Development of Design Support Tool for Ship Propulsion System

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1. Introduction

Authors have been developing the simulation that can estimate FOC (Fuel Oil Consumption) for the basic design of the ship [1].

The accuracy of the developed simulation had been evaluated by using the actual operation data measured in the actual sea condition [2]. As a result, it is reported that the measured value includes an error of about 4 [%] even in calm sea condition. It is pointed out that the estimated results of thermal efficiency in the engine may not be appropriate as one cause of the error. This paper proposes a novel method for estimating the thermal efficiency based on analyzing characteristics of several engines data base. The proposed method was evaluated by using a shop trial data.

2. Conventional method for estimating thermal efficiency and its problems

It is important to know the thermal efficiency of engine for calculating FOC. However, it is not always to be obtained necessary thermal efficiency data. In that case, the thermal efficiency has to be estimated. For example, assuming a condition that there is no data about engine T, and its rated output power is R_T, conventional method gives a fallowing procedure to estimate thermal efficiency. It is prepared to extract data relating to the thermal efficiency from two finished drawing books of engine S and engine U. Two reference data have to be extracted from different rated power engines. In addition, these rated powers R_S [kW] and R_U [kW] of each engine should be close to R_T [kW]. Thermal efficiencies η_S and η_U of each engine are calculated as a function of the output power x [%]. The thermal efficiency of engine tends to be high slightly as the rated power becomes larger between all output power. We assumed that the trend can be approximated as linear among engines with close rated output power. Based on this assumption, the thermal efficiency of the engine T was estimated by the following equation.

$$\eta_T = \frac{(R_S - R_T)\eta_U + (R_T - R_U)\eta_S}{R_S - R_U}$$

R_S: Rated output power of the engine S [kW]

R_T: Rated output power of the engine T which is estimated thermal efficiency [kW]

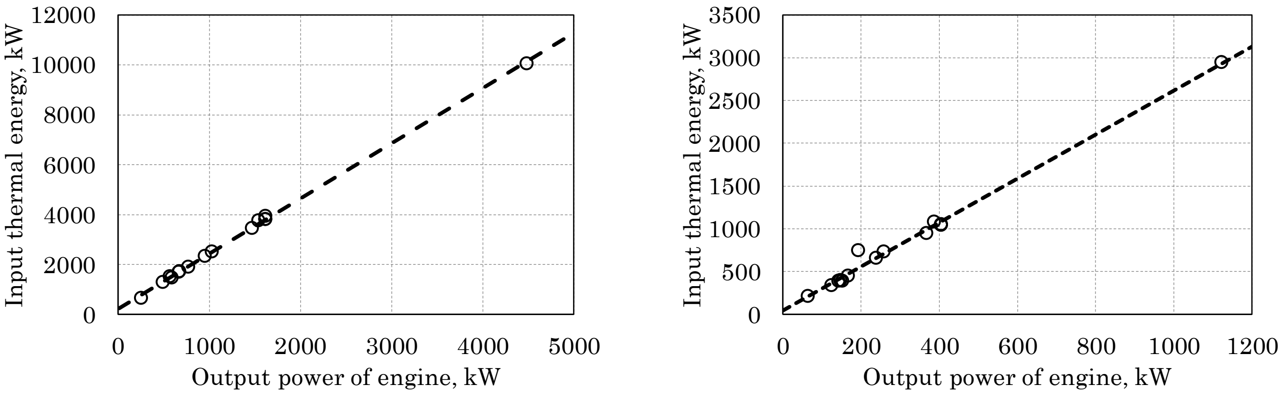
R_U: Rated output power of the engine U [kW]

η_S: Thermal efficiency when the engine S operates at output power ratio x [%]

η_T: Thermal efficiency when the engine T operates at output power ratio x [%]

η_U: Thermal efficiency when the engine U operates at output power ratio x [%]

Thermal efficiencies η_S and η_U are represented by trendline using measured values as a function of the output power ratio x [%]. However, it often does not fit measured values in the third-order trendline. On a trendline of the fourth or higher order, there are multiple poles within the output power ratio range of 25 to 100 [%]. Furthermore, the estimated trendline of thermal efficiency greatly exceeds or falls below the assumed range in the range of less than 25 [%]. Because there is no data with an output power ratio of less than 25[%] in the finished drawing book to be referenced. In addition, if derating ratio of engine S and engine U are extremely large or small, individual



(a) Each engine output 100 [%] power

(b) Each engine output 25 [%] power

Fig. 1 Input thermal energy to output power in engine

characteristics of the referenced data strongly influence the estimation result. So, for all these reasons, it is pointed out that estimating thermal efficiency of engine T may not have been sufficiently accurate.

This paper proposes a method to handle the database statistically for estimate thermal efficiency.

3. New estimating method based on engine profiles

3.1. Relationship between engine output power and input thermal energy

It is self-evident that the heat quantity inputting to engine increases as the engine output power increases. Fig. 1 shows a part of data selecting to 4-cycle variable speed engine. It shows the relationship between engine output power and input thermal energy per unit time when the output power ratio is 100 [%]. The specifications of the engines adopted in the database are within the following ranges.

- Rated output power: 257 to 4488 [kW]
- Rated engine speed: 520 to 2130 [rpm]
- Used fuel oil: A heavy oil (LHV = 42.7 [MJ/kg])

It should be noted that the trend can be approximated among linearly engines with different rated output power and rated engine speed. Fig. 1(b) shows the relationship between engine output power and input thermal energy per unit time when the output power ratio is 25 [%] from the engine database. There is a tendency to be linearly approximated in Fig. 1(b) similarly to Fig. 1(a). These trends are similar for other output power ratios. Therefore, a linear approximation expression is calculated from these data using the least squares method.

$$h_{Xm} = a_{Xm} \cdot p_{Xm} + b_{Xm} \quad \cdots (1)$$

h_{Xm}: input thermal energy at output power ratio Xm [%] [kW]

p_{Xm}: output power in which engine runs at Xm [%] load [kW]

a_{Xm}: slope of approximate expression at output power ratio Xm [%]

b_{Xm}: intercept of approximate expression at output power ratio Xm [%]

m= {1, 2, 3, 4, 5, 6}

X_1=25, X_2＝50, X_3=75, X_4=85, X_5=100, X_6=110

$$a_{Xm} = \frac{Cov(p_{Xm}, h_{Xm})}{\sigma^2_{p_{Xm}}}$$

$$b_{Xm} = \frac{1}{n}\sum_{i=1}^{n}\left(h_{Xm,i} - aXm \cdot p_{Xm,i}\right)$$

$$Cov(p_{Xm}, h_{Xm}) = \left(1 - \frac{1}{n^2}\right)\sum_{i=1}^{n}\left(p_{Xm,i} \cdot h_{Xm,i}\right)$$

$$\sigma^2_{p_{Xm}} = \frac{1}{n}\sum_{i=1}^{n}\left(p_{Xm,i} - \frac{1}{n}\sum_{i=1}^{n} p_{Xm,i}\right)^2$$

n: number of extracted data points

$Cov(p_{Xm}, h_{Xm})$: covariance of engine output power and input thermal energy [kW²]

$\sigma^2_{p_{Xm}}$: distribution of engine output power[kW²]

Table. 1 Decision coefficient for each output power ratio

Output power ratio[%]	25	50	75	85	100	110
Decision coefficient[-]	0.990	0.998	0.998	0.999	0.999	0.998

Table. 1 shows the result of evaluating the correlation between the calculated approximate line and the data in the database. It became clear that there is a high correlation at any output power ratio even though the rated output power of the engine, the rated engine speed, and the manufacturer are different. Therefore, we developed a method to estimate thermal efficiency based on these discovered profiles.

3.2. Novel estimating method of thermal efficiency

Defining the rated output power of engine T as R_T (=956 [kW]). The input thermal energy per unit time h_{T-Xm} [kW] with respect to the output power ratio Xm [%] can be expressed by the following equation.

$$h_{T-Xm} = a_{Xm} \cdot p_{T-Xm} + b_{Xm}$$
$$= a_{Xm} \cdot \frac{Xm}{100} R_T + b_{Xm} \quad \cdot\cdot\cdot (2)$$

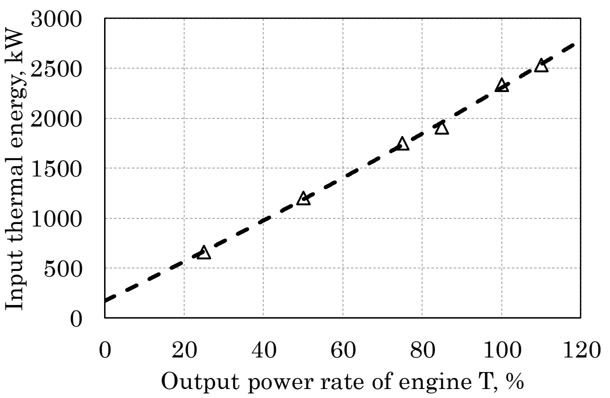


Fig. 2 Relationship between engine output power and input thermal energy for engine T

Fig. 2 shows the estimated results of relationship between the input thermal energy amount and the output power ratio Xm [%] of the engine T. We consider that the input thermal energy at each output power ratio can be approximated by a quadratic curve by using the least squares method.

$$h_T = \alpha p_T{}^2 + \beta p_T + \gamma \quad \cdot\cdot\cdot (3)$$

At this time, the square sum S of the residuals becomes as follows.

$$S = \sum_{j=1}^{m} \left(h_{T-Xj} - \alpha p_{T-Xj}^2 - \beta p_{T-Xj} - \gamma\right)^2$$

Partial differentiation of the above equation for α, β, γ gives the following.

$$\frac{\partial S}{\partial \alpha} = 2\sum_{j=1}^{m} \left(\alpha p_{T-Xj}^4 + \beta p_{T-Xj}^3 + \gamma p_{T-Xj}^2 - h_{T-Xj} p_{T-Xj}^2\right)$$

$$\frac{\partial S}{\partial \beta} = 2\sum_{j=1}^{m} \left(\alpha p_{T-Xj}^3 + \beta p_{T-Xj}^2 + \gamma p_{T-Xj} - h_{T-Xj} p_{T-Xj}\right)$$

$$\frac{\partial S}{\partial \gamma} = 2\sum_{j=1}^{m} \left(\alpha p_{T-Xj}^2 + \beta p_{T-Xj} + \gamma - h_{T-Xj}\right)$$

$$\sum_{j=1}^{m} h_{T-Xj} p_{T-Xj}^2 = \alpha \sum_{j=1}^{m} p_{T-Xj}^4 + \beta \sum_{j=1}^{m} p_{T-Xj}^3 + \gamma \sum_{j=1}^{m} p_{T-Xj}^2$$

$$\sum_{j=1}^{m} h_{T-Xj} p_{T-Xj} = \alpha \sum_{j=1}^{m} p_{T-Xj}^3 + \beta \sum_{j=1}^{m} p_{T-Xj}^2 + \gamma \sum_{j=1}^{m} p_{T-Xj}$$

$$\sum_{j=1}^{m} h_{T-Xj} = \alpha \sum_{j=1}^{m} p_{T-Xj}^2 + \beta \sum_{j=1}^{m} p_{T-Xj} + m\gamma$$

α, β, γ of the quadratic approximate expression can be obtained by substituting the value obtained by equation (2) and solving the simultaneous equations.

The correlation between the obtained quadratic approximation curve and the plot in Fig. 2 was evaluated. As a result, the coefficient of determination was 0.998. Therefore, it was confirmed that the relation between the input thermal energy amount of the engine and the engine output power can be approximated by a quadratic curve. By using the above equation, the thermal efficiency of the engine T at an arbitrary output power ratio x [%] can be calculated.

$$\eta_T = \frac{x}{100} R_T \div h_T \quad \cdots (4)$$

Using the formula (3), we can summarize it as follows.

$$\eta_T = \frac{10^2 x R_T}{\alpha x^2 R_T^2 + 10^2 \beta x R_T + 10^4 \gamma} \quad \cdots (5)$$

4. Validity of improvement proposal

In order to evaluate the accuracy of the proposed method, the estimated thermal efficiency of the engine T was compared with real data of a finished drawing book. To verify its validity, the engine data to be compared was excluded from the engine database used for estimation.

Fig. 3 shows the estimated thermal efficiency and real efficiency data provided in the finished drawing book. The rating of engine T is 956 [kW].

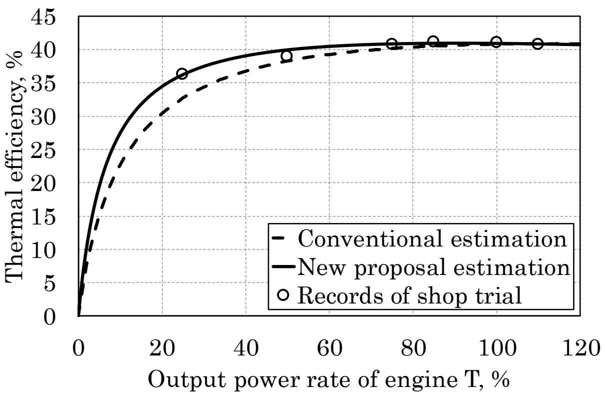


Fig. 3 Estimated thermal efficiency and real one

Table. 2 Determination factors of each estimation method

Method	Conventional	Proposed
Decision coefficient[-]	0.841	0.997

Table. 2 shows the result of evaluating the correlation between the estimated thermal efficiency and the thermal efficiency of the existing engine. With the estimated thermal efficiency by the conventional method, since the correlation of the output power ratio 25 [%] is not sufficient, the coefficient of determination is 0.841. On the other hand, the coefficient of determination is 0.997 for the estimated thermal efficiency by the proposed method, and the improvement of the estimation accuracy is confirmed.

Consequently, the estimation method can be improved by focusing on the profile relating to output power and input thermal energy in 4-cycle diesel engine.

5. Conclusion

This paper proposes a novel method for estimating the thermal efficiency based on analyzing characteristics of several engines data base in the simulation. In proposed method, it is possible to estimate the thermal efficiency of an unknown engine by using all the data described in finished drawing books. In the future, it is necessary to increase the number of samples of the database and increase its relevance.

References

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(2) Taisuke Inoue, Hiroyasu Kifune, Ken Katsumi, Yousuke Kitano," Evaluating Simulation of Fuel Oil Consumption by Using Measured Data in Electric Propulsion Ship", Proc. of 87th JIME Conference, pp. 153-154, 2017