Energy consumption reduction by battery-connected power management systems of ships under various operating modes

Jin-Seok Oh[†] ・ Young-Min Kang[1] ・ Hun-Seok Lee[2]

Abstract: In recent times, there have been a number of studies on reduction in energy consumption in ships. As part of those studies, research to reduce the energy usage of generators and the batteries are underway. In this study, an energy saving method is suggested by comparing a battery-powered ship with an existing ship. For this, we categorized the ship 's operations into different modes and calculated the ratio of the ship's energy consumption for different operation modes for one year. In addition, the average and maximum values of power consumption in each operation mode were obtained and modified to fit the implemented simulator. The experiment was carried out according to the operation mode through the simulator. We calculated the fuel consumption according to the operating mode using the specific fuel consumption (SFC) curve and the engine load obtained from the experiment. The energy saved is calculated by multiplying fuel consumption and operating rate.

Keywords: Battery connected power management system, Energy saving, operating mode

1. Introduction

In recent times, there have been many studies on the reduction of energy consumption in ships. In particular, the international maritime organization (IMO) mandated the ship energy efficiency management plan (SEEMP) in 2013. As part of those studies, research to reduce energy consumption when powered using the generator and battery are underway **[1]**. If the ship uses a hybrid system including batteries, energy consumption and CO_2 emission can be reduced in various ways. Because the generator operates at a high load owing to the battery, a hybrid system can reduce specific fuel consumption and incomplete combustion. In addition, this system can be used to reduce the capacity and number of generators. This study calculates the energy savings by comparing an existing ship and battery-powered ship.

2. Ship operation and power status

A ship has several operating modes, such as voyage, arrival, departure, port, unloading, drifting, and anchoring. The operating modes differ depending on the type of the ship. In this paper, we analyze select vessel operating modes (voyage, maneuvering, and port) to propose generally applicable power systems.

The load usage is different depending on the mode of operation of the ship as shown in **Table 1.**

Table 1: Load usage of general ships

Mode	Using loads
Voyage	- Sailing, communication equipment - Accommodation equipment - Ancillary equipment (fresh water generator, cooling System, HVACS, etc.)
Port	- Accommodation equipment - Heater
Maneuvering	- Sailing, communication equipment - Accommodation equipment - Ancillary equipment (fresh water generator, cooling System, HVACS, etc.) -Bow thruster

There are many loads while the ship is under the modes of maneuvering, voyage, and port. **Table 2** shows the operating mode rate and power load of the container vessel. The rate of the operating mode was calculated for one year.

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Table 2: Ship operation characteristics

Ship Types	Mode	Rate	Using power
4600TEU Container (HYUNDAI GOODWILL etc.)	Voyage	77 %	1,000~1,250 kW
	Port	12 %	800~950 kW
	Maneu.	7 %	2,100~3,350 kW
	Etc.	4 %	-
8,600TEU Container (HYUNDAI COURAGE etc.)	Voyage	68 %	1,250~1,750 kW
	Port	23 %	1,000~1,250 kW
	Maneu.	6 %	3,500~5,650 kW
	Etc.	3 %	-

Other modes can be broadly placed under the above-mentioned three modes. Based on **Table 2**, the operating mode rate of general container ships is shown **Figure 1**.
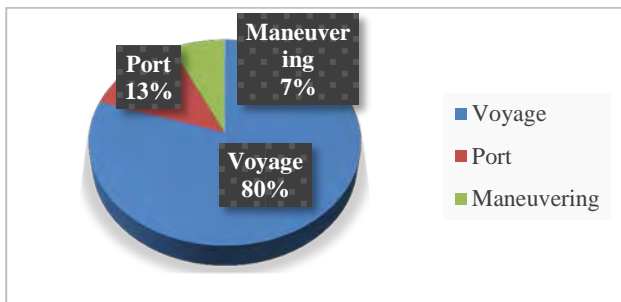

Figure 1: Operating mode rate of general container ships

The capacity of one generator is assumed to be 1700 kW at 4600 TEU and 3000 kW at 8600 TEU. Based on the power usage obtained in Table 2, the rate of electric loads and the rated power for one generator for the operating modes was calculated, shown in **Figure 2**.
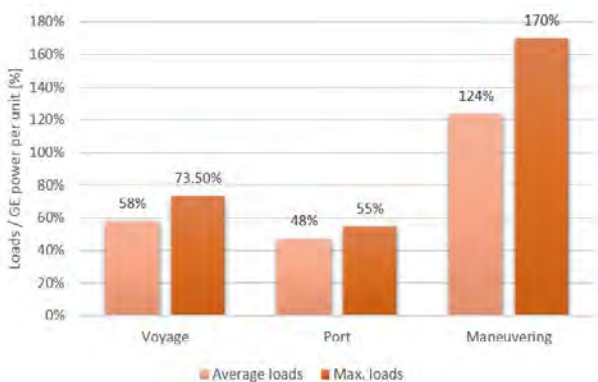

Figure 2: Electric loads/GE rated power by operating modes

Four generators are installed in all the surveyed ships. Up to three generators operate in the ship, except for spare generators, for which generally one or two units are operated. In the case of

a maximum load at the maneuvering mode, it is set slightly lower considering the number of generators in the simulator below. Using **Figure 1** and **Figure 2**, the electric power use status of a typical container ship can be assumed.

3. Battery-connected power management system

Power management system (PMS) on a ship is a system that manages generators and loads for a stable power supply of the ship. This system has functions such as the management of generator operation, load control between generators, synchronization control, non-critical load cut-off, and heavy load control. The battery connection power management system includes the above functions and adds an algorithm for battery management and energy efficiency through charging and discharging. The capacity of the generator in the vessel must be capable of supplying electric power in a stable manner [2]. When choosing a generator, the maximum load is taken into consideration, but a low load is used during the voyage, which takes up most of the operation of the ship. In addition, such low-load operation can degrade power generation efficiency and adversely affect generator life because of low temperature corrosion [3].

To know the power generation efficiency of the generator, specific fuel consumption (SFC) is used. SFC is defined as follows.

$$SFC = \frac{m}{p_b} \tag{1}$$

Here, m [kg/h] is the fuel consumption and P_b [kW] is the brake power of the engine. SFC [kg/kWh] is fuel consumption per 1 kWh. If the SFC is high, when it produces the same power, the fuel consumption too is high. **Figure 3** shows the SFC curve of the MAN V28 / 33D diesel.
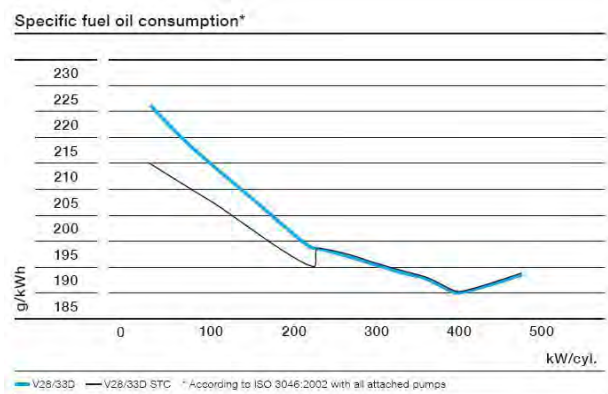

Figure 3: SFC curve of diesel engine MAN V28/33D

According to **Figure 3**, the overall SFC decreases with an increase in the generator output, and shows a minimum SFC in the load of approximately 85%. In other words, as the load increases to about 85%, the fuel efficiency increases **[4]**. Battery-connected power management systems utilize the battery and increase the power efficiency by operating at a higher average load **[5]**. In this paper, the integrated controller of the battery-connected power management system is referred to as the load control system (LCS) controller. The LCS controller monitors and controls the status of the generator and the battery via the PMS and the battery management system (BMS). Such a system is referred to as LCS. The LCS configuration diagram is shown in **Figure 4**.
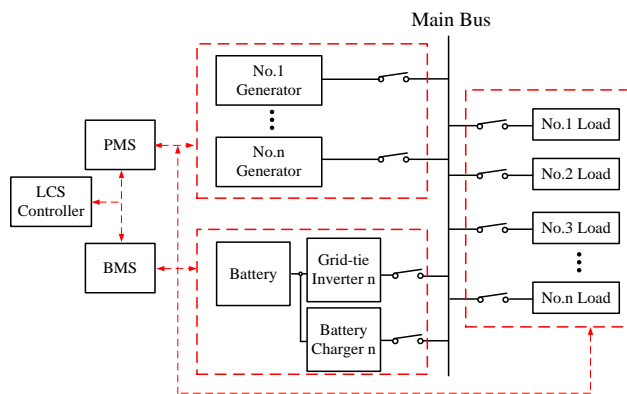

Figure 4: LCS configuration

In order to increase the total power generation efficiency using the LCS, the generator charges the battery to enable operation at 85%. This ensures that generators are not over-driving and have a high efficiency when in a low-load state. When a high load of the generator requires parallel operation, the battery discharges and supplies the power to the bus line, minimizing the low-load running time in an initial parallel operation.

When the battery is mounted on a ship, the battery should meet the IEC 62133 standard **[6]**. In addition, large capacity batteries can cause harmful or explosive gases. Therefore, the places where large capacity batteries are installed in ships should be isolated to explosion-proof areas to prevent explosion **[7]**. Location selection should be discussed in the case of future ship applications because there is a great difference depending on the type of ship, battery type, and installation capacity. Because of these problems, this system is difficult to apply to vessels in operation and should be considered during the designing of the vessel.

4. LCS simulator

We developed a simulator similar to the on-board power environment to test the battery-connected power management system. The LCS simulator tests the operation of the LCS by generating an output power of 220 V / 60 Hz / 2 P using two generator units and applying a constructed on-board load. The wiring diagram of the LCS simulator is shown in **Figure 5**.
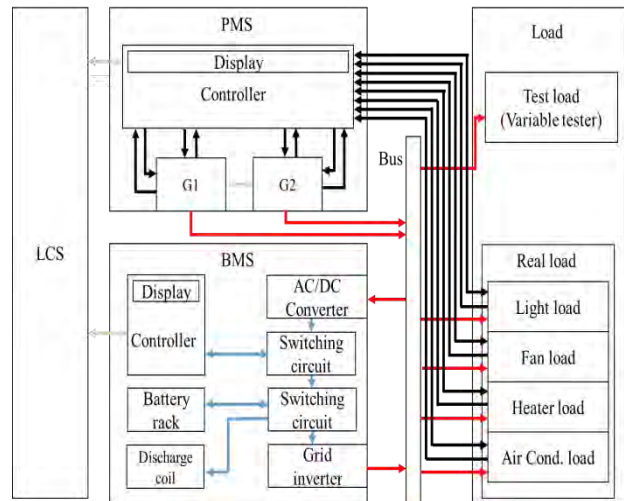

Figure 5: Connection wiring diagram of the LCS simulator

The generator supplies power to a load via a magnetic contactor of the front of each load. The generator is configured to enable the phase-lock between different generators for parallel operation. The parallel operation and battery discharge are controlled by the LCS. Load power switches are controlled by PMS. Specifications of the simulator are shown in **Table 3**.

Table 3: Equipment specifications of the LCS simulator

Equipment	Detail
Generator	220V 3kVA * 2
Battery	12V 65AH * 12
Electric loads	Real load Test load(AC load tester)
Power management system	Generator start/stop control Parallel operation
Battery management system	Charge, discharge control SOC calculate
Load control system	Integrate control

The generator used is the EU30 model manufactured by Honda and the batteries are lead acid batteries. LCS is developed as LabVEIW based on laptop, PMS is developed as PLC of LS Industrial, and BMS is developed as its own board. The photograph of generation parts and panels is shown in **Figure 6**.

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Figure 6: Photograph of generation parts and panels

Figure 7: Photograph of Real loads

The electric loads consist of the real load and test load; real load is the equipment to reflect the characteristics of each device. **Table 4** shows the constructed electric loads in the LCS simulator.

Table 4: Electric loads configuration in the LCS simulator

No.	Loads	Power	Classification
1	No.1 real load	57 W	Normal load
2	No.2 real load	40 W	Normal load
3	No.3 real load	765 W	Heavy load
4	No.4 real load	1,262 W	Heavy load
5	No.1 test load	1,000 W	Normal load
6	No.2 test load	300 W	Normal load
7	No.3 test load	300 W	Normal load
8	No.4 test load	400 W	Normal load
9	No.5 test load	0~1,000 W	Normal load

The test load is divided programmatically using the AC load test. The real loads are composed of electric lamp, electric fan, heater, and air conditioner. Real load pictures are shown in **Figure 7**.

Electric loads are virtually divided into typical loads and heavy loads. Heavy load operations are used by a heavy load control algorithm. Real load No. 3 and 4 and test load No. 1 and 5 can take up high loads above 700 W. Test load No. 1 and 5 are set to typical loads for the test, while real loads No. 3 and 4 are set to heavy load.

5. Experiment

Experiments applying the LCS were conducted to evaluate the energy savings. The performance of the ship load was divided by the average load and max load as shown in **Figure 2**. The generator has a capacity of 3 kVA in the LCS simulator. The electric load analysis is shown **Table 5**.

Table 5: Loads by operating modes in the LCS simulator

Mode	Average load	Max load
Voyage	1740 W	2205 W
Port	1425 W	1650 W
Maneuvering	3720 W	5100 W

The experiments were performed for 10 minutes for each mode as shown in **Figure 8**.
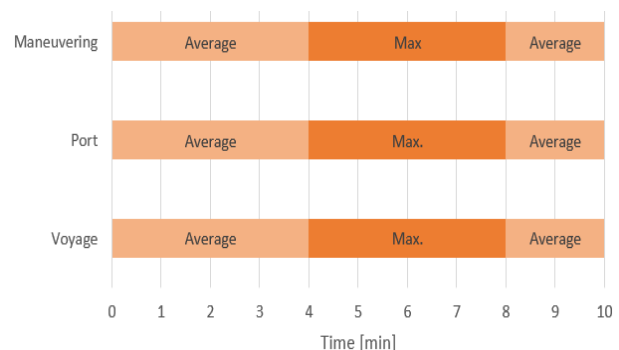

Figure 8: Electric loads test according to test time

Based on this, the performance of the LCS vessel and the ordinary vessel are analyzed. All batteries are fully charged and are used as needed by the LCS.

In the ordinary ship voyage mode, only one generator is used. In the LCS vessel, one generator is operated with low load, such that the remaining power is charged to the battery. **Figure 9** and **Figure 10** show power usage in the ordinary ship and LCS ship during the voyage mode.
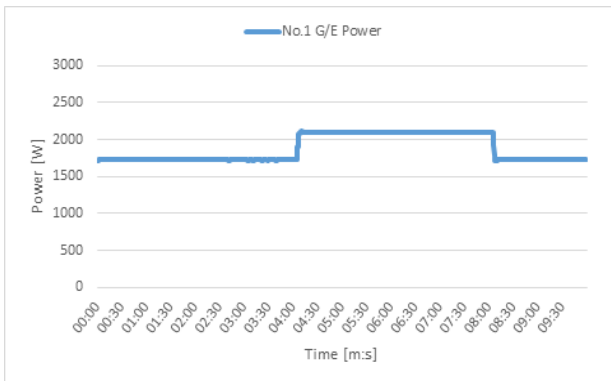

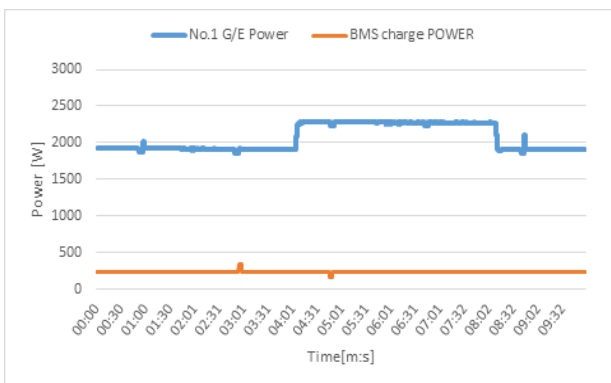**Figure 9:** Power graph of the ordinary ship voyage mode

Figure 10: Power graph of LCS ship voyage mode

The power usage in the port mode appears to be similar to that in the voyage mode. **Figure 11** and **Figure 12** show power usage in an ordinary ship and LCS ship during the port mode.
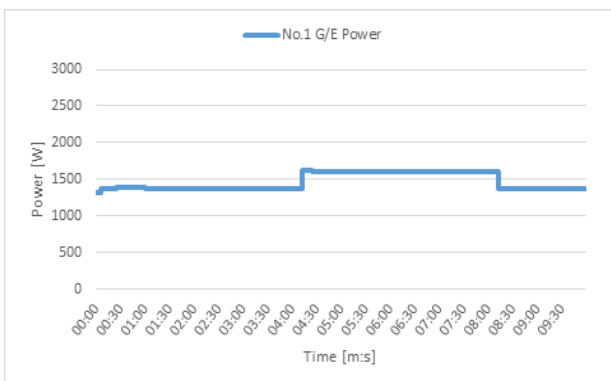

Figure 11: Power graph of ordinary ship port mode
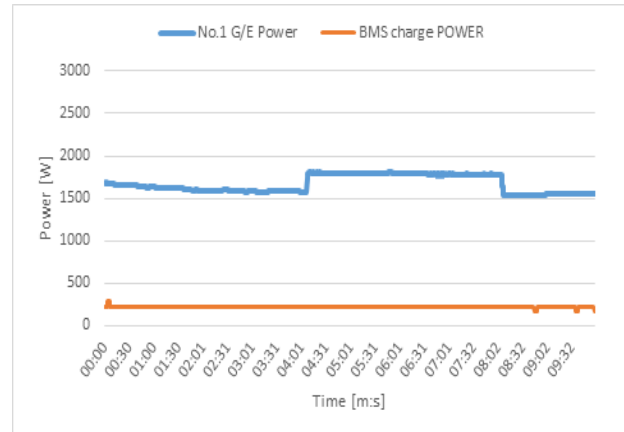

Figure 12: Power graph of the LCS ship port mode

Even if the battery is charged under the maximum load condition of the voyage and port modes, the generator is not charged to 85% (2550 W) load, it is continuously charged. Therefore, the power consumption of the LCS vessel is higher than the ordinary vessel. **Figure 13** shows the power graph of the ordinary ship maneuvering mode.
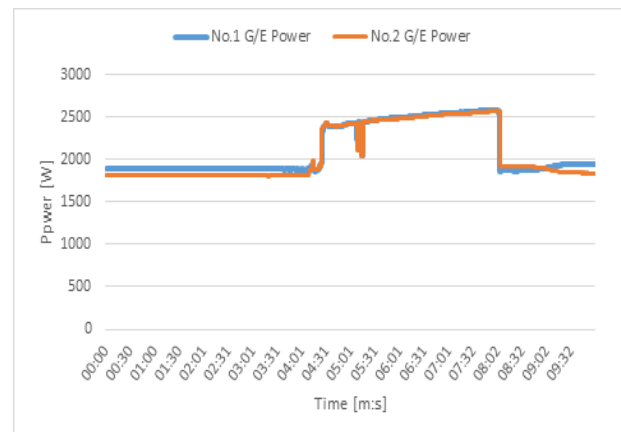

Figure 13: Power graph of ordinary ship maneuvering mode

Bow Thruster (B / T) is a device that consumes the most power of the vessels by a single appliance. In this paper, it is assumed that heavy loads like the B / T are also used in both average load and max load of the maneuvering mode. Because the load is high, two generators operate. In the actual ship, three generators work frequently, but the simulator has only two generators, and therefore, only two generators operate. If three generators are driven, the generators will have a number of disadvantages of low loads. **Figure 14** shows the power graph of the LCS maneuvering mode.
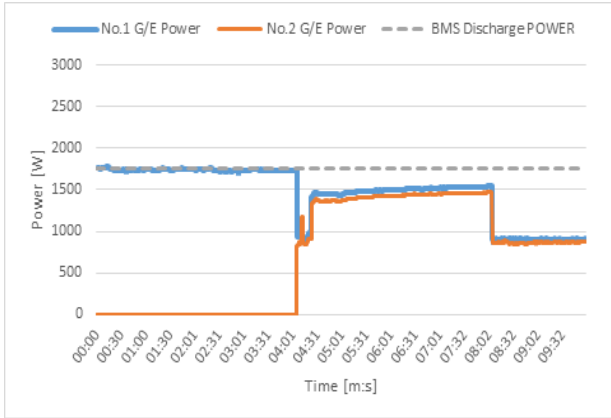
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Figure 14: Power graph of the LCS maneuvering mode

Rapid power consumption of the B / T maneuvering is covered by the battery. The battery is discharged, depending on when the heavy load (B / T) is used. As the load increases, the generator runs in parallel. However, when the load decreases, because the heavy loads are still on, even if the load is reduced and reaches the release point, the parallel operation will not be stopped. When heavy loads are operating on the ship, the parallel operation of the generator is not cancelled considering the amount of change of the power. In the simulator, low-load operation is more common in the vessel with LCS than in an existing vessel. However, when applied to maritime, the vessel with LCS can operate at high loads depending on load usage when maneuvering.

The fuel consumption of the ship can be obtained from the following equation.

$$G_{ship} = \sum_{k=1}^{n} \int_0^t (P_{Gn} \times SFC)\, dt \qquad (2)$$

Considering the operating mode, we can obtain an average fuel consumption of an ordinary ship using the following Equation.

(3)

$$G_{ordinary} = M_V \times \sum_{k=1}^{n} \int_0^{t_{Vn}} (P_{Gn} \times SFC)\, dt$$

$$+ M_P \times \sum_{k=1}^{n} \int_0^{t_{Pn}} (P_{Gn} \times SFC)\, dt$$

$$+ M_M \times \sum_{k=1}^{n} \int_0^{t_{Mn}} (P_{Gn} \times SFC)\, dt$$

M_V is voyage mode rate, n is the number of generators, t_{Vn} is generator running time for voyage, P_{Gn} is Generator output, SFC

is fuel consumption per 1 kWh, M_P is the port mode rate, and M_M is the maneuvering rate. SFC was determined using a similar expression in **Figure 3**. The average fuel consumption of the ship in which LCS is applied can be determined using the following equation.

(4)

$$G_{LCS} = M_{V(CH)} \times \sum_{k=1}^{n} \int_0^{t_{V(CH)n}} (P_{Gn} \times SFC)\, dt$$

$$+ M_V \times \sum_{k=1}^{n} \int_0^{t_{Vn}} (P_{Gn} \times SFC)\, dt$$

$$+ M_{P(CH)} \times \sum_{k=1}^{n} \int_0^{t_{P(CH)n}} (P_{Gn} \times SFC)\, dt$$

$$+ M_P \times \sum_{k=1}^{n} \int_0^{t_{Pn}} (P_{Gn} \times SFC)\, dt$$

$$+ M_M \times \sum_{k=1}^{n} \int_0^{t_{Mn}} (P_{Gn} \times SFC)\, dt$$

$M_{V(CH)}$ is the voyage mode rate when the battery is charging and $M_{P(CH)}$ is the port mode rate when the battery is charging. During the rest of the periods, the battery does not charge, and the fuel consumption of the ordinary vessel is used. Assuming that the discharge continues for the duration of the maneuvering, the charging period is calculated.

The calculation results after charging up to 56%, which is a combination of the charging from the voyage and port operating modes, is equal to the discharge amount of the battery. It can be presumed that 12% of the 13% charge occurs while at the port, while 44% of the 80% charge occurs at the voyage mode. The fuel consumption when estimated using the proposed formula is shown in **Figure 15**. The power consumption shown in **Figures 9** to **14** is converted to fuel consumption according to the SFC curve.
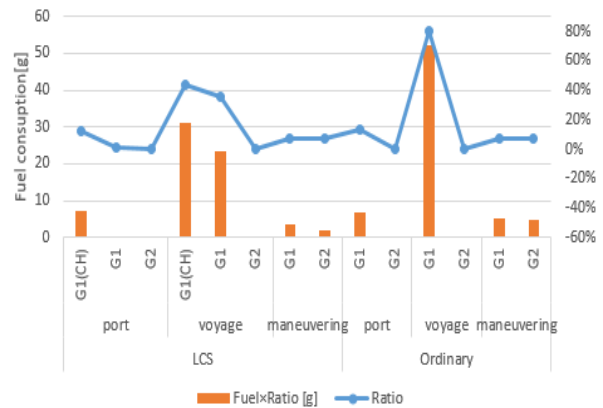

Figure 15: Fuel consumption by operating mode rate

Figure 15 shows the ship's operating ratio according to the mode in Figure 1 as a blue line. The orange bar graph represents the product of the fuel consumption and the operating ratio according to equations 3 and 4. G1 (CH) represents a period for charging using Generator 1. Fuel consumption at the operating mode can be found by adding fuel consumption of G1 (CH), G1, and G2. In the LCS-applied vessel, the graph shows that fuel consumption during the voyage and port mode is high because of the battery charge, but fuel consumption during maneuvering is low. Based on the fuel consumption from Figure 15, the total fuel consumption and the energy consumption rate are shown in **Figure 16**.
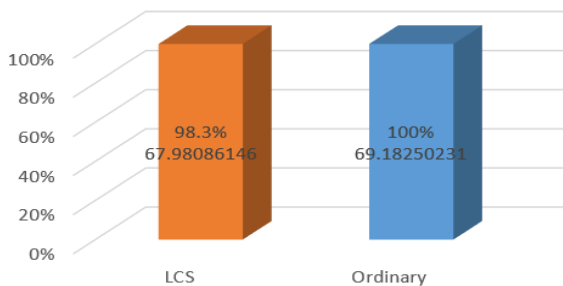

Figure 16: Energy consumption reduction of the vessel in which LCS is applied.

The total fuel consumption of the LCS applied vessel is approximately 67.98 g according to the operating ratio, and the total fuel consumption of the ordinary vessel is approximately 69.18 g by the experiment. As a result, it was confirmed that 1.7% of the energy is saved.

6. Conclusions

In this paper, we classified the operations of the ship into different modes and analyzed the load according to each operation mode. Based on the analyzed load, experiments on ordinary ships and battery-applied ships were conducted. As a result, it was confirmed that the battery-applied ships saved 1.7% of the energy. However, a further reduction in energy consumption can be achieved if we improve the point that the load is low when the battery is discharged during the maneuvering mode because the number of points where three generators run is changed to two due to the limitations of the simulator. This paper can be used as a reference for studies on the reduction of energy consumption of a ship and be helpful for the development of a green ship.

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