Calculation Method of Marine Ship Fuel Consumption

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Abstract: Based on the current situation of fuel consumption management and technical measures of marine transportation ships in domestic shipping enterprises, this paper determined the calculation model of fuel consumption of marine transportation ships, and provided technical support for shipping enterprises to formulate energy consumption assessment index of single ship and realize fine management over energy consumption. It is verified by an example that the error of the calculation model is small.

1. Introduction
China is a big shipping country. By the end of 2019, it has 10,364 coastal transport ships with a net load of 70.7998 million tons, which have completed annual cargo turnover of 3.360356 trillion ton-kilometers; and it has 1,664 ocean transport ships with a net load of 55.2491 million tons, which have completed annual cargo turnover of 5.405747 trillion ton-kilometers[1]. Although there is no official water transport energy consumption statistics, if we calculate according to the unit consumption of 4.8kg standard coal per kiloton nautical mile for ocean and coastal freight enterprises under key monitoring, in 2019, marine ships fuel consumption is about 22.72 million tons of standard coal, which is relatively more. Therefore, strengthening the management of fuel consumption in marine transportation ships is of great significance for reducing greenhouse gas and pollutant emissions and protecting the environment.

For shipping enterprises, high proportion of fuel cost to total operating cost can stimulate enterprises to produce an endogenous power to save oil and reduce consumption, and to keep pursuing the fine management of fuel consumption under the condition of limited technical measures[2]. The assessment of fuel consumption of single ship is one of the important means of fine management. Because the energy efficiency of ship is affected by the main engine structure, hull structure, propeller type selection and installation angle, hull-propeller-engine matching, vessel age, route design, and other factors, the comparability between different ships is poor. Therefore, the comparison between the actual fuel consumption and the quota can better reflect the operation skills and energy-saving awareness of different steerers and maintenance managers of the same ship[3]. Based on the study of the revised national standard “Fuel oil consumption for transportation ships Part 1: Calculation method for marine ships” (GB/T 7187.1-2010), combined with the application of electric fuel injection (EFI) engine and shore-to-ship power technology, this article has studied and put forth the calculation method of fuel consumption voyage quota of marine ships in the current stage.

2. Identification of calculation methods
According to the different energy consumption equipment of ship, the fuel consumption is divided into four parts: fuel consumption of main engine (M/E), fuel consumption of auxiliary engine (A/E), fuel consumption of marine boiler and fuel oil substitution for using shore-to-ship power in port[4]. The fuel
consumption of main engine is divided into two parts according to working conditions: the fuel consumption in constant speed sailing and the fuel consumption in maneuver navigation. The fuel consumption of auxiliary engine is divided into three parts: the fuel consumption of the auxiliary engine during sailing, the fuel consumption during berthing under non-self-unloading condition, and the additional fuel oil consumption for the auxiliary engine according to the sailing state and the electric equipment. The fuel consumption calculation framework determined in this paper is shown in figure 1.

![Figure 1: Calculation Framework for Ship’s Fuel Consumption in Voyage.](image)

In this paper, the fuel consumptions of some dry bulk carriers and container ships are selected, as shown in figure 2. It can be seen from figure 2 that the proportion of fuel consumption for the main engine as the main energy consumption equipment during constant speed sailing is relatively large, which is the focus of this paper.

![Figure 2: Composition of partial ships’ fuel consumption.](image)

### 2.1. Calculation of fuel consumption for main engine

(1) The fuel consumption of main engine is calculated according to formula (1).

\[ Q_x = \sum_{i=1}^{n} (Q_{x1} + Q_{x2}) \]  

(1)

Wherein:
Q_{zi1} ——The fuel consumption of the main engine during the constant speed sailing of the ship in each segment, in the unit of toe. The calculation is carried out based on the controllable-pitch propeller ship and fixed-pitch propeller ship respectively.

Q_{zi2} ——Fuel consumption of main engine for maneuver navigation of ships in each segment, in the unit of toe.

m——The number of sailing segments for the same voyage.

(2) The fuel consumption of the main engine in each segment of the controllable-pitch propeller ship and fixed-pitch propeller ship during constant speed sailing is calculated according to formula (2) and formula (3), respectively [5].

\[ Q_{zi1} = 10^{-3} \left[ \alpha + \frac{(1-\alpha)D_1}{D_e} \right] kP_{z1}g_{ez1}t_1 \]  

(2)

Wherein:
\( \alpha \)——The influence coefficient of ship’s deadweight on fuel consumption of main engine;
\( D_1 \)——Actual deadweight of the ship, in the unit of t;
\( D_e \)——Rated deadweight of the ship, in the unit of t;
\( k \)——Conversion standard oil coefficients for various energy sources;
\( P_{z1} \)——Power under frequent running state of the main engine, in the unit of kilowatts (kW);
\( g_{ez1} \)——Fuel consumption rate under main engine frequent running state, in the unit of kg/ (kW·h);
\( t_1 \)——The constant speed sailing time of the ship, in the unit of h.

\[ Q_{zi1} = 10^{-3} \left[ \alpha + \frac{(1-\alpha)D_1}{D_e} \right] \left( \frac{n_{zdi}}{n_e} \right)^3 P_e g_{sdi}t_1 \]  

(3)

Wherein:
\( n_{zdi} \)——The set speed of the main engine, and the pre-set speed of the main engine according to the schedule, in the unit of r/min;
\( n_e \)——Rated speed of main engine, in the unit of r/min;
\( P_e \)——Rated power of main engine, in the unit of kW;
\( g_{sdi} \)——The set fuel consumption rate of main engine, in the unit of kg/kw h [kg/ (kW·h) ], which is the fuel consumption rate corresponding to the ship when the engine speed is \( n_{zdi} \), power is \( P_e (n_{zdi}/n_e)^3 \), which is determined by the power-fuel consumption rate variation characteristic curve in the ship’s main engine specification.

The range of the influence coefficient of the ship’s deadweight on the fuel consumption of the main engine is shown in Table 1, which is the ratio of the fuel consumption per hour of the main engine for ship in ballast during sailing to that of the main engine for ship in full load during sailing. The linear interpolation method is used to calculate the actual value according to the actual deadweight of the ship.

| Ship type          | Container ship | Dry bulk carrier | General cargo ship | Liquid bulk carrier | Passenger ship | Other ships |
|--------------------|----------------|------------------|--------------------|---------------------|----------------|-------------|
| \( \alpha \) value | 0.90-0.98      | 0.90-0.98        | 0.85-0.95          | 0.85-0.95           | 1.00           | 0.85-1.00   |

(3) The fuel consumption of the main engine is calculated according to formula (4) when ship is maneuvering in various sailing segments.

\[ Q_{zi2} = 10^{-3} kq_{z2}t_2 \]  

(4)

Wherein:
\( q_{z2} \)——Fuel consumption of main engine per hour when ship is in maneuver navigation, in the unit of kg/h. For ships with mechanical fuel injection(MFI) system, \( q_{z2} \) is calculated according to 38% - 44% of the fuel consumption per hour under the rated condition of the main engine; and for ships with EFI system, \( q_{z2} \) is calculated according to 28% - 34% of the hourly fuel consumption under the rated condition of the main engine.
In the process of research, considering that the fuel consumption of MFI system and EFI system is quite different in maneuver navigation, the fuel consumption statistical data on many voyages of different types of ships with different fuel injection methods are selected for analysis[6]. After verification, the main engine fuel consumption calculation coefficient $q_{zj}$ of MFI system and EFI system ship during maneuver navigation comply approximately with normal distribution, and the coefficient value range is selected according to 95% confidence interval of average value. The normal distribution Q-Q diagram and normal distribution curve generated by SPSS are shown in Fig. 3 and Fig. 4.

2.2. Calculation of fuel consumption of auxiliary engine

(1) The fuel consumption of auxiliary engine is calculated according to formula (5).

$$Q_f = \sum_{i=1}^{n} (Q_{fi1} + Q_{fi2} + Q_{fi3})$$

Wherein:
- $Q_{fi1}$ —— The fuel consumption of auxiliary engine when the ship is sailing, in the unit of toe;
- $Q_{fi2}$ —— The fuel consumption of auxiliary engine in non-self-unloading state when the ship is berthed, in the unit of toe;
- $Q_{fi3}$ —— Additional fuel oil consumption for auxiliary engine, in the unit of toe.

(2) The fuel consumption of auxiliary engine when the ship is sailing is calculated according to formula (6).

$$Q_{fi1} = 10^{-3} k q_{fi1}(t_1 + t_2)$$
Wherein:

$q_{fi1}$ —— Fuel consumption per hour of auxiliary engine during sailing, in the unit of kg/h. $q_{fi1}$ is calculated according to 62% ~ 68% of the hourly fuel consumption of an auxiliary engine under rated conditions. The determination process is the same as that for the calculation coefficient of fuel consumption of the main engine during maneuver navigation. The normal distribution Q-Q diagram and normal distribution curve are shown in Fig. 5.

\[ q_{fi2} = 10^{-3} k q_{fi2} t_0 \]  

(7)

Wherein:

$q_{fi2}$ —— Fuel consumption per hour of auxiliary engine when the ship is berthed in non-self-unloading state, in the unit of kg/h. For ships equipped with axle generators, $q_{fi2}$ is calculated as per 61% - 68% of the hourly fuel consumption of an auxiliary engine under rated conditions. As for the other ships, $q_{fi2}$ is calculated as per 47% - 54% of the hourly fuel consumption of a single auxiliary engine under rated conditions. The determination process is the same as that for the calculation coefficient of fuel consumption for main engine of maneuver navigation. The normal distribution Q-Q diagram and normal distribution curve are shown in Fig.6 and Fig.7.

t_0 —— The actual service time of auxiliary engine when the ship is berthed in non-self-unloading state, in the unit of h.
Figure 7. Normal distribution of $q_{fi2}$ in other ships.

(4) The additional fuel oil consumption for marine auxiliary engine is calculated according to formula (8).

$$Q_{fi3} = 10^{-3} k q_{fi3} t_j$$  (8)

Wherein:

$q_{fi3}$——Additional fuel consumption per hour of marine auxiliary engine, in the unit of kg/h;

$t_j$——Additional service time of marine auxiliary engine, in the unit of h.

2.3. Calculation of boiler fuel consumption

The fuel consumption of marine boiler is calculated according to formula (9).

$$Q_s = 10^{-3} \sum_{i=1}^{n} k s q_{gi} t_{gi}$$  (9)

Wherein:

$s$——The actual operation quantity of marine boilers;

$q_{gi}$——Fuel consumption per hour of marine boilers, in the unit kg/h;

$t_{gi}$——Actual service time of marine boilers, in the unit of h.

2.4. Calculation of fuel oil substitution for using shore-to-ship power

The fuel oil substitution for using shore-to-ship power is calculated according to formula (10).

$$Q_e = 10^{-3} k E$$  (10)

Wherein: $E$——Consumption of shore-to-ship power, in the unit of kWh.

3. Case Research

In this paper, the voyage fuel oil consumption of the ship is calculated by the method in this paper by taking a liquid bulk carrier as an example. The basic parameters of the ship are shown in Table 2. The sailing condition of a voyage and the actual fuel consumption are shown in Table 3.

| $D_e$ (t) | Rated operating conditions for main engine | $q_{fe}$ (kg/h) | $q_{go}$ (kg/h) | Fuel injection system of the main engine |
|----------|------------------------------------------|-----------------|-----------------|-----------------------------------------|
| 159149   | $P_e$ (kW) | $g_e$ (kgkW⁻¹h⁻¹) |                 |                                         |
|          | 16860     | 0.1675           | 236.90          | 1016 | Machinery |
Table 3. Sailing and actual fuel consumption on a particular voyage.

| Sailing segment | $D_1$ (t) | $t_1$ (h) | $t_2$ (h) | $t_0$ (h) | $t_3$ (h) | $t_{gi}$ (h) | $E$ (kWh) |
|-----------------|----------|----------|----------|----------|----------|------------|----------|
| 1               | 133855   | 342      | 27       | 43.4     | 30.5     | 30.9       | /        |
| 2               | 136147   | 144      | 4        | 78       | 42.5     | 64.2       | /        |
| 3               | 143839   | 262.5    | 7        | 137.5    | 55.25    | 53.9       | /        |

(1) The ship refers to a fixed-pitch propeller ship, the fuel consumption of the main engine is 1194.66 toe. The fuel consumption of the main engine during constant speed sailing and maneuver navigation in each segment are shown in Table 4 and 5, respectively.

Table 4. Calculation of the fuel consumption of the main engine at constant speed.

| Sailing segment | $\alpha$ | $D_1$ (t) | $D_e(t)$ | $P_e \left( \frac{\text{Rad}}{\text{Ne}} \right)^3$ (kW) | $g_{adi}$ (kg/kW•h) | $t_1$ (h) | $Q_{zi}$ (t) |
|-----------------|----------|----------|----------|------------------------------------------------|---------------------|----------|--------------|
| 1               | 0.93     | 133855   | 159149   | 8545.13                                           | 0.178               | 342      | 514.41       |
| 2               | 0.94     | 136147   | 9305.26  | 144                                               | 0.175               | 144      | 232.46       |
| 3               | 0.94     | 143839   | 8764.22  | 262.5                                             | 0.177               | 262.5    | 404.86       |

Table 5. Calculation of fuel consumption for main engine during maneuver navigation.

| Sailing segment | $q_{zi}$ (kg/h) | $t_2$ (h) | $Q_{zi}$ (t) |
|-----------------|-----------------|----------|--------------|
| 1               | 2824.05×41%     | 27       | 31.26        |
| 2               | 4               | 4        | 4.63         |
| 3               | 7               | 8.11     |              |

(2) A total of 172.29-toe fuel consumption for the ship's auxiliary engines, shown in table 6 for each segment.

Table 6. Calculation of fuel consumption for ship auxiliary engine.

| Sailing segment | $q_{ai}$ (kg/h) | $t_{i+1}$ (h) | $t_0$ (h) | $q_{ai}$ (kg/h) | $t_3$ (h) | $Q_{ai}$ (t) | $Q_{a2}$ (t) | $Q_{a3}$ (t) | $Q_i$ (t) |
|-----------------|-----------------|--------------|----------|----------------|----------|-------------|-------------|-------------|-----------|
| 1               | 236.9           | 369          | 43.4     | 186.89         | 30.5     | 56.82       | 5.24        | 5.70        | 67.76     |
| 2               | 236.9           | 148          | 78       | 115.29         | 42.5     | 22.79       | 9.42        | 4.90        | 37.11     |
| 3               | 236.9           | 269.5        | 137.5    | 168.33         | 55.25    | 41.50       | 16.61       | 9.30        | 67.41     |

(3) Fuel consumption of the ship's boiler is 237.7toe, as shown in table 7.

Table 7. Calculation of fuel consumption for marine boilers.

| Sailing segment | $q_{bo}$ (kg/h) | Actual operation quantity of boilers | $t_{gi}$ (h) | $Q_d$ (t) |
|-----------------|-----------------|--------------------------------------|---------------|-----------|
| 1               | 1016            | 2                                    | 30.9          | 62.70     |
| 2               | 1016            | 1                                    | 64.2          | 65.20     |
| 3               | 1016            | 2                                    | 53.9          | 109.50    |

(4) During berthing, the ship was not connected to shore-to-ship power, and the fuel substitution for using shore-to-ship power was zero.

To sum up, the total fuel consumption of the ship is 1605.72toe, compared with the actual fuel consumption of the ship of 1551.2toe, the error is 3.51%, which indicates that the method determined in this paper is feasible.
4. Conclusion
Based on the current situation of fuel consumption management and fleet operation for marine transportation ships of domestic shipping enterprises, in this paper, the calculation model and parameters of fuel consumption for marine transportation ships, amends the calculation method and the coefficients specified in the “Fuel oil consumption for transportation ships Part 1: Calculation method for marine ships” (GB/T 7187.1-2010) are researched, the relevant contents of EFI diesel engine and axle generator are supplemented, and the calculation method of fuel oil substitution for using shore-to-ship power is added. The calculation model is more scientific and reasonable, and the calculation results are more accurate and reliable. The method established in this paper can provide basis and technical support for shipping enterprises to formulate energy consumption assessment indicators and strengthen the supervision of energy conservation work.

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