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Discussion of Marine Stirling Engine Systems

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ABSTRACT

Many kinds of internal combustion engines are used as a prime mover of traffic systems. Also the electric power systems, such as fuel cells, an electric propulsive ship and an electric automobile, are developed for the environmental preservation. On the other hand, a Stirling engine, which is an external engine, has excellent characteristics, which are a high thermal efficiency, multi-fuel capability and low pollution. In this paper, we discuss about marine applications using the Stirling engine. They are a prime mover for a large ship, a hybrid system for a small vehicle and waste heat recovery systems with a marine Diesel engine. We also consider the technical problems of the marine Stirling engine systems.

Key Words: Stirling Engine, Marine Application and Heat Recovery System

1. INTRODUCTION

Many kinds of internal combustion engines are used as a prime mover of traffic systems. For examples, a small automobile is used a petrol engine, whose characteristics are compact size and lightweight. An airplane is used a jet engine which obtains large propulsion force. And a primary power source of a ship is a Diesel engine, which has high thermal efficiency. Also, from a viewpoint of an environmental preservation and energy saving, a new power source, such as fuel cells, an electric propulsion ship and an electric automobile are actively developed in this field.

In this paper, we discuss Stirling engine systems for marine applications. A Stirling engine is one of external thermal engines, whose principle was invented in 1816 by R. Stirling. Thenceforward, the engine has been researched and developed by many engineers and researchers in the field.

We focus on the excellent characteristics of the Stirling engine, which are a high thermal efficiency, multi-fuel capability and low pollution, and consider possibility for its marine applications.

2. CHARACTERISTICS OF STIRLING ENGINE

As the Stirling engine does not have explosions of the fuel, it has a silent operation compared with the internal combustion engines. Also the engine can obtain the effective power using many kinds of heat source, such as biomass, solar, exhaust gas and waste heat. Still more, the Stirling engine has a special heat exchanger called a regenerator. The thermal energy of the cooling process is kept in the regenerator, and it is reused in the heating process at the cycle. Then the engine has high efficient performance.

When the engine shows these excellent characteristics, it is clarified that the engine is used in the various practical applications. However, the thermal efficiency of the actual Stirling engine has not reached to only the ideal efficiency but also that of a large marine Diesel engine. Because, it has some thermal losses, such as a heat conduction in the engine, a radiation from the engine, a pressure loss in the heat exchangers and the mechanical loss.

In order to get the high power for practical use, the working space of the Stirling engine is pressurized with helium or hydrogen gas. Therefore, the pressurized structure and the seal device become one of the technical subjects for the practical applications. Especially, as the heater tubes are needed high-strength under the high-temperature and high-pressure condition, a special nickel alloy is often used as the material. It is caused to high production cost.

Many engineers and researchers have tried to solve the technical subjects with the new technologies, such as unique heat exchangers, a high-efficient generator and a special mechanism for the pistons. In the case of the Stirling engine systems on the ground, various Stirling engine systems are developed to aim at the practical applications. They are a high-efficient cogeneration system using natural gas or petroleum, a waste heat recovery system for an industrial factory or an incinerator plant and a biomass energy system using fermented methane or wood chips.

3. DISCUSSION OF MARINE APPLICATIONS WITH STIRLING ENGINE

The Stirling engine systems have been developed actively for the ground institutions. However, the authors have hardly heard about a development of the marine application with the Stirling engine except a military submarine. In this chapter, various marine Stirling engine systems for freight ships and passenger ships are discussed.

3.1 Primary Mover for Large Freight Ship

The output power of the previous high-performance Stirling engines are about 3~100 kW. A more enormous power Stirling engine, such as the marine Diesel engine, has not developed yet. Then, based on a simple performance prediction method with a similarity rule [1], the enormous power Stirling engine for a prime mover of a large freight ship

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is designed conceptually, and discussed the possibility for the application [2].

A Diesel engine is used as a prime mover for a large ship. The output power of the engine for a freight ship, which has the length of 200~300 m, is about 15,000~20,000 kW. The engine size and specifications are shown in Fig. 1. These values are based on the UEC68LSE marine Diesel engine of Mitsubishi Heavy Industries, Ltd. [3]. In the following consideration, a 20,000 kW class Stirling engine is discussed compared with the same range of the Diesel engine.

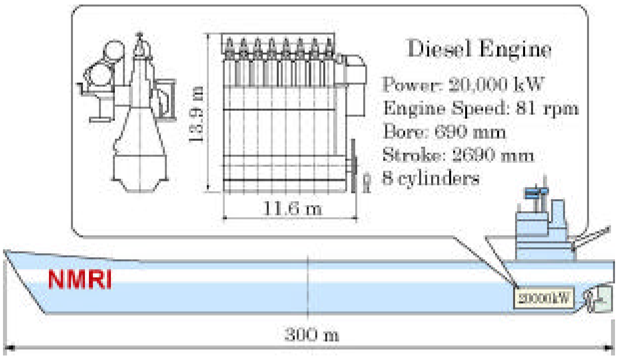

Fig. 1, Marine Diesel Engine for Large Freight Ship

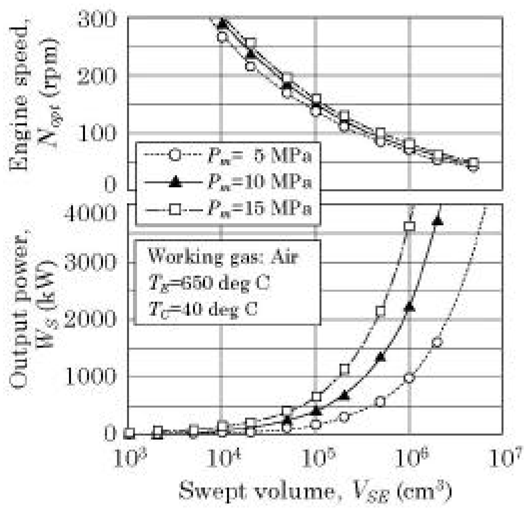

Fig. 2, Calculated Results of Stirling Engine Performance by Simple Prediction Method

It is difficult to obtain the output power of 20,000 kW with one-cylinder Stirling engine. Then an 8-cylinder Stirling engine, which has the output power of 2,500 kW per one cylinder, is proposed. In the case of the calculation for the power, the simple prediction method [1] is used. It is based on the experimental results of previous Stirling engines, and it can calculate the maximum output power and the optimal engine speed from the engine size and the operating conditions.

Figure 2 shows the calculated results of the relation the swept volume of each piston, V_{SE}, the output power, W_S and the optimal engine speed, N_{opt} at the mean gas pressure, P_m=5, 10 and 15 MPa. From the figure, the target output power of 2,500 kW is obtained at V_{SE}=1.2 m^3 and P_m=10 MPa using air as the working gas, and the optimal engine speed is about 73 rpm. It is the same range to the above Diesel engine.

Additionally, in the case of the calculation using helium as the working gas, the swept volume and the operating conditions are predicted to V_{SE}=0.4 m^3, P_m=10 MPa and N_{opt} =240 rpm to get the target output power. This result means that there is a possibility to develop a compact Stirling engine. But it is considered that the handling of the high-pressurized helium is very difficult for the large-scale Stirling engine. Therefore, the air is used as the working gas for the following conceptual Stirling engine.

Table 1, Specifications of the marine Stirling engine

Type		Double acting type
Working gas		Air
Mean engine pressure		10 MPa
Output power		20,000 kW (2,500 kW x 8 cylinders.)
Bore x Stroke (Swept volume)		1200 x 1060 mm (1.20 m^3)
Rated engine speed		73 rpm
Fuel		Heavy oil
Heater wall temperature		700 deg C
Gas temperature, Hot / Cold		650 deg C / 40 deg C
Heater	Type Diameter Length No. of tubes	Multi-tube type 20 mm (ID), 30 mm (OD) 3000 mm 1200
Regenerator	Type Diameter Length Mesh	Annular tube 1420 mm (ID), 1960 mm (OD) 300 mm #100 x 1500 seats
Cooler	Type Diameter Length No. of tubes	Multi-tube type 10 mm (ID), 15 mm (OD) 500 mm 5000

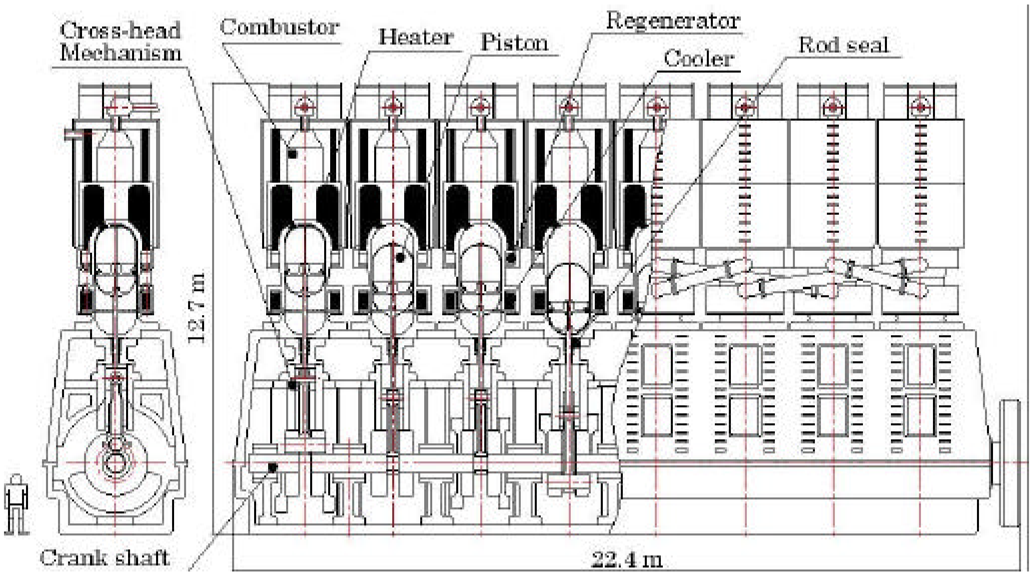

Fig. 3, Conceptual Drawing of the 20,000 kW class Marine Stirling Engine

Figure 3 shows a conceptual drawing of the 20,000 kW class Stirling engine, and its specifications are listed in Table 1. The engine size and the structure are decided from the above results of the simple prediction method and the other calculations for the strength of a pressurized vessel and the heat transfer of the heat exchangers. The engine has the height of 12.7 m, and the width of 22.4 m. The height is the same range to the above Diesel engine as shown in Fig. 1. However, the width is two times wider than that of the Diesel engine approximately. It is caused that the cylinder head and the heat exchanger are needed high strength for the high-pressurized structure. In order to develop a compact Stirling engine, it is important to design the engine optically including the pressurized structure and reduce any thermal losses.

From another simulation code for the Stirling engines, the indicated efficiency of the engine, which is defined the ratio of the indicated power and the heat input, is calculated to 45 % approximately. As the mechanical efficiency is not clarified, it is difficult to predict the total thermal efficiency accurately. However, we think that the Stirling engine cannot achieve the higher efficiency than that of the high efficient Diesel engine.

From above discussions, it is not confirmed that the Stirling engine has higher performance than the marine Diesel engine, though the above Stirling engine is not optimized. In addition, the accuracy of the calculations cannot be estimated suitably. We need a more detailed analysis method for the enormous power Stirling engine.

3.2 Stirling Engine Hybrid System for Small Passenger Vehicle

From the balance of a pressurized structure and a thermal strength of the heat exchanger, a large-sized Stirling engine may be not suitable for the practical use. The large-sized Stirling engine does not have predomination compared with other thermal engines. On the other hand, from actual results of previous developed engines, it is considered that a several kW or several hundred kW class Stirling engine has a possibility of the practical applications. After solving of technical subjects, a high-efficient and high-performance engine will be completed. We discuss the marine application with the middle class Stirling engine in follows.

Figure 4 shows a conceptual drawing of a sightseeing amphibious vehicle with a 200 kW class Stirling engine generator. The engine generates an electric power using combustion of natural gas. And an electric motor drives the vehicle on the ground and on the water. The generator is located in the pressurized crankcase of the engine, and the engine has a suitable size for the vehicle.

This sightseeing vehicle needs the silence operation and low pollution. Then it is considered that the Stirling engine is very valuable. On the other hand, in order to develop a practical used engine, we must solve some technical problems, such as confirmations of safety and reliability with an actual engine.

3.3 Heat Recovery System with Exhaust Gas of Marine Diesel Engine

A Diesel engine rejects about 30 % of the total heat energy into the exhaust gas. We discuss waste heat recovery systems with the exhaust gas of the marine Diesel engine.

<u>**Ideal Heat Recovery System for Large Ship**</u>

Figure 5 shows the ideal calculated result of the energy balance with a 20,000 kW class Diesel engine. The exhaust gas has the total waste heat of 12,000 kW and the temperature of 400 deg C. The Stirling engine recovers the exhaust heat, and obtains the generated power of 700 kW. This power level is the same in an auxiliary Diesel engine generator of a large ship. It is not difficult to achieve the thermal efficiency of 5 % with combustion gas for the Stirling engine. However, when the engine uses the low temperature heat source, the engine size becomes too large. Therefore, in the case of these heat recovery systems, it is important to discuss about the effective

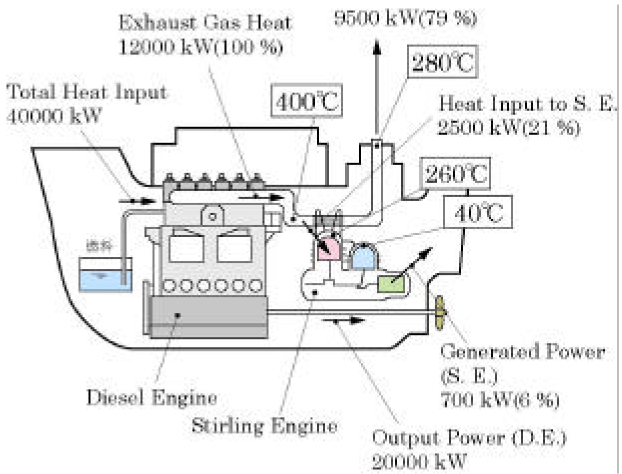

Fig. 5, Energy Balance of Heat Recovery System for Large Ship

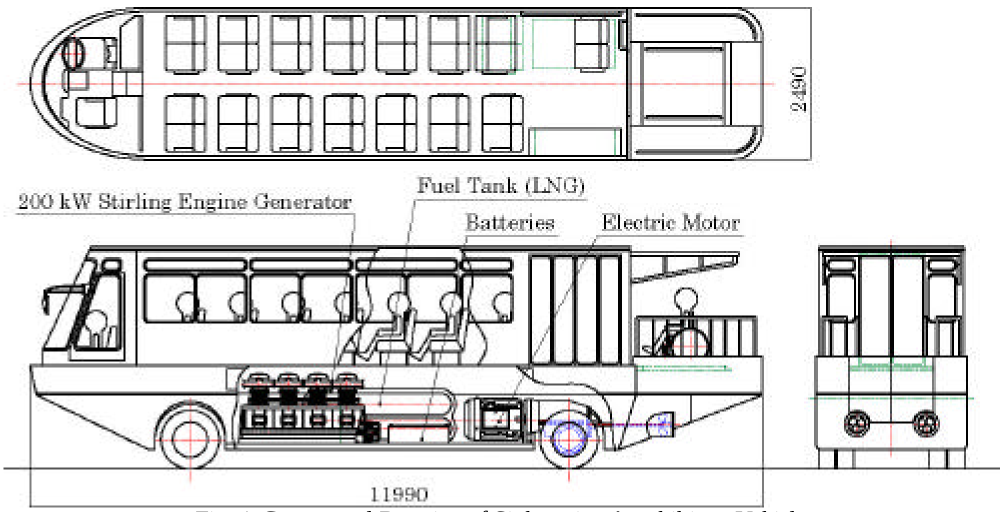

Fig. 4, Conceptual Drawing of Sightseeing Amphibious Vehicle application with a small Stirling engine and a new concept for the application.

Heat Recovery System to Keep Clean the Harbor Area

Figure 6 shows a new concept of the waste heat recovery system with a small Stirling engine generator. The generated power of the Stirling engine is only 2~5 kW. When the ship is at sea, the Stirling engine generator operates with the exhaust heat of the Diesel engine, and charges batteries in the ship. When the ship is at anchor in the harbor, the charged batteries supply the electric energy into the ship without the operation of the Diesel engine generator. This system is expected that the harbor area is kept clean, because the exhaust gas of the Diesel engine decreases in the area.

Additionally, we have started the project regarding this waste heat recovery system to keep clean the harbor area since 2005 with sponsored by JRTT (Japan Railways Construction, Transport and Technology Agency).

Multi-cylinder Stirling Engine

As another project in our laboratory, we have developed a multi-cylinder Stirling engine for a waste heat recovery system since 2003 [4], [5]. Figure 7 shows a design concept of the multi-cylinder Stirling engine. The engine is composed plural engine unit arranged in the series. When the engine units take in the heat in order, the temperature of the exhaust

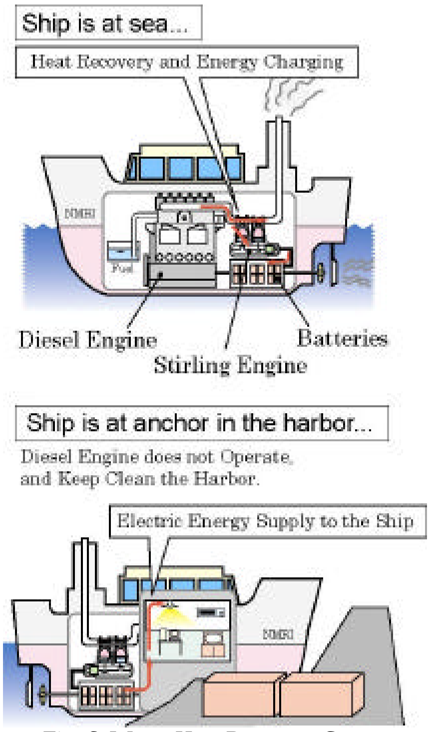

Fig. 6, Waste Heat Recovery System to Keep Clean the Harbor Area

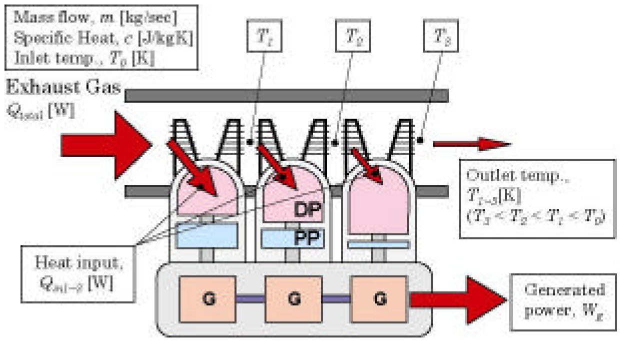

Fig. 7, Concept of Multi-cylinder Stirling Engine

Fig. 8, Photograph of the Prototype Stirling Engine

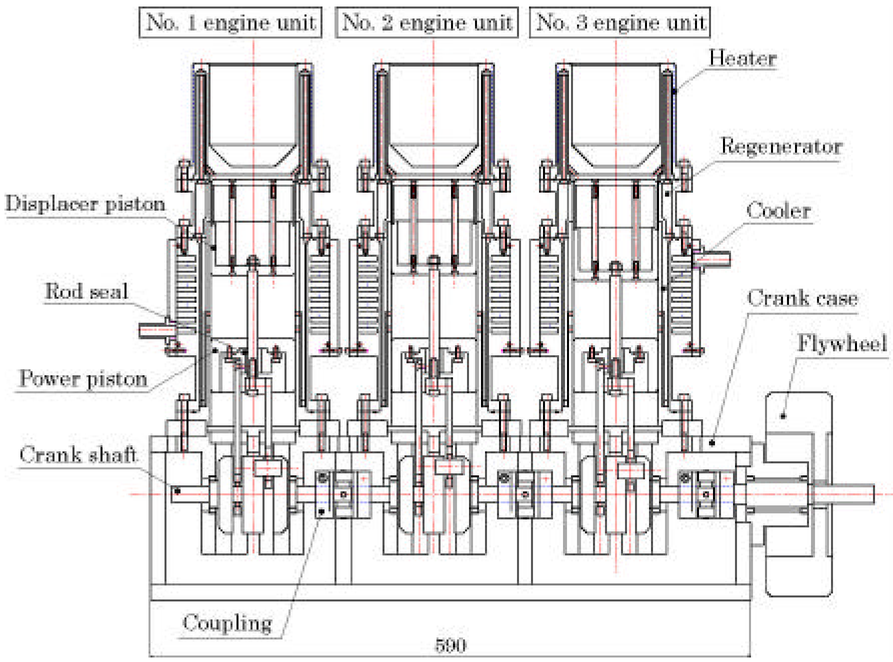

Fig. 9, Schematic View of the Prototype Stirling Engine

Table 2, Specifications of Prototype Engine

Engine Unit No.	No. 1	No. 2	No. 3
Engine Type	Beta-type		
Working Gas	Air		
Mean Pressure	Atmospheric Pressure (101.3 kPa)		
Piston Phase Angle	90 deg		
Expansion Space Gas Temp. (Design)	270 degC	190 degC	110 degC
Compression Space Gas Temp. (Design)	60 degC	50 degC	40 degC
Displacer Piston Piston Dia. x Stroke	84 x 52 mm	84 x 54 mm	84 x 46 mm
Power Piston Piston Dia. x Stroke	84 x 48 mm	84 x 44 mm	84 x 46 mm
Target Engine Speed	1100 rpm		
Target Power	43 W	33 W	20 W
Total Target Power	96 W		

gas becomes low. Therefore, the multi-cylinder Stirling engine can recover the waste heat efficiently. It is note that the swept volumes of the engine units must be adjusted suitably, because each engine units have different thermal conditions.

Figure 8 and Figure 9 show the photograph and the schematic view of the prototype of the multi-cylinder Stirling engine. Table 2 lists the specifications and target performance of the prototype engine. The three engine units are located on the crankcase. The crankshafts of each unit are jointed with the couplings. As one of the important characteristics, the piston stroke of each engine unit is adjusted to get the suitable power and the heat input. Also the piston diameter of each engine unit is the same size, and many of engine parts, such as a cylinder and heat exchangers, are the same features.

The engine has been experimented in our laboratory, and it has been confirmed that the multi-cylinder Stirling engine is valuable for getting higher output power.

We expect that these new concepts will be effective technologies to develop the waste heat recovery system.

4. CONCLUSION

In this paper, we informed the characteristics of the Stirling engine and discussed about the marine applications. It is difficult to develop a large-sized and high-pressurized Stirling engine. Therefore, it has low possibility to apply the Stirling engine to the prime mover of a large ship. On the other hand, the thermal efficiency of a large-sized marine Diesel engine is very high, and it is difficult to increase the efficiency in near future. Then it is considered that the heat recovery system using the Stirling engine is one of the effective applications in this field. Also we are very interested in the marine application for the small passenger vehicle, though the technical problems must be solved to the practical application.

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