Proceedings of the
International Symposium on Marine Engineering
(ISME) September 15-19, 2014, Harbin, China
Summary or Paper-ISMExxx

A study on simulations of fuel consumption in hybrid propulsion system for tugboat

Takaaki Nishio*, **Hiroyasu Kifune***

*Dept. of Marine system engineering, Tokyo University of Marine Science and Technology
2-1-6, Koto-ku, Tokyo, Japan

ABSTRACT This study aims at saving fuel consumption in a tugboat to propose on a hybrid propulsion system. The hybrid propulsion system is combined a main shaft with an electric system by using electric motors and power converters. The fuel consumption model was developed to find out advantages and disadvantages of the hybrid propulsion system. This fuel consumption model consists of efficiency evaluation models including main engine, motor generator, and power converter. Efficiency evaluation models estimate on each efficiency value based on actual mathematical model, respectively. The fuel consumption both new hybrid and conventional tugboat can be calculated by using the fuel consumption model. In this paper the fuel saving effects of the hybrid propulsion system are discussed on the basis of these calculation results.

Keywords: Tugboat, Hybrid propulsion system

1. Introduction

Tugboat has two or three huge engines to push and pull large vessels in harbor. Although a hall is not so big, it would be necessary that a propulsion system of tugboat meets the exhaust gas emission control in the same way of the large vessel. Some technical developments have been advanced to reduce the exhaust gas, especially NOx, SOx and PM. One of new challenges for reducing the harmful gas is utilization of gas fuel engine.[(1)-(3)] Another approach is a hybrid propulsion system. There are several tugboats equipped with operating on service in the globe.[(4)-(7)]

Propulsion system configuration in a conventional tugboat is that a main engine (M/E) and a diesel generator (D/G) system are set in independent (Fig.1). On the other hand, the most hybrid propulsion system has some electric power converters, electric motors and large capacity batteries. Their systems are realized to bring in high efficiency, save fuel consumption and reduce exhaust gas. However, there is some disadvantage that a building cost becomes high as a rechargeable battery is expensive.

Hence, this study proposes a hybrid propulsion system without using the rechargeable battery (Fig.2).[(8)] A proposed system can save its initial cost compared to the hybrid system with large capacity batteries.

This study aims at saving fuel consumption in the hybrid propulsion system. It is necessary to compare amounts of fuel consumption in a conventional propulsion system with a proposed one. A fuel consumption model is proposed to simulate the fuel consumption in the conventional system and the proposed one. In this paper, a fuel consumption characteristic is evaluated by using this model.

2. Configuration of proposed hybrid system

Fig.2 shows a proposed hybrid tugboat system. Main engines and generators are connected with motor generators (M/G) and electric power converters (PC1, PC2, and PC3). In this proposed hybrid tugboat system, the motor generator is connected in series with an intermediate shaft which links the main engine to propeller. Therefore, the main engine can be assisted by the motor generator when it is needed. On the other hand, electric power is also supplied from the main shaft through the motor generator. A pure electrical propulsion mode is also possible.

The electric power converter enables to convert the power in a bi-directional way. And it is possible that one main engine drives both side propellers by using the motor generators as a shaft generator and a driving motor.

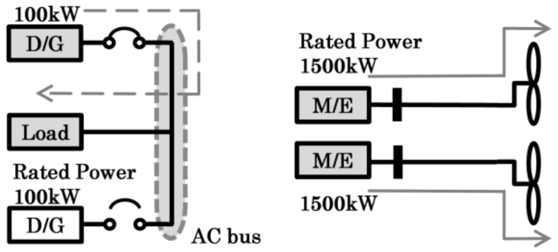

Fig1: Conventional propulsion system
and an energy flow example

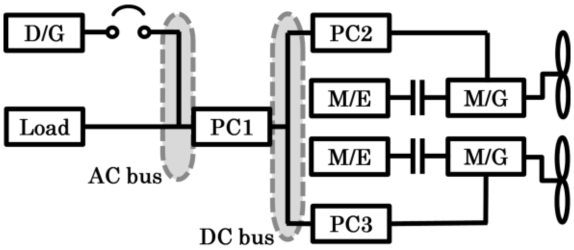

Fig2: Proposed hybrid tugboat system

3. Fuel consumption model

Fuel consumption model can be calculated amounts of the fuel consumption of a tugboat propulsion system. To calculate amounts of fuel consumption, an efficiency of apparatus is required respectively for configuring the fuel consumption model. However, the efficiency data of main engine, diesel generator, motor generator and electric power converter changes by their rated and the load factor respectively. It comes to be necessary to estimate the thermal efficiency and electric conversion efficiency according to different load factor and their rating. Therefore, it has to be cleared the relationship of the efficiency, the load factor and its rating. The methods for estimating efficiency of respective apparatus are discussed as follows.

4. Estimating efficiency method

4.1 Efficiency of main engine, diesel generator and motor generator

Efficiency of the main engine, diesel generator and motor generator are different depending on respective rated power and their load factor. In this research, apparatus efficiency is estimated by actual data from several completion drawing books and open data from several each supplier respectively.

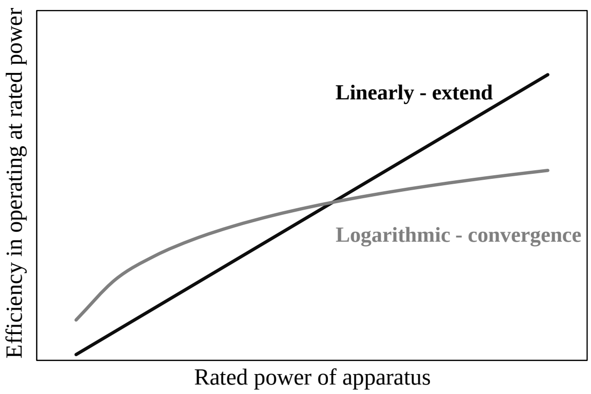

Fig.3 Relation of rating apparatus size and its efficiency

As long as several data is investigated, the relations between the apparatus efficiency and their rating are classified into two (see Fig.3). One is a linearly-extended trend of efficiency and its rating while the other is a logarithmic-convergence trend of efficiency and its rating.

The higher rating, the higher efficiency tends to be achieved when the apparatus operates in rated power.

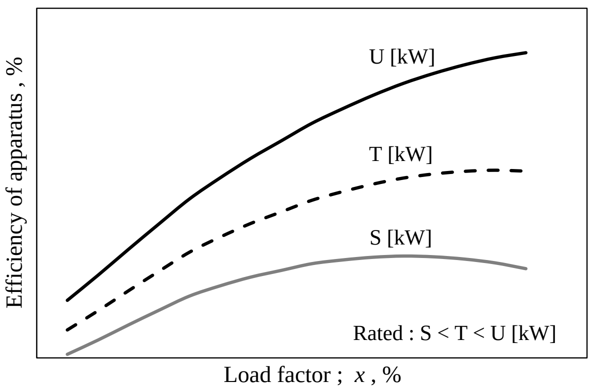

Fig.4 Relation of load rate and its efficiency

After the rated value of apparatus was given, the relation between a load factor and its efficiency were investigated. Regardless of the rating of apparatus, as shown in Fig.4, it becomes clear that the efficiency tends to be low when the load factor is low. Based on their relation between the rating and load factor, the efficiency is estimated in various conditions. For instance, the efficiency characteristic curve of rated S and U is defined as following.

$$\eta_{\mathrm{s}} = f_{(x)} \,, \eta_{\mathrm{u}} = g_{(x)} \qquad (1)$$

where, *x* is a load factor of apparatus.

If an efficiency characteristic curve is a linearly-extend type, the efficiency of apparatus T would be estimated only when a load factor is *x*.

$$\eta_{\mathrm{T}} = \frac{(U-T)f_{(x)}+(T-S)g_{(x)}}{U-S} \qquad (2)$$

On the other hands, if an efficiency characteristic curve is a logarithmically type, η_{T} is defined.

$$\eta_{\mathrm{T}} = \frac{ln\frac{U}{T}f_{(x)}+ln\frac{T}{S}f_{(x)}}{ln\frac{U}{S}} \qquad (3)$$

4.2 Electric power converter

A power electronics simulation is implemented to estimate an efficiency of the power converters.

Electric power converters (PC1, PC2 and PC3) consist of several block converters. The number of the block in each power converter should be designed appropriately depending on maximum electric power. After it is designed, the number of operating blocks is determined depending on the demanded electric power. The main circuit topology of the block converter is a full-bridge type circuit using 6 IGBTs as main switching devices.

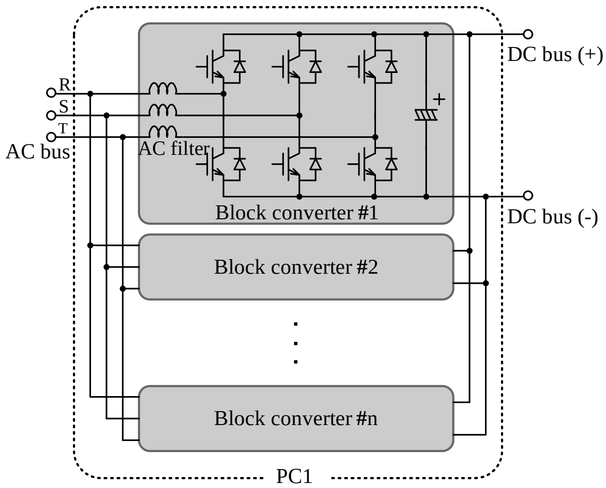

Fig.5 Main circuit of PC1

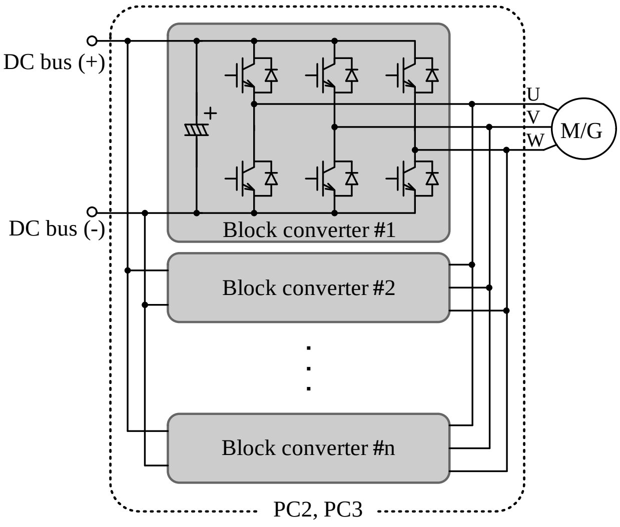

Fig.6 Main circuit of PC2 and PC3

Every power converter operates under PFC (Power Factor Correction) scheme when the 3 phase AC power is converted into DC power in order to reduce THD (Total Harmonic Distortion). The power converter also operates under PWM (Pulse Width Modulation) scheme when the DC power is converted into 3 phase AC power in order to make the current sinusoidal waveform. In addition to that, AC bus voltage is determined 440V and DC bus voltage is designed to 690V

4.2.1 PC1 efficiency estimation

Estimating an electric conversion efficiency of PC1, the electric power loss is calculated by using the power electronics simulation. The simulation condition is shown in Table 1.

Table.1 Simulation condition of PC1

Item	Value	Unit
Rated Voltage of IGBT	1200	V
Rated Current of IGBT	600	A
AC Bus Power Factor	80	%
Switching Frequency	5	kHz
Input / Output Frequency	60	Hz
DC Bus Voltage	690	V
AC Bus Voltage	440	V

By implementing the simulation, the power loss on each IGBT module; $Loss_{\mathrm{IGBT}}$ the conduction loss of in the main circuit; $Loss_{\mathrm{circuit}}$, and the necessary power for cooling IGBTs; P_{Cooling} are calculated. Therefore, the efficiency of PC1 is defined as follows.

$$\eta_{\mathrm{PC1}} = \frac{P_{\mathrm{in}} - (Loss_{\mathrm{IGBT}} \times 6) - Loss_{\mathrm{circuit}} - P_{\mathrm{Cooling}}}{P_{\mathrm{in}}} \qquad (4)$$

where P_{in} is an input power to PC1.

Fig.7 shows a relation between the PC1 electric power conversion efficiency and an input/output current. The numbers of operating blocks are altered by demanded conversion power.

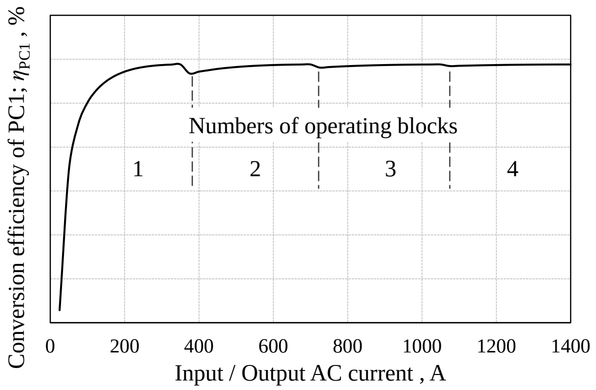

Fig.7 Relation of PC1's efficiency and Input / Output AC current

The main circuit of each blocks are designed that IGBTs are used in de-rating as 80% of maximum rating in current. Therefore, an input/output current per block is set to 340[A]. If an input/output current is more than 340[A] per block, several converters have to be operated in parallel.

4.2.2 Efficiency PC2 and PC3 estimation

In a similar way of PC1, efficiency of PC2 and PC3 are calculated by using the power electronics simulation. The simulation condition is shown in Table 2.

Table.2 Simulation condition of PC2 and PC3

Item	Value	Unit
Rated Voltage of IGBT	1200	V
Rated Current of IGBT	600	A
Power Factor of M/G	95	%
Switching Frequency	2.5	kHz
DC Bus Voltage	690	V

By implementing the simulation, the power loss on each IGBT module, the conduction loss of main circuit and the necessary power for cooling IGBTs are calculated. Therefore, the efficiency of PC2 and PC3 is defined as follows.

$$\eta_{\mathrm{PC2,PC3}} = \frac{P_{\mathrm{in}} - (Loss_{\mathrm{IGBT}} \times 6) - Loss_{\mathrm{Conduction}} - P_{\mathrm{Cooling}}}{P_{in}} \qquad (5)$$

where P_{in} is an input power to PC2 and PC3.

The electric power conversion efficiency of PC2 and PC3 is altered not only an input/output AC current but also AC voltage changed by main shaft power and shaft speed. Hence, the efficiency map is made to figure out the characteristics of electric conversion efficiency in PC2 and PC3 (see Fig.8). Fig.8 shows a case that PC2 and PC3 are consisted of four block converters. Efficiency tends to be high when the terminal voltage of M/G is high because of the saturation characteristic of IGBT device.

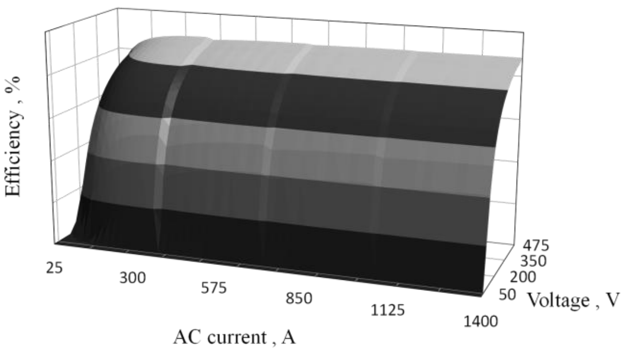

Fig.8 Conversion efficiency of PC2 and PC3

5. Classification of tugboat operation pattern

Fig.9 shows a sample of measured value on main engine’s load factor data in a real tugboat.

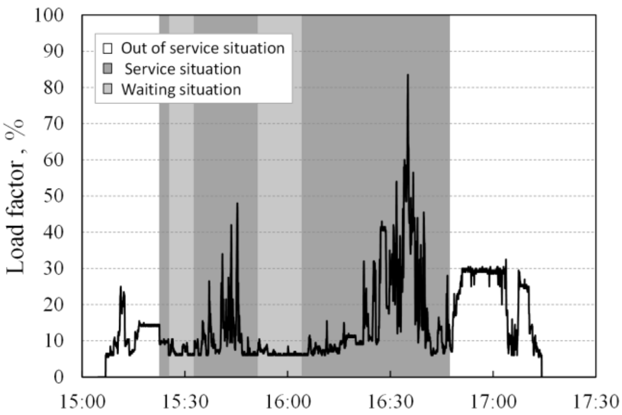

Fig.9 Sample of measured total load factor of both side main engines

It is clear that the main engine’s load factor fluctuates frequently comparing a tugboat with a general cargo ship. The duration time that high propulsion power is demanded is quite short. On the other hand, the low load time is long. The idling time is especially long when the tugboat is waiting till it starts on service for a large vessel.

Taking advantage of this characteristic, an operation of tugboat in a port is classified into three situations. One is service situation, the second is waiting situation and the last is out of service situation.

5.1 Service situation

The service situation is defined as that the tugboat supports to berth a large vessel safety. Therefore, tugboat’s demanded propulsion power changes widely from low to high depending on its working condition.

5.2 Waiting situation

Under the waiting situation, the tugboat is idling until service starts. In the conventional tugboat, the main engine’s power is used only to keep the tugboat’s position. Hence, the required propulsion power is very low.

5.3 Out of service situation

Out of service situation is defined as that the tugboat goes between its base and work place in a harbor. Sometimes the tugboat might be required to go at a regulation speed in a harbor. Therefore, tugboat’s propulsion power changes from low to middle.

Fig.9 shows clearly that demanded high power duration is short. Even in the service situation, the average load factor of the main engine rarely exceeds 50%. Therefore the load factor is also low in the waiting situation and the out of situation. In general, the low load condition results in low efficiency. The proposed propulsion system can select a suitable operation mode in order to improve the efficiency for these situations. It is reasonable that total numbers of operating main engine and generator are reduced when the demanded power is small. In this way, the load factor per one prime mover becomes high and total efficiency of the propulsion system can be improved. In this study, several modes are defined as total numbers of operated main engine and generator. A characteristic of each mode had been calculated to select a suitable mode for these three situations. In chapter 6, a characteristic of two modes is described as samples. One is Mode A that two main engines and one diesel generator are running (refer to Fig.10). Another one is Mode B that one main engine and one diesel generator are running (refer to Fig.11).

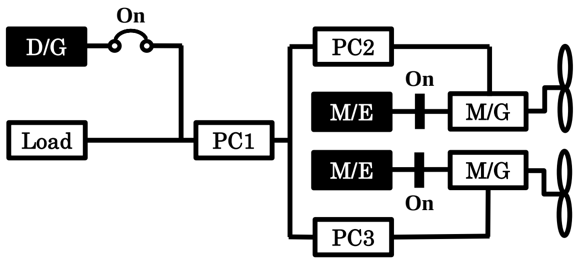

Fig.10 System state of Mode A

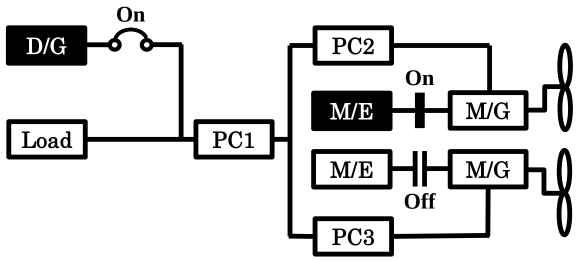

Fig.11 System state of Mode B

6. Simulation result

The fuel consumption simulation was implemented in various conditions. Table.3 shows a sample of simulation condition. The main engines ratings are set to 1,350kW each, and the diesel generator rating is set to 300kW in hybrid system. In same manner, the fuel consumption in the conventional system was calculated in order to compare to the hybrid system. The simulation condition is indicated in Table.4. The main engine rating is set to 1,500kW based on general rating of tugboat in Japan.

Table.3 Simulation condition of proposed system

Item	Rating	Number
Main Engine	1,350 kW	2 equiped
Diesel Generator	300 kW	1 equiped
Motor Generator	860kVA	2 equiped
Power converter 1	270kVA	2 block
Power converter 2	880kVA	4 block
Power converter 3	880kVA	4 block

Table.4 Simulation condition of conventional system

Item	Rating	Number
Main Engine	1,500 kW	2 equiped
Diesel Generator	100 kW	1 equiped

Fig.12 shows a simulation result of fuel consumption characteristic in Mode A and Mode B.

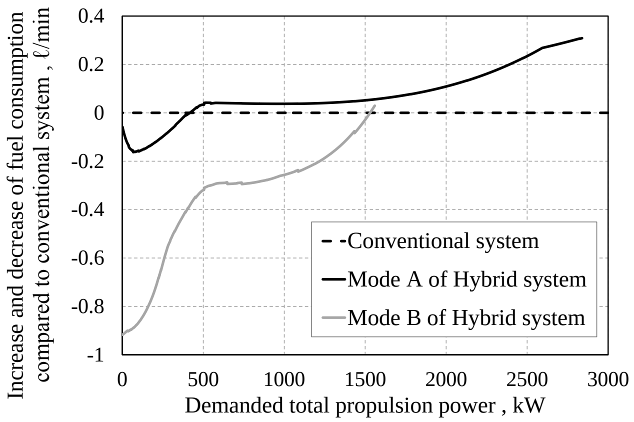

Fig.12 Fuel consumption characteristic

The vertical axis indicates the increase and decrease of fuel consumption compared with the proposed hybrid system to the conventional system. The horizontal axis indicates the total demanded output power of starboard and port side.

In Mode B, the load factor of one main engine becomes high by stopping another one. In this mode, the fuel consumption can be reduced comparing to conventional system in a range of below 1,550kW. On the other hand, this mode can output around 1,550kW maximum because one main engine stops. Therefore, this mode cannot be selected in the service situation which is required to output high power. However, this mode can be selected the out of service situation and the waiting situation which is not required to output high power for saving fuel.

In Mode A, two main engines and one generator are operated. Output power can be achieved around 2,850kW maximum. This mode can be selected in the service situation required high output power. However, the fuel consumption tends to be increased when the total power of the conventional system is demanded over 400kW.

Even in the range under 400kW, the efficiency is slightly improved comparing to the conventional system. It is considered that the load factor of the main engine becomes slightly high because its rating is smaller than the conventional system (refer to Table 3 and Table 4). Fig.9 shows clearly that the duration of high load factor is extremely short in an actual operation of tugboat. Therefore, it is possible that the fuel consumption is reduced by selecting appropriate mode in the proposed hybrid propulsion system.

References

(1) Mikael Wideskog, "Introducing the world's Largest gas engine", Proc. of Wartsila teqnical journal, (2011), pp.14-20

(2) Noel Dunstan, Oskar Levander, "LNG-fuelled hybrid tug concept" , Proc. of The 20th International Tug & Salvage Convention and Exhibition in Singapore (2008),pp.157-162

(3) "Green tug technology heralds bold new era", International Tug & OSV (March/April 2014),pp.70

(4) Gary Faber, Jason Aspin, "The Foss Hybrid Tug: From Innovation to Implementation" , Proc. of The 20th International Tug & Salvage Convention and Exhibition in Singapore (2008), pp.149-156

(5) Susan Hayman, Elizabeth Reynolds Boyd, "The Foss Hybrid Tug: The Journey to the Future" , Proc. of The 21st International Tug & Salvage Convention and Exhibition in Canada (2010), pp.155-158

(6) Jason Aspin, Aspin Kemp & Associates, "The Hybrid Tug Reality – The Business Case for Green Technology in the Tugboat Industry", Proc. of Tugnology in Amsterdam (2009)

(7) Paul Jamer, John Eldridge, Aspin Kemp & Associates, Canada, "Conversion of Kotug's RT Adriaan to become Europe's First Hybrid Tugboat" , Proc. of The 22nd International Tug & Salvage Convention and Exhibition in Spain (2012), pp.209-223

(8) Hiroyasu Kifune, Takaaki Nishio, "A study on hybrid propulsion system without battery for tugboat", Proc. of International Symposium on Marine Engineering & Technology 2013 in Busan (2013), pp.193-196