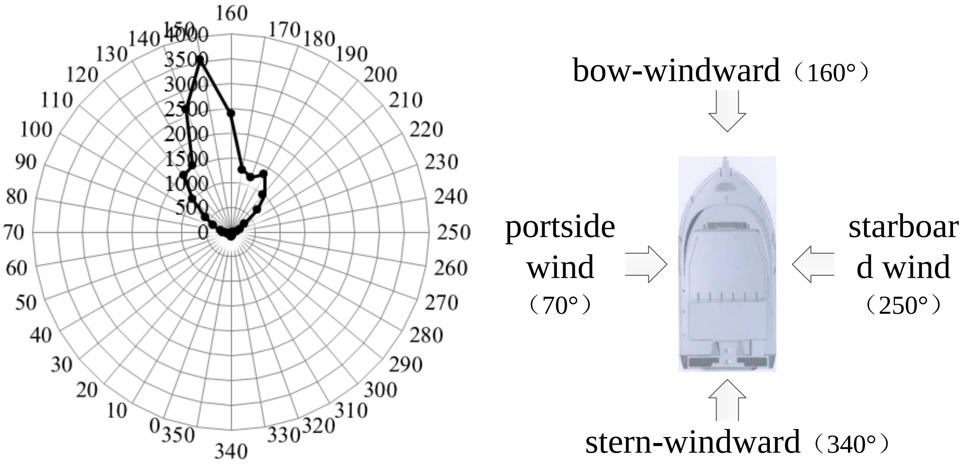


Fig. 4 Radar chart of wind direction distribution.

As shown in Fig. 4, the wind directions were generally bow-windward with deviation to the left; while the frequency of stern-windward (downwind) was low. This is mainly because that the dogvane only measures the relative wind direction. Therefore, the collected wind speed is a relative wind speed. The scattered distribution of wind speed is shown in Fig. 5.

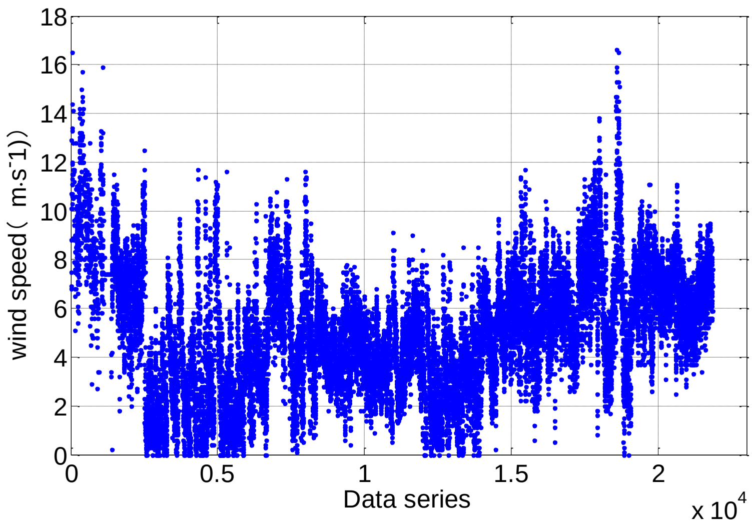


Fig. 5. Scattered distribution of wind speed.

It can be observed in Fig. 5 that the wind speed of the whole voyage segment is generally between 0 and 12 *m/s*, and the distribution is scattered with rapid changes, which reflects the variability of the wind speed in Yangtze voyage segment. The voyage segment is classified into 7 levels of wind power: Calm (0.0-0.2 *m/s*), Light air (0.3-1.5 *m/s*), Light breeze (1.6-3.3 *m/s*), Gentle breeze (3.4-5.4 *m/s*), Moderate breeze (5.5-7.9 *m/s*), Fresh breeze (8.0--10.7 *m/s*) and Strong breeze (10.8-13.8 *m/s*). The statistical characteristics of the frequency distribution of all the wind scales are shown in Fig. 6. It is clear that the wind scales of the whole voyage segment are mainly light breeze, gentle breeze, moderate breeze and fresh breeze.

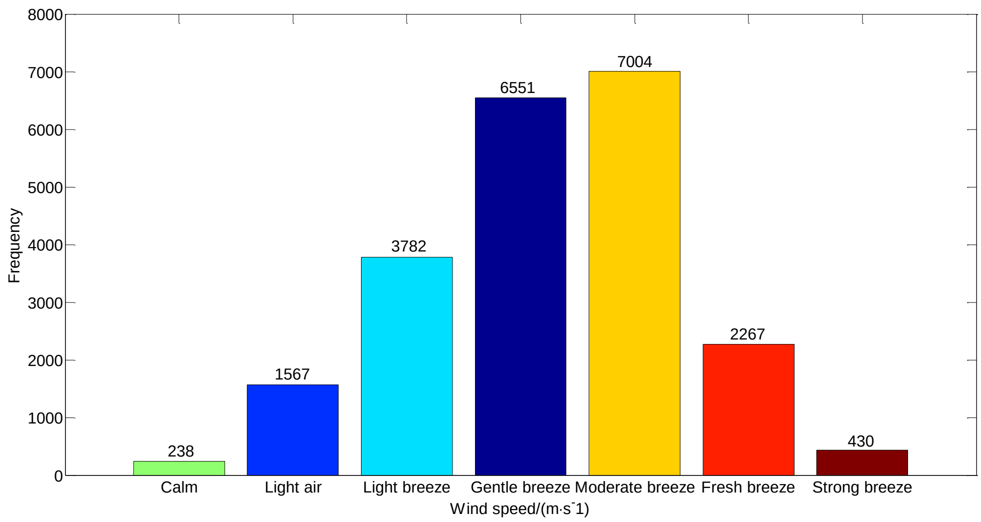


Fig. 6. Histogram of frequency distribution of all wind scales

The longitude distribution of water depth and speed in Chongqing-Nanjing Segment is shown in Figs. 7 and 8.

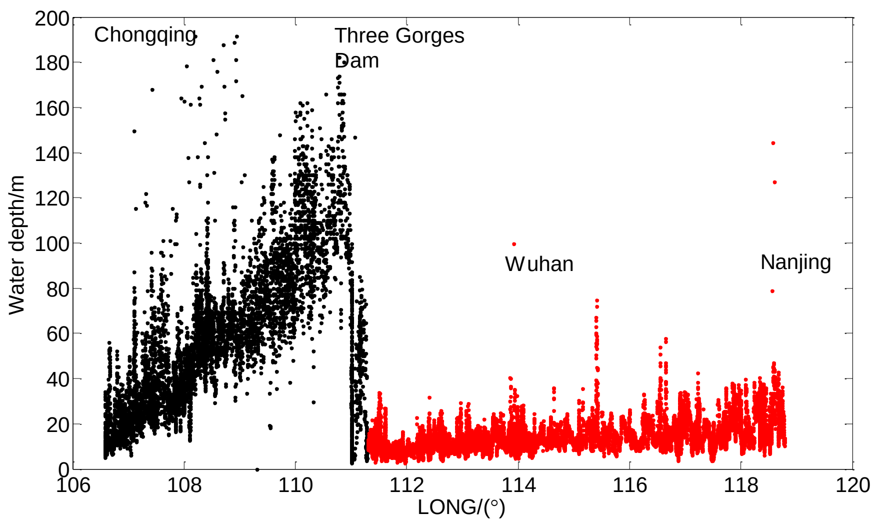


Fig. 7.Scatter plot of water depth distribution.

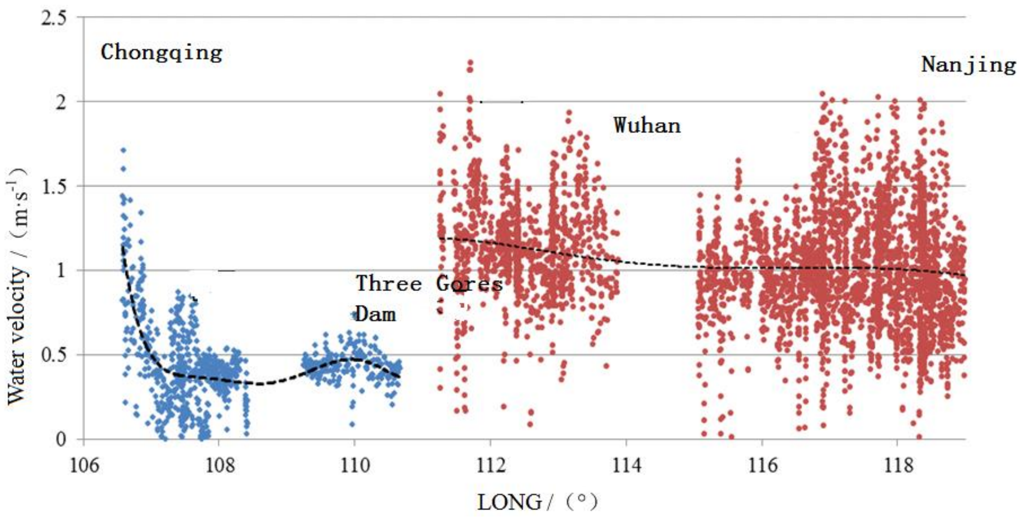


Fig. 8. Scatter plot of water speed distribution.

Figs. 7 and 8 demonstrate that the water depth of the Three Gorges Dam segment (from Chongqing to Yichang) increases with the increase of longitude, due to the impoundment of the Three Gorges Dam. Particularly, the water depth in the reservoir region between Badong and Zigui is as high as 160*m* to 180*m* while the water depth under the dam dramatically reduces to less than 20*m*. The water depth in the main channel of the midstream and downstream segments is between 10*m* and 25*m*. The difference of the water speed distribution upstream and downstream of the dam (longitude: E111.006) is significant. In the regions upstream of the dam (shown as the blue data points in Fig. 8), the water speed from Chongqing (longitude: E 106.587) to Fengjie rapidly decreases from 1.5 *m/s* to less than 0.5 *m/s*. The water speed remains slow all the way down to the Three Gorges Dam. In the regions downstream of the dam (shown as red data points in Fig. 8), i.e., midstream and downstream segments of Yangtze River, the water speed maintains at around 1*m/s*.

In general, during stable travel, the propeller torque equals to the torque provided by the main engine. Actually, the voyage of ships depends on a number of exterior factors. The navigation environment factors, including wind, wave, current and water depth, may change. In corresponding conditions, ship working states, such as voyage speed, propeller, main engine operation conditions, change consequently. This affects the level of ship operation energy efficiency. The data collected on ship have presented the complex navigation environment of Yangtze River, with high fortuity and ambiguity. However, the effect of factors like wind speed and depth on ships can be reflected by the changes of ship resistance. A larger the ship resistance is associated with higher oil consumption and more work done by the main engine to maintain voyage speed. Therefore, the navigation environment is related to ship operation energy efficiency level. Next, we use gray correlation analysis to analyze the effect of wind speed, water depth, water speed and voyage speed on ship EEOI levels. Let γ_{01} , γ_{02} , γ_{03} and γ_{04} represent the correlation of EEOI to wind speed, water depth, water speed, and voyage speed, respectively. According to the collected data, the following can be obtained by calculation:

$$\gamma_{0i} = \{0.927, 0.832, 0.8509, 0.801\} \quad i = 1, 2, 3, 4$$

with

$$\gamma_{01} > \gamma_{03} > \gamma_{02} > \gamma_{04}$$

The correlation between wind speed and ship EEOI is the strongest. So wind is the dominant factors which influencing the energy efficiency of ship. Since the superstructure of the tourist ship hasa relatively large height, the wind in the whole voyage segment is generally in the direction towards the bow,with slight deviation to the left (see Fig. 2). The wind resistance of the ship is smaller than waterresistance. As wind speed increases, the wind resistance of the ship rises significantly, which affects the EEOI level.

5.Analysis of energy efficiency level during operation

It can be known from Section 4 that wind speed is the main factor affecting the efficiency level of tourist ship operation energy. The relation between wind speed and EEOI is analyzed as follows. It is clear in Fig. 6 that the wind scales in the whole voyage segment mainly consist of light breeze, gentle breeze, moderate breeze and fresh breeze. The water depth and water speed downstream of Three Gorges Dam are relatively uniform. Therefore, the Wuhan-Nanjing segment (downstream) and the Nanjing-Wuhan segment (upstream) are selected for analysis.

According to real data (with invalid data removed) collected in Wuhan-Nanjing segment, the relation between the main engine speed under different wind speed conditions and EEOI is shown in Fig. 9.

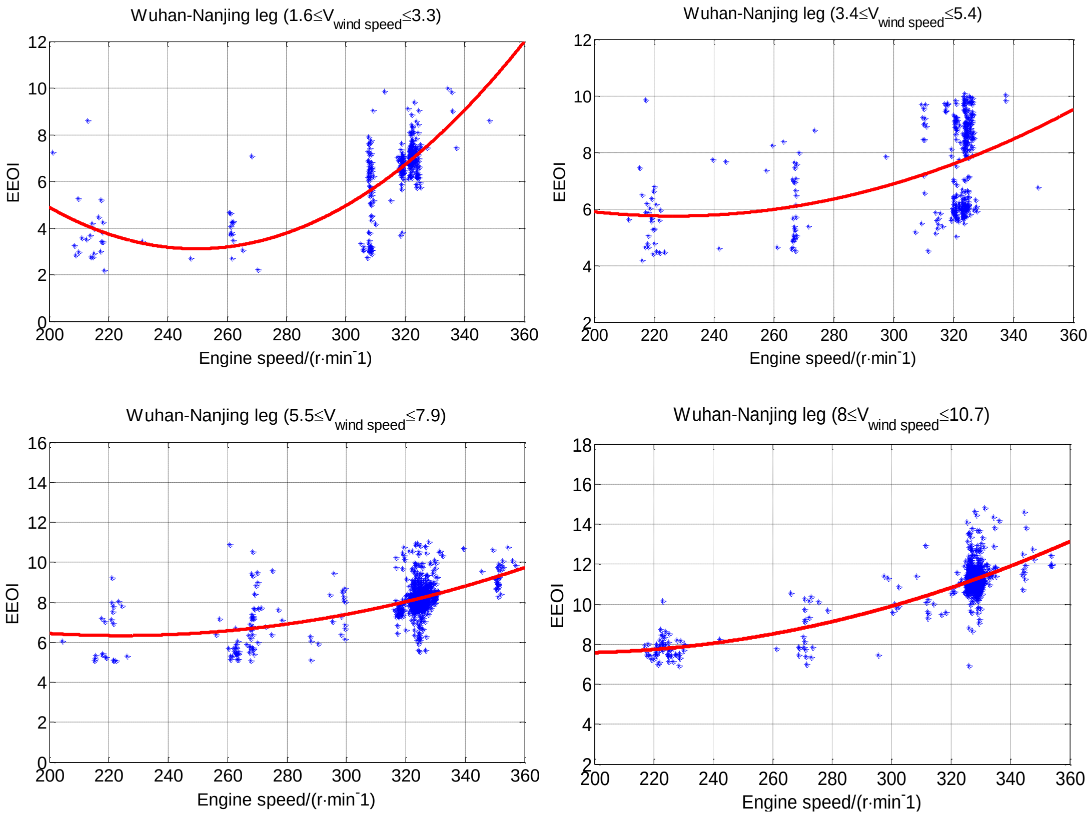


Fig. 9. Wind speed conditions versus ship EEOI in Wuhan-Nanjing segment

The red solid lines in the figure show the result of polynomial fitting. Generally, in Wuhan-Nanjing segment, the EEOI generally increases with the increase of ship main engine speed. Moreover, at the same main engine speed, the higher the wind speed is, the higher the ship EEOI levels are. When the wind scale is Light breeze, the EEOI has an initial decreasing process, which reaches the valley at a main engine speed of 250*r/min*. This is because the combustion thermal efficiency decreases if the main engine speed is too low, causing EEOI to increase. However, EEOI rapidly increases as the engine speed increases. When the wind scales are gentle breeze, moderate breeze and fresh breeze, the EEOI generally increases with the increase of main engine speed. However, the increase of EEOI gradually slows down. In summary, in Wuhan-Nanjing downstream segment, at relatively low wind speed (light breeze and gentle breeze), ships should travel at a speed closest to the most economic engine speed (250-280*r/min*) as long as the navigation schedule is not affected. Conversely, when wind speed is relatively high (moderate breeze and fresh breeze), the main engine speed can be increased to maintain voyage speed and guarantee travelers' tour.

The main engine speed under different wind speed conditions versus ship EEOI for Nanjing-Wuhan segment is shown in Fig. 10.

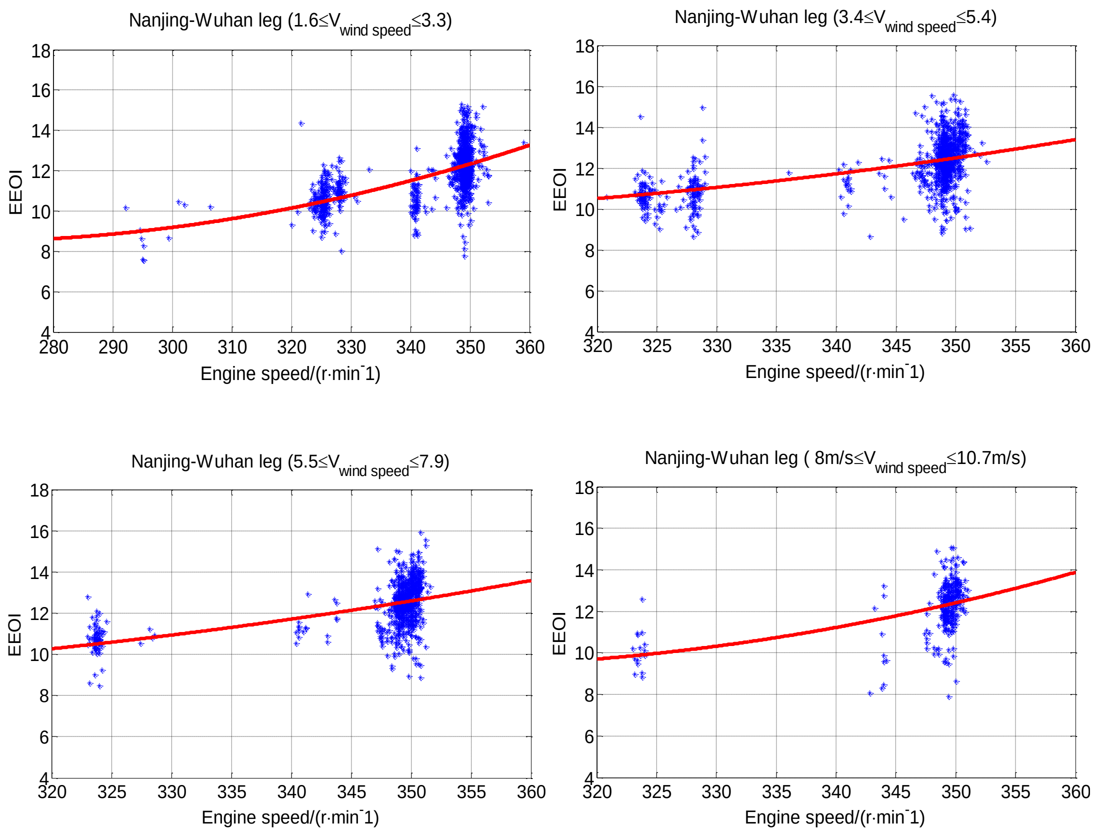


Fig. 10. Wind speed conditions versus ship EEOI in Nanjing-Wuhan segment

In Nanjing-Wuhan segment, at different wind scales, the ship EEOI also increases with the increase of main engine speed at the same increasing rate. The EEOI level does not change significantly when the main engine speed maintains unchanged. Moreover, in the whole voyage segment, the main engine speed stays above 320*r/min*. Since traveling against the current is affected not only by wind resistance, but also by water resistance, the main engine speed should be increased to guarantee the navigation safety and travelers' tour.

We also analyzed the data collected after May. 2014 in Wuhan-Nanjing segment and Nanjing-Wuhan segment. Figs. 11 and 12 present the ship EEOI at the main engine speed of 220*r/min*, 250*r/min*, 300*r/min* and 320*r/min* for downstream segment and 320 *r/min*, 330 *r/min*, 340 *r/min* and 350*r/min* for upstream segment.

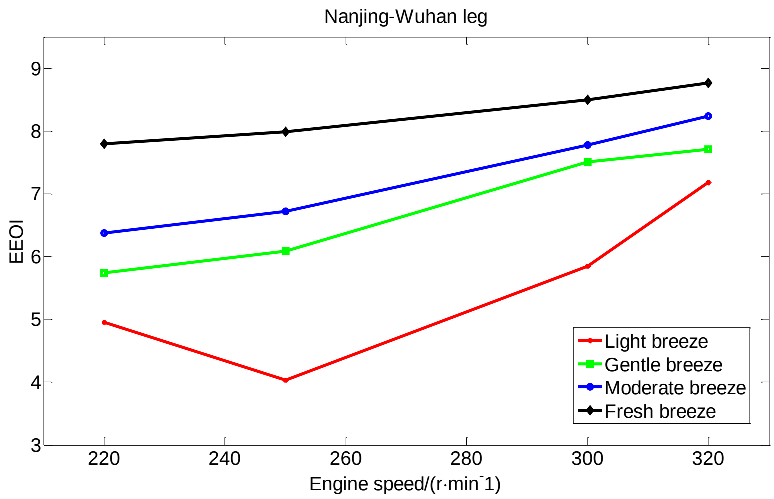


Fig. 11. Main engine speed versus ship EEOI in Wuhan-Nanjing segment

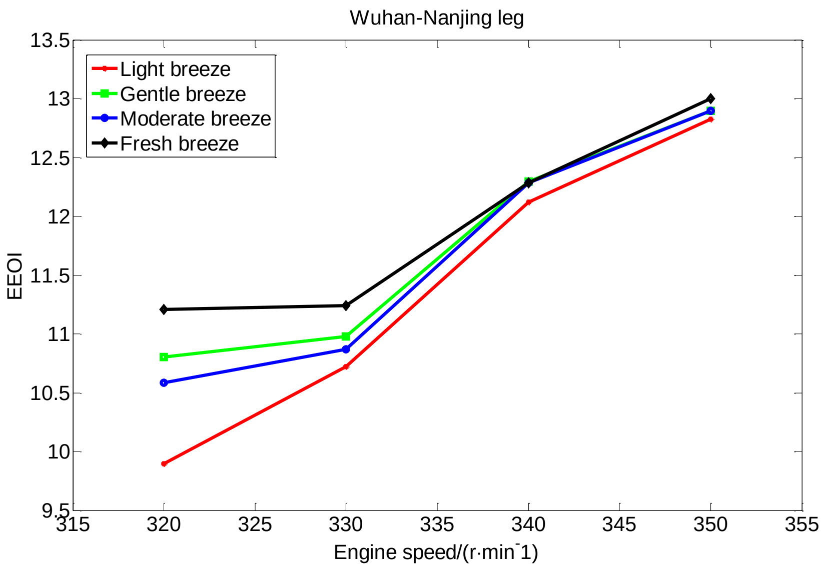


Fig. 12. Main engine speed versus ship EEOI in Nanjing-Wuhan segment

Multiple statistical analyses have shown that wind speed has significant impact on ship EEOI, especially in downstream segments. At the same main engine speed, EEOI is positively correlated with the wind speed. Conversely, in upstream segments, the wind speed has more significant effect on EEOI at relatively low main engine speed than that at relatively high main engine speed. When the engine speed is above 335*r/min*, the EEOI level has no significant change. Therefore, the ship main engine speed can be appropriately reduced in Wuhan-Nanjing downstream segment and increased in Nanjing-Wuhan upstream segment. This can improve ship operation energy efficiency without influencing the navigation safety and schedule of the whole segment.

6. Conclusions

In this study, the energy efficiency data acquisition system of a tourist ship has been designed. According to the collected data in real operation and statistical analysis of ship navigation environment factors and energy efficiency, it was concluded that the inland navigation environment factors, including wind speed, water speed and depth, have major impact on ship operation energy efficiency. On this basis, we analyzed in detail the effect of wind speed on ship operation energy efficiency for both upstream and downstream segments. There are many tourist ships similar as the research object sail in Yangtze River. Those ships should travel at economic main engine speed (250-280r/min) in Wuhan-Nanjing downstream segment and at 335r/min or higher in Nanjing-Wuhan upstream segment. The conclusion of this study can help shipping companies and ship operators achieve economic ship management and improve the efficiency of ship operation energy.

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