A NEW FUEL CONSUMPTION MONITORING SYSTEM WITH A DOUBLE-LOOP FOR THE RETURN OIL OF MARINE DIESEL ENGINE

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This paper develops a fuel monitoring system that is applied to fuel consumption monitoring on vessels engaged in offshore wind power construction. Results show that the developed oil-gas separation device can eliminate the air bubbles in the return oil pipeline of the diesel generator, enabling real-time monitoring of engine oil consumption through an ultrasonic flow meter, with a deviation of no more than 1%. Cross-checking the fuel consumption of engine with that of the daily-use oil tank, while comparing the fuel consumption with the refueling amount over one refueling cycle, enabled refined management of marine fuel, reducing and eliminate the fuel leakage. This research provides feasible measures for enterprises to address fuel consumption of marines engaged in offshore wind power construction.

Keywords: fuel consumption; monitoring; double-loop; return oil

1. Introduction

Marine fuel is an important cost in the maritime industry. Currently, marine fuel consumption is mainly obtained by calculating the tank capacity and the oil level of the tank which is manually measured. This method is largely influenced by human factors due to apparent measurement error. Some ships measure the daily tank level remotely by installing electronic dipstick in the oil tank and by this way to calculate the fuel consumption of engines. As the ship is pitching and rolling, tank measurement methods may inevitably cause error. Use flowmeters could be a better solution for real time engine fuel consumption monitoring. Normally we measure the inlet and outlet flow of oil consumers such as diesel generators, and the difference is the real time fuel consumption.

However, the accurate measuring of return oil of a marine diesel engine is not easy [1-3]. The oil in the outlet pipe has the following characteristics:

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1) Return oil flow rate is unstable, the air contained in the tank and the fuel oil will form a mixture of oil and gas, coupled with inadequate pressure in the return oil pipe, which result in a large amount of turbulence in the return oil pipe.

2) The density of oil in the return oil pipe is not evenly distributed. As the ship's hull is always moving during the sailing, the return oil pipe is subject to high-frequency shaking, which result in the oil density in the return oil pipe uneven distribution.

The above characteristics of marine diesel engine return oil pipe make it not easy to accurately measure the volume and mass of fuel oil by only using mass flow meter or volume flow meter.

For monitoring techniques, computational techniques such as Artificial Neural Networks (ANN) have been used to monitor different industrial processes [4-5]. The adoption of new testing technologies has replaced the original manual monitoring, resulting in more accurate measurements and propelling the advancement of detection technology in the process [6-8]. For example, in marine diesel engines, by real-time monitoring of fuel consumption and related parameters, any deviation of normal working condition can be detected. Zhu et al. [9] established diagnosis methods for the diagnosis of multiple faults in the ocean-going marine diesel engine based on thermal parametric analysis combined with different neural network algorithms and provide references for the online diagnosis of single faults and multiple faults in ocean-going marine diesel engines. Parekh et al. [10] introduce an AI and blockchain-assisted intelligent and secure framework for predicting energy consumption in ships to enhance efficiency and sustainability. They found the proposed framework not only refines predictive accuracy but also ensures the confidentiality and integrity of the predicted data. Boullosa-Falces et al. [11] proposed a detection process deviation method (SSDM) to detect the correlation situation between diesel fuel consumption and variables during marine propulsion with emergent and small variable factors. Gao et al. [12] proposed a prediction framework based on incremental learning by dynamically adjusting the input features and the target labels through a dual adaptive mechanism, while incorporating rolling retraining to achieve continuous model updating. Yin et al. [13] designed a real-time monitoring system for marine fuel consumption. The correlation between the main engine fuel consumption and the main engine shaft power, main engine speed, ship speed, as well as the correlation between power generation and auxiliary engine fuel consumption was established. And the accurate measurement and alarm function of marine fuel consumption was realized based on the measured data. Shi [14] used three times fitting model to determine the key environmental factors, combined with artificial neural network to explore the correlation law between navigation factors and fuel consumption, and realized the remote monitoring and management of marine 's fuel consumption. Tian [15] built a remote fuel monitoring system based on data acquisition system, fuel system monitoring software, GPRS transmission technology, Internet server and Web browser, and realized the real-time monitoring of the fuel status of the marine from the shore-based end. Xiao [16] utilizes the method of replacing oil with water, and monitors the change of fuel volume with the help of liquid level sensors, so as to meet the on-line monitoring requirements of the marine fuel system, and to achieve the management purpose of automatic intelligent control of related equipments.

How to ensure the accuracy of engine fuel consumption measurement is a fundamental issue in ship energy efficiency calculation [17-18]. Additionally, exhaust parameters and cylinder pressure parameters are the main factors affecting the performance of the monitoring model [19-20]. From the above research background and current status, it can be seen that existing studies mostly use prediction methods, and there are still few reports on direct measurement by flow meter. The problems existing in its measurement and its error range are still unclear. Based on the previous research on direct measurement methods of flow meters, this study proposed a dual-circuit tank measurement method for the return oil flow of marine diesel engines, which improves the accuracy of flow meter measurement by reducing the oil and gas concentration in the return oil pipe.

2. Physical modeling

2.1 Physical model building

The marine fuel monitoring system shown in Fig. 1 achieves fuel monitoring by measuring the initial amount of bunkering, the amount of fuel change in the daily tank, and engine fuel consumption. In order to monitor the engine fuel consumption accurately, the system added a venting tank to make the oil and gas separation, and the remaining oil back to the daily oil tank to reduce the error of the daily oil tank monitoring. Through the long-term monitoring of bunkering volume, oil tank inventory changes and daily oil tank volume, compared with engine fuel consumption measured by flowmeters, the mutual verification can be obtained to ensure the accuracy of the system.

In this paper, the fluid used in the simulation process is an incompressible fluid, and diesel fuel is used to conduct experiments on the fuel monitoring system to detect the consumption of fuel in the ship 's operating conditions.

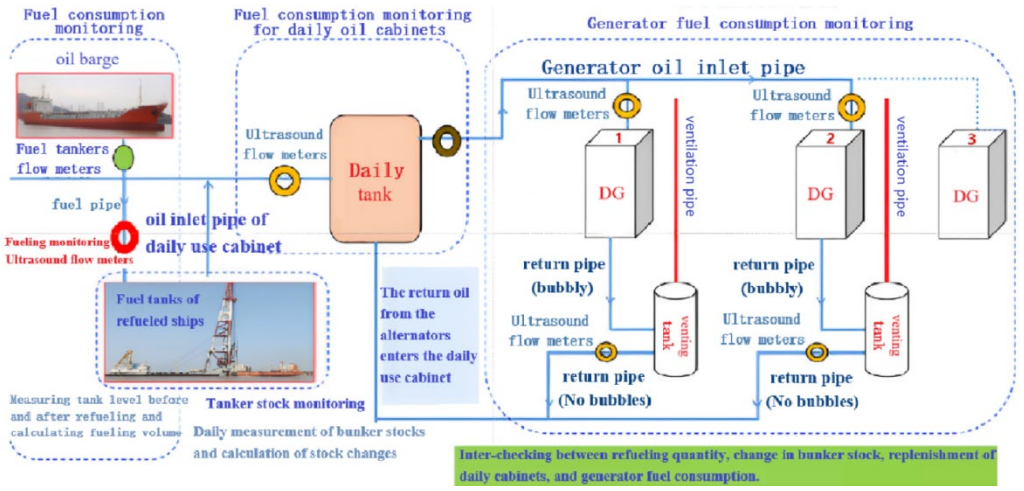


Fig. 1. Marine fuel monitoring system

To improve the accuracy of marine diesel engine fuel oil return fuel monitoring, dual circuit storage tank measurement device for oil return monitoring is used as shown in Fig. 2.

1) Under normal operating conditions:

The dual circuit oil storage tank forms a closed space, which meets the ideal gas movement state. When oil return from the engine, and flow to the tank, the tank gas volume compresses, pressure increases so that the tank pressure is greater than the pressure in the return pipe, the one-way solenoid valve opens under the action of the pressure. The gas in the tank carried by the return oil exit to the daily oil tank. The fuel level oil storage tank continues to increase until it reaches a high level, and during this period the gas in the tank continues to vent. The oil level sensor sends a high-level signal, then a pump is energized and starts to discharge, at the same time the one-way solenoid valve in the return oil pipe is open. Oil is pumped through the flow meter to the daily tank. The air pressure in the oil storage tank drops as well. In order to ensure the ideal gas movement balance in the tank, the inlet one-way solenoid valve will be open by the outside air pressure automatically while pressure inside the tank is 0.2 kilograms lower than the outside. Air enters into the tank, and maintain the pressure in the tank. The air inlet pipe is equipped with a filter with 5um filtration, which is used to filter out oil mist.

2) Abnormal working condition:

When discharge pump failed, the return oil level reached the high level, oil continue to enter the tank, the liquid level rise until it reaches the return air pipeline one-way solenoid valve position, the oil and gas mixture will flow through the one-way solenoid valve and the ventilation pipe to the daily tank by pass the flow meter with no flow monitoring, but does not affect the normal operation of the diesel engine, nor other components in the system.

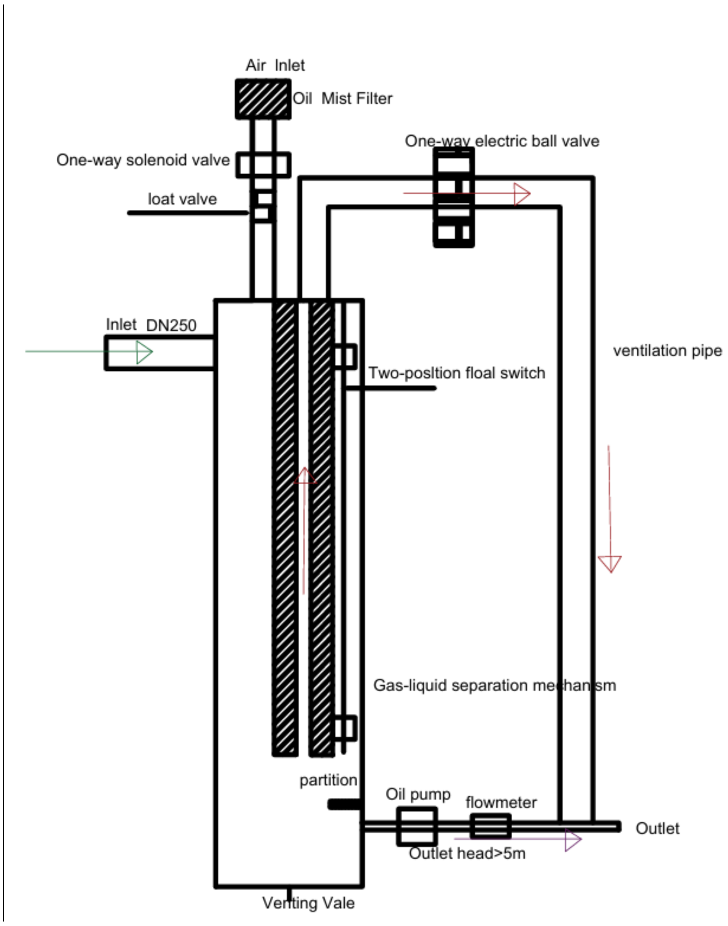


Fig. 2. Model of the measuring device for the dual-loop fuel return storage tank

2.2. Experimental model

In order to verify the function and accuracy of the dual circuit storage tank measurement device, a test model equipment shown in Fig. 3 is established on the basis of the physical model. During the test, we intentionally add some air to the return oil pipe to simulate the real working condition for measuring a diesel engine fuel consumption. By controlling the flow rate of oil and air, the desired gas content of the oil and gas mixture can be obtained. The oil/gas mixture will be separated in this equipment using the principle of negative pressure debubbling to remove air bubbles from the liquid. This is usually accomplished using a vacuum pump or other negative pressure device. The specific steps of the negative pressure degassing method are: when the liquid level in the tank reaches a high level, the pump station automatically starts, and by setting the pump flow rate to be greater than 50% of the return oil inlet flow rate, a negative pressure of 0.5 kg will be generated in the oil tank, and negative pressure will be used to achieve efficient and rapid gas-liquid separation.

When negative pressure is applied to the liquid, the gas bubbles are forced out of the liquid by the negative pressure and into a negative pressure pipe or container. This part of the gas will be discharged into the daily oil tank, which plays a role in diluting the concentration of oil and gas in the vent port of the daily tank. At the same time, the return oil can also play the role of cooling, decrease the oil temperature in the daily tank, reduce the amount of oil and gas volatilization. In order to test the fuel monitoring data equipment accuracy, we adjust the gas content of the oil and gas mixture injected into the return oil measurement device, discharged after the recording of electronic scales readings and flowmeter readings, also measure the density of diesel fuel through the mass flowmeter.

Fig. 3. The experimental model for fuel monitoring

Different ultrasonic flowmeters were tested on site, and we choose the one with smallest deviation for the system. Table 1 shown the comparison of ultrasonic flowmeters we choose with mass flow meter. The design accuracy of ultrasonic flowmeter can reach 1%, and the design accuracy of mass flowmeter can reach 5‰, but the price of mass flowmeter is 15-20 times that of ultrasonic flowmeter, and mass flowmeter can only measure the medium with uniform density. It is impossible to directly measure this oil-gas mixture with mass flowmeter. In addition, we tested ultrasonic flow and mass flowmeter in diesel without air, and found that the maximum instantaneous measurement deviation of mass flowmeter and ultrasonic flowmeter was 2.02%. From the perspective of economy and applicability, ultrasonic flowmeter fully meets the needs of ship fuel monitoring.

Table 1

Comparison of test results of different flow meters

Flow meter type	**Ultrasonic flow meter (FM12DN15)**	**Mass flow meter (LK-015)**	**Deviation(instantaneous maximum)**
Design accuracy	**1%**	**5‰**	
Measured flow	0.302m³/h	0.296m³/h	2.02%

3. Analysis of experimental test results

Fig. 3 shows the in the return oil dual circuit tank measurement device for marine engines, and the experimental conditions are as follows:

(1) Tank volume: 25.12 L (0.02512 m^3, specifically to match the diesel engine fuel return volume)

(2) Tank pressure: 1 bar (tank normal operating air pressure in 0.3 bar)

(3) Inlet piping: DN25, outlet piping: DN20 (matching with the original generator)

(4) The flow rate through the return oil measurement device: 2 m^3/h

From the test data shown in Table 2, it can be seen that after the gas-liquid separation, the error of the data measured by the ultrasonic flowmeter is always less than 1% compared with mass flowmeter. To realize accurate oil return measurement, the measurement accuracy depends on the accuracy level of the flowmeter. This device will not increase the measurement error combined with the back-end digital acquisition system and data sending unit, it can be composed of fuel consumption monitoring system of marine engines.

Table 2

The amount of fuel oil return of the oil-gas mixture with a gas content of 20%

NO.	Mass of fuel measured by flow meter(kg)	Weight of fuel measured on electronic scales(kg)	deviation
1	13.40	13.36	-0.3%
2	14.90	14.22	-0.2%
3	16.357	16.42	0.4%
4	23.29	23.4	0.5%
5	39.753	40.02	0.6%
6	40.34	40.70	0.9%
7	44.4	44.26	-0.3%
8	44.69	44.62	-0.15%

By changing the content of the oil-gas mixture, the higher the gas content, the greater the deviation of the flow meter reading through the monitoring device, resulting in a greater deviation in the measurement result, as shown in Table 3. Increasing the flow rate per unit time, the gas mixture passes through the monitoring device at the same time, which has little effect on the measured results. However, when the negative pressure in the oil tank is increased, the gas-liquid separation speed increases with the increase in negative pressure, the density of the oil sample passing through the detection device increases, and the deviation of the detected data will be smaller. In order to ensure the safety and reliability of the working operation, the pump station uses a magnetic pump, the speed will change with the change of negative pressure, and the pressure in the oil tank will be controlled at 0.3 kg. In this way, the consumption of fuel can be better monitored during the operation of the ship.

Table 3

Measurement deviation of fuel monitoring system under different working conditions

NO.	Mass of fuel measured by flow meter(kg)	Weight of fuel measured on electronic scales(kg)	deviation	Different working conditions
1	16.357	16.42	0.4%	20% gas content oil and gas mixture, flow rate 0.2m³/h
2	15.76	15.68	-0.51%	40% gas content oil and gas mixture, flow rate 0.2m³/h
3	50.68	50.59	0.17%	20% gas content oil and gas mixture, flow rate 0.6m³/h
4	48.69	48.45	-0.49%	40% gas content oil and gas mixture, flow rate 0.6m³/h
5	44.4	44.26	-0.3%	20% gas content oil and gas mixture, negative pressure of 0.3 kg in the oil tank
6	30.69	30.74	0.16%	20% gas content oil and gas mixture, negative pressure of 0.5 kg in the oil tank

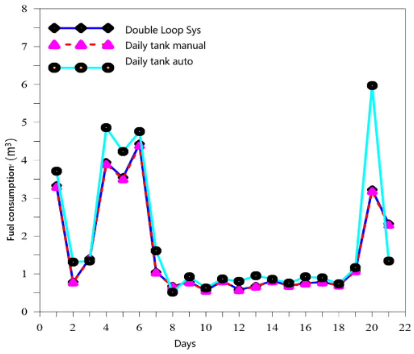
4. Analysis of real ship fuel monitoring

4.1 Sand piling vessels case

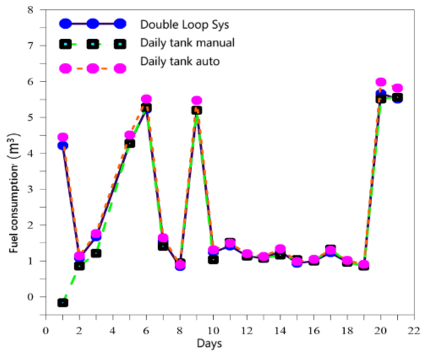
The comparison of manual measurement, daily tank monitoring system measurement, and double loop diesel engine fuel consumption monitoring system of two sand piling vessels and a pile sinking vessel are shown in Fig. 4.

The measurement of the daily tank is done by the flowmeters installed at the inlet and outlet of the daily tank, and the difference between the oil quantity measured is the fuel consumption. In the process of oil return at the inlet of the daily oil tank, there is sometimes air, which leads to the large measurement error. The total diesel fuel consumption is the fuel consumption monitored by the double loop system. If there is no air, the fuel consumption of diesel engine is equal to the fuel consumption of the daily cabinet system. We also compare the data measured with the manual measure which is calculated by tank level difference.

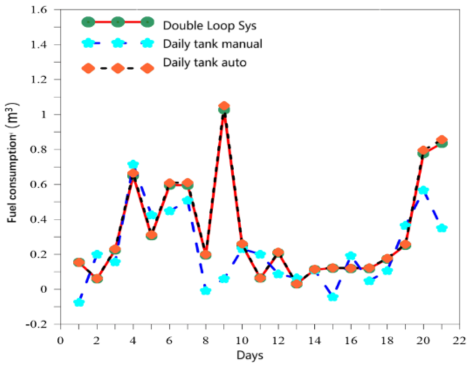
When the sand pile ship is sinking sand piles, the fuel consumption increases suddenly due to the increasing of load during the time of the on-site pile sinking operation, as shown in Fig 4(a) and Fig 4(b), in this period, the deviation between manual measuring and tank monitoring system measurement for fuel consumption increased obviously. When the ship is anchored and standing by, the ship 's fuel consumption is reduced greatly. At this time, the fuel consumption is mainly used for living, lighting, air conditioning, etc., to maintain the basic requirements for normal operation of the marine. In Fig. 4 (a) and Fig. 4(c), there is an obvious deviation between the manual measuring and the system-measured fuel consumption, and the manual measuring is affected by the pitching and rolling of the ship, which makes measurement deviation larger and affects the final measurement results. In Fig. 4 (d) shows deviation of the fuel consumption measured by double loop system, the daily tank system and the manual measurement. Through the analysis of the maximum deviation, it is found that the generator oil inlet manifold flowmeter of SANHANGSHA 7 does not meet the installation standard as required by the flowmeter description, leading to large measurement error. By using the same flowmeter as that of SANHANGSHA 3 at the time of use, the measured oil consumption deviation was controlled within 1.5%. This error meets the needs of fuel consumption monitoring.



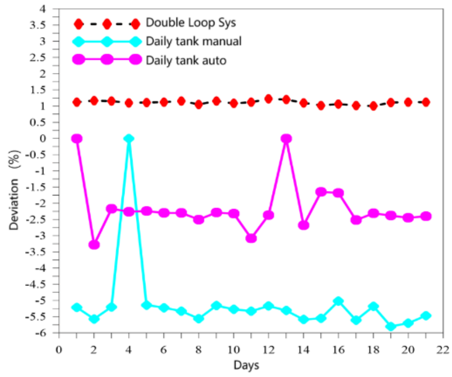
(a) Fuel consumption measurement of SANHANGSHA3



(b) Fuel consumption measurement of SANHANGSHA7



(c) Fuel consumption measurement of SANHANGZHAUNG9



(d) Fuel consumption deviation comparison

Fig. 4. Fuel consumption measurement analysis of Sand Piling Vessels

4.2 Traffic vessel case

Fig. 5 shows the statistics of 27 days oil consumption monitoring process of a traffic vessel Wenqi 89. It can be seen that the fuel consumption of main engine will increase significantly when the vessel is heavily loaded with fresh water or other materials. In general, the traffic vessel pick up and drop off personnel to and from the construction site, the fuel consumption is about 27-40L / h. Such a wide range of fuel consumption is because of the different sailing speed and sea conditions. For example, if the vessel is sailing downstream or sailing at a slow speed, the fuel consumption per hour could be much more lower. During the time when the vessel is in the period of sheltering from wind and typhoon or the project is temporarily stopped, the main engine fuel consumption is zero. Auxiliary engine fuel consumption varied between 2.5 and 7.5 L/h. During the period of day 23 to day 25, the fuel consumption of 1# auxiliary engine increased significantly, which was due to the fact that the traffic vessel was assisting the construction at the wind power site, and the auxiliary engine was supplying power to the wind turbine to carry out construction work in the wind turbine.

Fig. 6 shows the fuel consumption analysis graphs of the main engines of the 4 traffic vessels within 22 days. C&D Marine 10 had a sudden increase in fuel consumption in the 8th day, and there are generally 3 factors that caused such data changes. The first factor is that the fuel monitoring equipment was failed causing data loss of main engine fuel consumption. Secondly, the network signal is lost when the ship is traveling, which also causes the running time of the main engine is not uploaded to the management platform in time. Thirdly, part of the fuel was provided separately to the generator set for construction, resulting in the increase of fuel consumption of the main engine in a short period of time. The change of fuel consumption of the main engine of Baoheng 89 has a larger range than that of other vessels. This is due to the increase of the construction task, which leads to the increase of the vessel's load, and the fuel consumption per unit of time is obviously increased. The normal fuel consumption of other vessels is controlled within the range of 40L/h. Wenqi 89, Hai Rui Transportation & Maintenance 303 and Baoheng 89 showed zero fuel consumption of main engine, which was due to the vessels docking for repairing and maintenance or anchoring at the site for standby.

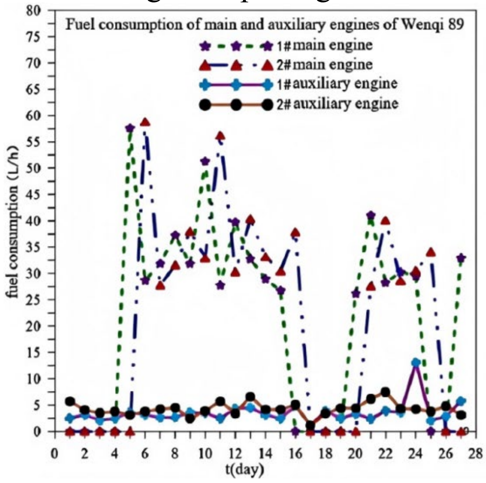


Fig. 5. Analysis diagram of the fuel consumption of Wenqi 89

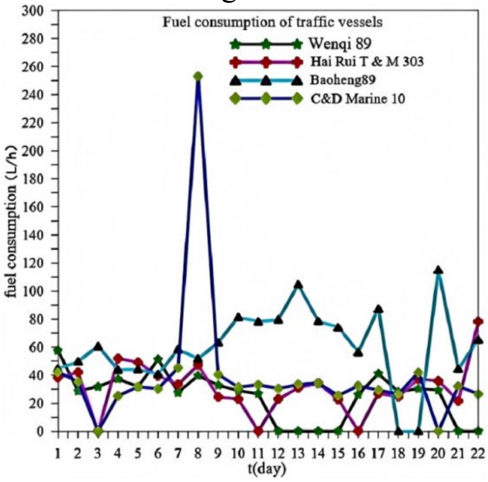


Fig. 6. Fuel consumption analysis diagram of traffic boat

4.3 Anchor boat case

Fig. 7 shows the fuel consumption monitoring of an anchor boat Fuxingtuo 5008. It can be seen that the fuel consumption of NO.2 main engine is significantly higher than that of NO.1 main engine, that could be the captain favors the use of NO.2 main engine during sailing, or the fuel consumption per kilowatt power of NO.2 engine is higher that NO.1. The second aspect, with the direction of the water flow, the ship's form direction and the direction of the water flow presents a certain angle, will lead to a certain side of the main engine oil consumption increases. The third aspect, related to the captain's habit of driving the marine. The lower fuel consumption of NO.2 auxiliary engine is mainly because it only provides the basic electricity for the ship. NO.2 auxiliary engine's fuel consumption suddenly increases because it assists the anchor boat to anchor other transportation marines.

Fig. 8 shows a comparison of main engine fuel consumption of four anchor boats. With the increasing of anchor boat main engine power, the ship's main engine oil consumption increases accordingly. The power of main engine of Heli 8 is 661KW, the power of main engine of Huarong 21 is 600KW, the larger the power, the higher of fuel consumption, the power of main engine of Fuxingtuo 5008 is 2059KW, the power of main engine of Pengrui 7 is 2206KW, as can be seen in the Fig. 8 the smaller the power of main engine, the lesser the deviation of the fuel consumption. On the third day, the fuel consumption of Fuxingtuo 5008 increased significantly, through the inspection we found that the fuel consumption is normal, but the engine fuel consumption data are partially lost, resulting in the third day of abnormal fuel consumption.

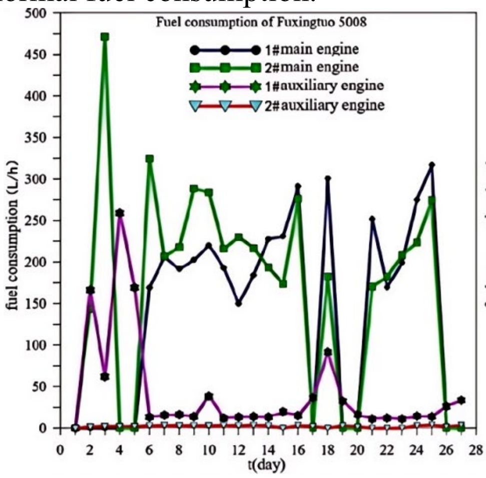


Fig. 7. Fuel consumption analysis diagram of Fuxingtuo 5008

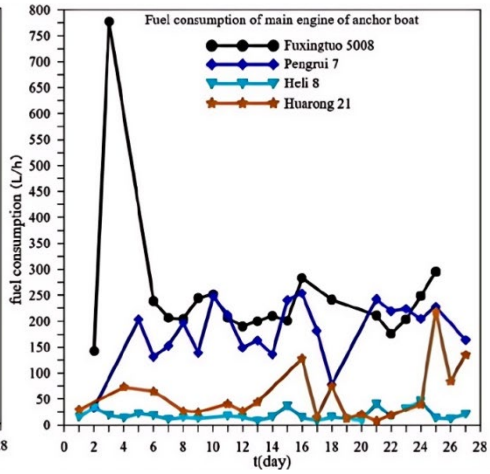


Fig. 8. Fuel consumption analysis diagram of anchor boat

5. Conclusion

This paper is based on the research and development of the fuel monitoring system, and uses the fuel monitoring system to analyze the fuel consumption of ships commonly used in the construction of offshore wind power generation, to provide certain management measures for the subsequent enterprises in the construction of offshore wind power generation, and to effectively control the cost:

(1) The oil and gas separation device is utilized to eliminate the air bubbles in the generator return oil pipeline, so that the ultrasonic flowmeter can accurately and real-time measure the generator's fuel consumption. Through mutual calibration of engine fuel consumption, daily oil cabinet fuel consumption, and comparison of fuel consumption and refueling volume in a refueling cycle, it realizes the fine management of ship's fuel, and reduces or even eliminates the phenomenon of fuel running and leaking.

(2) Through the analysis of fuel consumption of each ship, we found that the fuel consumption changes with the ship load and sailing condition, the fuel consumption is also determined by the working nature and type of the vessel.

(3) This equipment can monitor the working condition and fuel consumption of each diesel engine in real time, and combine with the operating hours of the ship's main engine, other generator sets and other oil-using equipments to measure the marine fuel consumption coefficients and the statistical analysis of the marine fuel consumption in each working condition.

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