DEVELOPMENT OF A MULTI-CYLINDER STIRLING ENGINE

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ABSTRACT

We have researched a multi-cylinder Stirling engine for a waste heat recovery system. The multi-cylinder Stirling engine has a possibility to achieve higher efficiency than a single-cylinder engine. In this paper, we discuss a simple thermal analysis for the multi-cylinder engine. And based on the analyzed result, a prototype engine is designed and built in our laboratory. The prototype engine consists of three engine units that have different piston stroke for each unit to getting the optimal thermal condition. Also it has unique components, such as a heater made from a block of aluminum alloy and an assembling cooler. As the result of the previous operating test, it is confirmed that the shaft power of the prototype engine is bigger than the sum of shaft power of each engine units.

INTRODUCTION

It is important to develop a waste heat recovery technique in a viewpoint of the global energy saving. Since Stirling engines can utilize various heat sources. The feature is valuable to the waste heat recovery system. However the temperature of the waste heat, such as waste energy from plant facilities, is almost lower than that of a fuel combustion gas. Also the quantity of the waste heat is not often sufficient. Therefore, the optimal design method and the engine structure for the waste heat recovery Stirling engine are very important.

In this paper, we discuss a multi-cylinder Stirling engine used for the waste heat recovery system, and introduce a prototype Stirling engine for experiments.

DISCUSSION OF MULTI-CYLINDER STIRLING ENGINE

Quantity and temperature of a waste heat are not often sufficient. When a waste heat recovery Stirling engine is developed, it is important to establish the working gas temperature in the engine suitably. In this chapter, we discuss the engine structure for development of a high efficient Stirling engine using the waste heat, and propose a simple thermal analysis corresponded to the heat conditions.

Discussion of Engine Structure

Figure 1 shows a concept of a waste heat recovery Stirling engine with a single cylinder. In this figure, the waste heat has the heat quantity, Q_{total} and the inlet temperature, T_0. In order to use the waste heat efficiently, the heat input into the engine, Q_{in} must be increased. The outlet temperature,

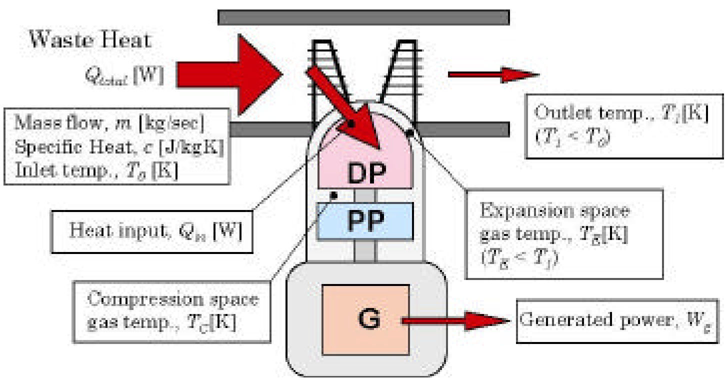


Figure 1, Concept of Waste Heat Recovery Stirling Engine with Single-cylinder

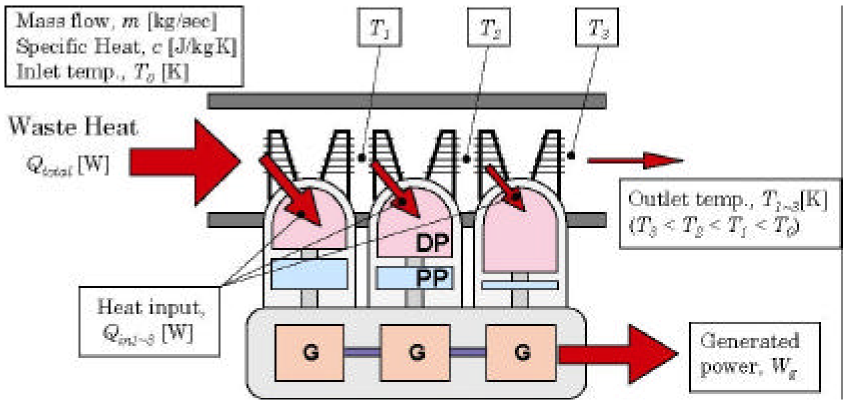


Figure 2, Concept of Multi-cylinder Stirling Engine

T_1 decreases with increasing of the heat input, Q_{in}. In the case of a general Stirling engine, the expansion space gas temperature, T_E is lower than the outlet temperature, T_1. Then the thermal efficiency of the Stirling engine decreases with increasing of the heat input, Q_{in}, and the maximum power cannot be obtained when the heat input, Q_{in} is over the optimal point. Namely, the Stirling engine has the optimal point of the heat input and temperature range. The single cylinder Stirling engine cannot achieve an ideal high performance.

Figure 2 shows a design concept of a multi-cylinder Stirling engine. The engine is composed plural engine units arranged in the series. When the engine units take in the heat in order, the temperature of the waste heat becomes low. Therefore, the multi-cylinder Stirling engine can recover the waste heat efficiently. It is note that the swept volumes of a displacer piston and a power piston of the engine units must be adjusted suitably, because each engine units have different thermal conditions.

Simple Thermal Analysis for Multi-Cylinder Stirling Engine

In the case of the multi-cylinder Stirling engine, it is important to set the suitable temperature range to obtain the maximum performance. Then, we calculate the engine performance related to the temperature range using a simple thermal analysis model.

Figure 3 shows the analysis model for the multi-cylinder Stirling engine. The calculated conditions of the waste heat are setting to a mass flow, *m* [kg/sec], the inlet temperature, T_0 [K] and specific heat, *c* [J/kgK]. When the outlet temperature from the first engine unit, T_1 [K] is given as a parameter, the heat input into the first engine unit, Q_{in1} [W] is calculated by Eq. 1.

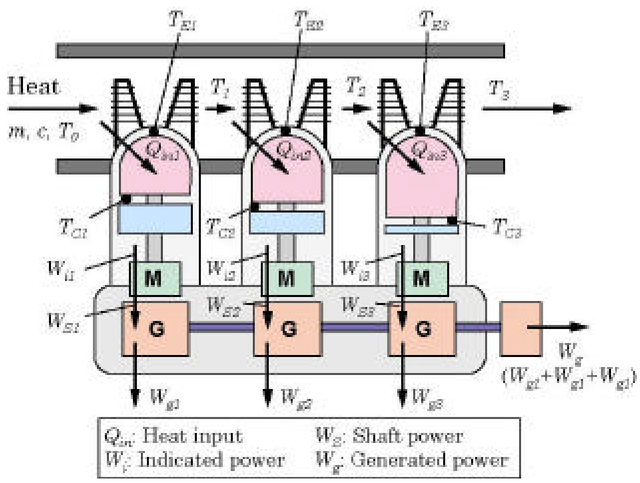


Figure 3, Analysis Model for Multi-cylinder Engine

$$Q_{in1} = cm(T_0 - T_1) \tag{1}$$

The Carnot efficiency, h_{car1} of the first engine unit is calculated by Eq. 2.

$$h_{car1} = 1 - \frac{T_{C1}}{T_{E1}} \tag{2}$$

Here, T_{C1} is the compression space gas temperature, and T_{E1} [K] is the expansion space gas temperature. The expansion space gas temperature, T_{E1} [K] is calculated with a temperature drop, ΔT_1 [K] by Eq. 3.

$$T_{E1} = T_1 - \Delta T_1 \tag{3}$$

The indicated efficiency, h_{ind1}, the engine efficiency, h_{S1}, the shaft power, W_{S1} [W], and the generated power, W_{g1} [W] are calculated by Eq. 4 to Eq. 7 using the Carnot coefficient, k_{car1}, mechanical efficiency, h_{m1} and generator efficiency, h_{g1}. The Carnot coefficient, k_{car} is used to revise the effects of thermal loss and pressure loss from the ideal efficiency.

$$h_{ind1} = K_{car1} \times h_{car1} \tag{4}$$

$$h_{SE1} = h_{ind1} \times h_{m1} \tag{5}$$

$$W_{S1} = Q_{in1} \times h_{SE1} \tag{6}$$

$$W_{g1} = W_{S1} \times h_{g1} \tag{7}$$

The generated power of the first engine unit is obtained from above equations. Also, when the inlet temperature to the second engine unit equals to T_1, and the inlet temperature to the third engine unit, T_2 equals to the outlet temperature, T_3, the performance of the multi-cylinder Stirling engine is calculated.

Additionally, in the case of a two-cylinder Stirling engine, the optimal outlet temperature from the second engine, T_{2opt} can be obtained analytically corresponded to optional temperature, T_1 by Eq. 8.

$$T_{2opt} = \Delta T_1 + \sqrt{T_{C1}(T_1 - \Delta T_1)} \tag{8}$$

In the case of the three or more-cylinder engine, the optimal temperature conditions are obtained from matrix calculations in follows analysis.

Analysis Results of Multi-Cylinder Stirling Engine

The performance of the multi-cylinder Stirling engine is calculated from the analysis model. Figure 4 shows the calculated results of a single-cylinder engine and a two-cylinder engine. The calculated conditions are listed in Table 1. From the figure, the maximum generated power of the single-cylinder engine is obtained about 62 W at T_1=230 degC. The maximum generated power of the two-cylinder engine is about 83 W at T_1=290 degC and at T_{2opt}=184 degC. It is confirmed that the power of the two-cylinder engine is 1.3 times as large as that of the single-cylinder engine. And the optimal condition of T_1 of the two-cylinder engine is different from that of the single-cylinder engine. This means that we should set a different design temperature by the engine structure.

Figure 5 shows one of the calculated results of a three-cylinder engine. The calculated conditions are the same as Table 1. The maximum generated power is about 96 W at T_1=320

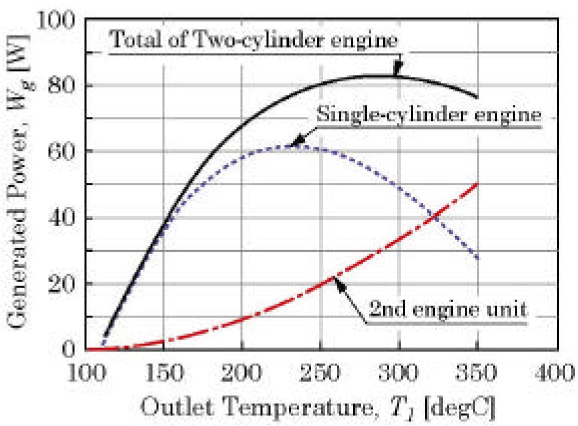


Figure 4, Calculated Result of Single- and Two-cylinder Stirling Engine

Table 1, Calculated Conditions

Item	Symbol	Value
Mass flow	m	0.0035 kg/s [=175 NL/min of Air]
Specific heat	c	1004 J/kgK
Inlet Temperature	T_0	400 degC
Compression space gas temperature	T_{Ci}	60 deg C
Temperature drop	DT_i	50 K
Carnot coefficient	k_{cari}	0.7
mechanical efficiency	h_{mi}	0.7
generator efficiency	h_{gi}	0.8

degC, T_2=240 degC and T_3=160 degC. The temperature of the optimal condition is obtained from the matrix calculations.

Figure 6 shows the maximum generated power of multi-cylinder engines at the fixed inlet temperature to the first engine unit, T_0=200 degC and T_0=400 degC respectively. Other calculated conditions are the same as Table 1. From the figure, the multi-cylinder engine can achieve larger power than the single-cylinder engine. Also it is confirmed that the increasing rate of the power at T_0=200 degC is larger than that of T_0=400 degC. It means that the multi-cylinder structure is effective for the Stirling engine using low temperature heat source especially.

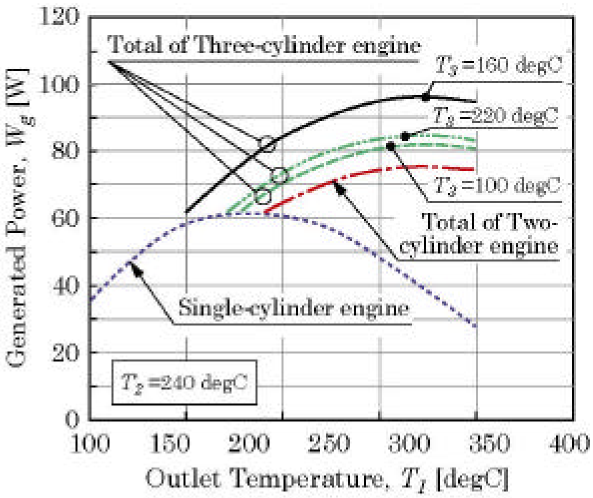
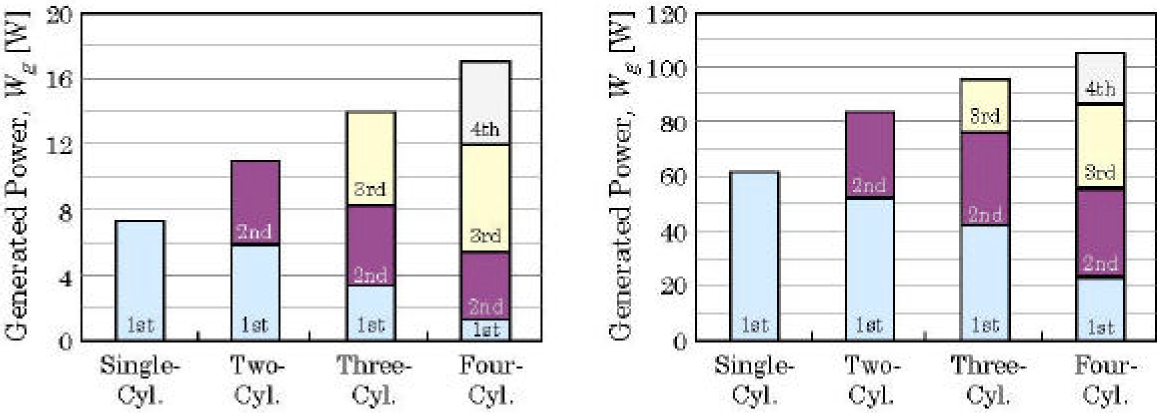


Figure 5, Calculated Result of the Three-cylinder Stirling Engine



(a) Inlet temperature, T_0=200 degC (b) Inlet temperature, T_0=400 degC

Figure 6, The Maximum Power of Multi-cylinder Stirling Engine

PROTOTYPE OF MULTI-CYLINDER STIRLING ENGINE

Based on the above discussion, we designed and built a prototype of the multi-cylinder Stirling engine for experiments. The prototype engine is decided three-cylinder structure. The target performance and design temperature of the prototype engine are decided based on the calculated results shown in Fig. 5.

Outline of Prototype Stirling Engine

Figure 7 and 8 show the photograph and the schematic view of the prototype engine, respectively. Table 2 lists the specifications and target performance of the prototype engine. The three engine units are located on the crank case. The crank shafts 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

Figure 7, Photograph of Prototype Stirling Engine

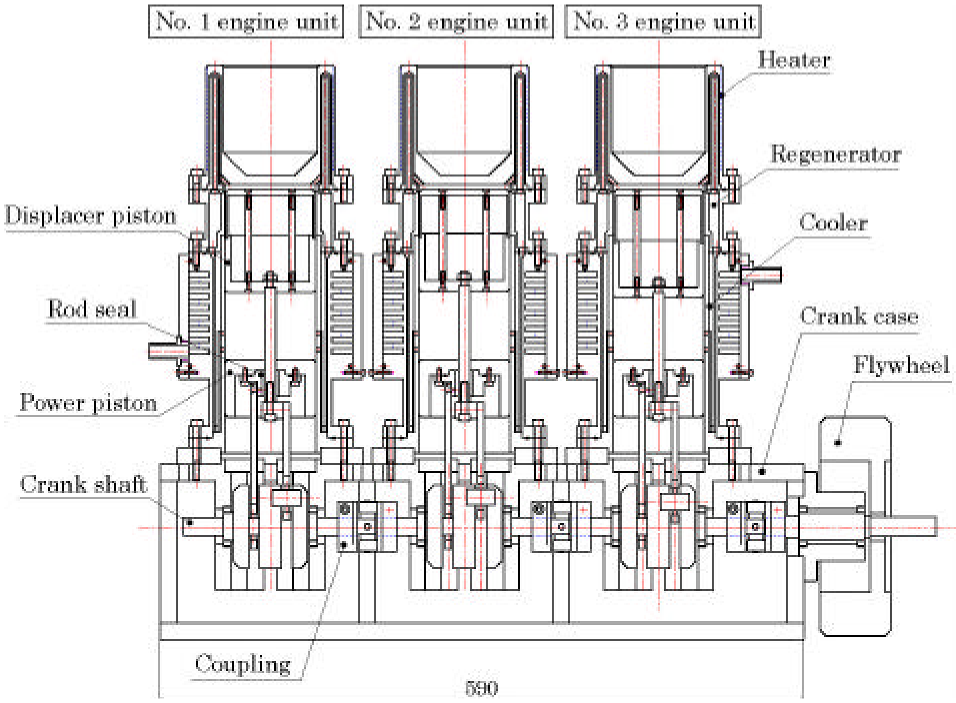


Figure 8, Schematic View of the Prototype Stirling Engine

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		

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.

It was very difficult to decide the suitable piston stroke and other specifications, because we could not predict the mechanical loss and the engine speed of the prototype engine accurately. We decided the piston stroke based on a simple isothermal model with constant mechanical efficiency. Figure 9 shows an example of the calculated results. In this figure, it is confirmed that the prototype engine gets the target power, 96 W at 1100 rpm of the engine speed. Also, the power of each engine unit is set to the ideal conditions shown in Fig. 5 approximately.

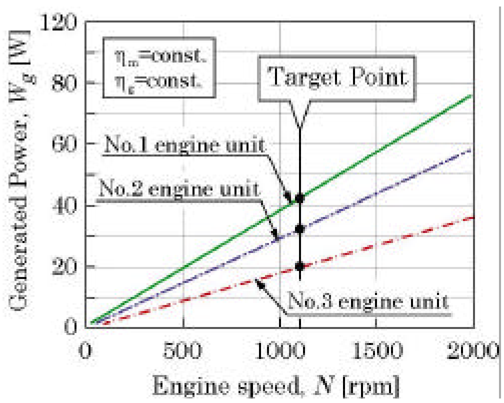


Figure 9, Calculated Power of the Prototype Stirling Engine

Components of the Prototype Stirling Engine

The prototype engine has unique components. A heater and a cooler have very simple structure, because the shapes of these parts are decided to fit our processing machines.

Figure 10 shows the configuration layout of the heat exchanger. The heater consists of a heater head and inner tubes as shown in Fig. 11. The heater head is made from a block of aluminum alloy. The operating temperature of the prototype engine is lower than that of general Stirling engine. Then we use the aluminum alloy that has high heat conduction coefficient. Twenty of the inner tubes are inserted into the heater head. The tubes are made of copper, and they have 6 mm of inner diameter and 8 mm of outer diameter. The heater type is called bayonet type, the working gas flows from the expansion space to the regenerator through the outside and inside of the inner tubes.

A regenerator housing consists of two parts, and a rolled regenerator matrix is located in the housing. As the material of the regenerator housing, a low heat conduction material, such as stainless steel, is suitable. But the regenerator housing of the prototype engine is made of aluminum alloy from the limitation of the machining ability of our machine tools. It is clarified that the prototype engine has a large heat conduction loss, and we must change the material to improvement of the engine.

The special cooler is arranged outside of cylinder in the same axis. In order to get high heat transfer performance, the outer surface of the cooler inner ring has plural vertical fins as shown in Fig. 12. The cooler outer cover is located around the cooler inner ring, and the water jacket is located around the cooler outer cover. These parts are made of aluminum alloy.

As a piston drive mechanism, we adopted a Scotch-yoke mechanism as shown in Fig. 13. In order to be compact, the yoke boards of the displacer piston and the power piston are shifted from the center line of the cylinder. As guides of the yoke boards, the Teflon plates are attached to side of the yoke boards.

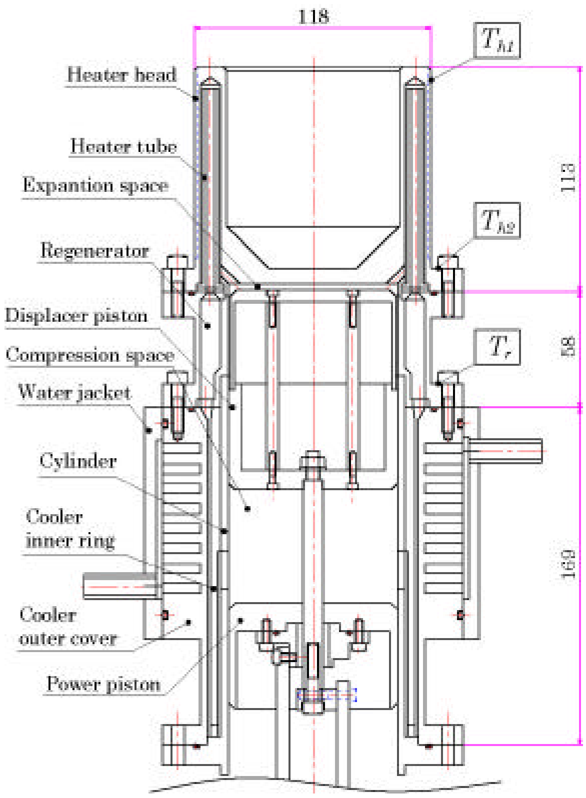


Figure 10, Configuration Layout of Heat Exchanger

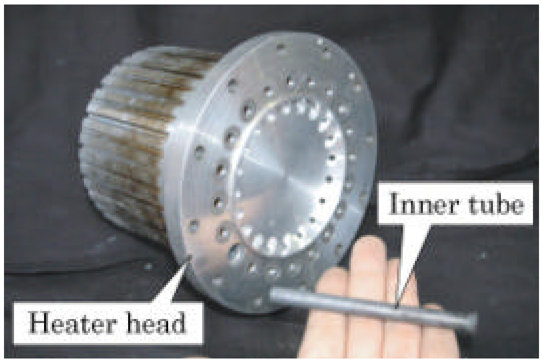


Figure 11, Photograph of Heater

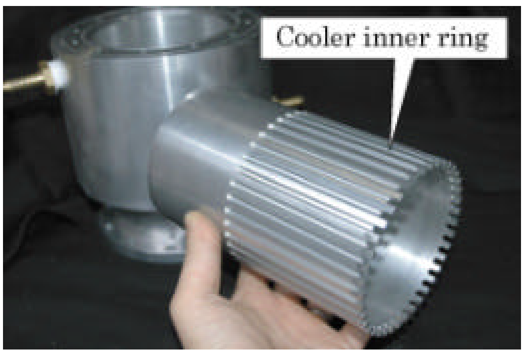


Figure 12, Photograph of Cooler Inner Ring

The displacer piston and the power piston are made of stainless steel. The cylinder is made of aluminum alloy. The power piston and the cylinder touch together with small clearance, 0.03 to 0.05 mm of diameter. In order to get smooth motions for the displacer piston, the special joint mechanisms is adopted in the piston and the end of the piton rod as shown in Fig. 13. The rod seal in the power piston is made of Teflon.

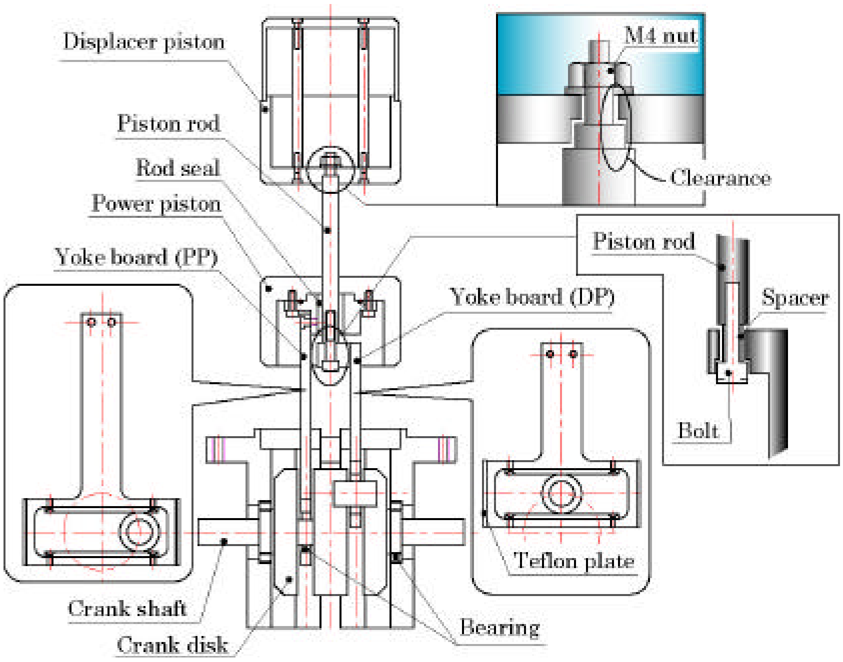


Figure 13, Structure of Piston Drive Mechanism

Operating Tests of the Prototype Engine

After four engine units had been built, we tried the operating tests on all engine units. Measuring points of wall temperature, T_{h1}, T_{h2}, and T_r are shown in Fig. 10. Electric heaters, which have each 1 kW capability, are rolled at the heater heads as the heat source in the operating tests.

Figure 14 shows the relation between the engine speed and the shaft power of each engine units. Four engine units are tested. The specifications of No. 1, No. 2 and No. 3 engine units are listed in Table 2. A specification of a reserved engine is the same of No. 3 engine unit.

From the figure, the maximum shaft power of No. 1 engine unit is 1.5 W at 130 rpm of the engine speed, T_{h1}=330 degC, T_{h2}=250 degC and T_r=55 degC. The maximum shaft power of No. 2 engine unit is 4.7 W at 160 rpm of the engine speed, T_{h1}=340 degC, T_{h2}=280 degC and T_r=50 degC. In the case of these engine units, the heater heads could not be enough heated by the electric heaters, then they were unstable operations.

The maximum shaft power of No. 3 engine unit is 1.8 W at 210 rpm of the engine speed, T_{h1}=390 degC, T_{h2}=250 degC and T_r=80 degC. And the maximum shaft power of the reserved engine unit is 3.2 W at 210 rpm of the engine speed, T_{h1}=390 degC, T_{h2}=270 degC and T_r=60 degC.

The shaft power of the each engine units did not reach the target power fairly. It is considered that the engine units have large friction loss between the pistons and the cylinder. In order to improve the engine performance, the engine should have a small mechanical loss and high engine speed.

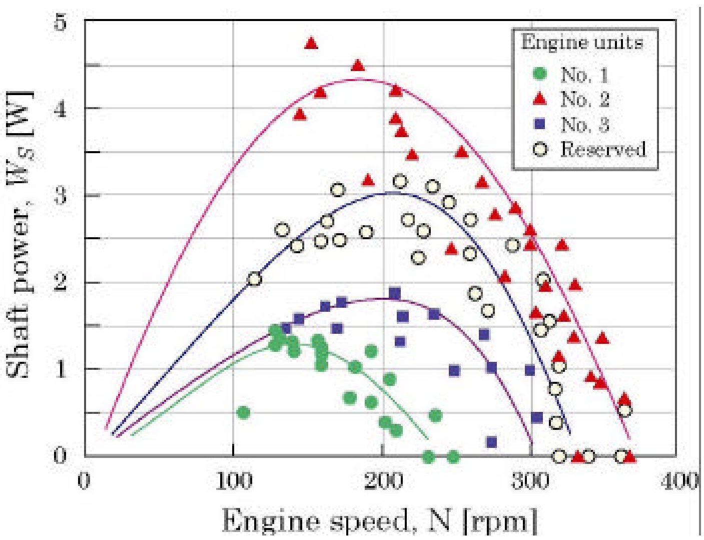


Figure 14, Test Results of Each Engine Units

Based on the above tests, the multi-cylinder Stirling engine is assembled with No. 2, No. 3 and the reserved engine units. Figure 15 shows the relation between the engine speed and the shaft power of the multi-cylinder Stirling engine. Additionally, the test result of the engine assembled with No. 3 and the reserved engine units is shown in the figure. From this figure, the maximum shaft power of the engine is 13.5 W at 210 rpm of the engine speed. This power is bigger than the sum of shaft power of each engine units. It is considered that the multi-cylinder engine has a smaller mechanical loss. The multi-cylinder engine gets a smooth motion with small torque changes in a cycle by plural engine units.

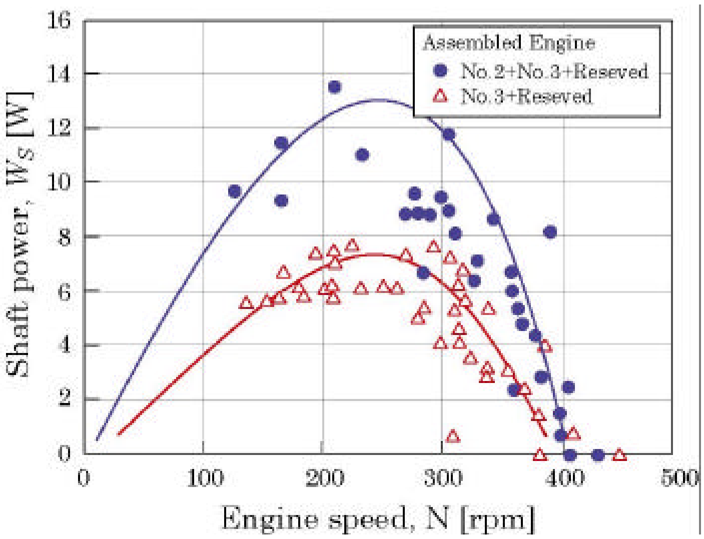


Figure 15, Test Results of Prototype Engine

In the present situation, the prototype engine is operated with the electric heaters as the previous operating test. As the next step, we will try to operate the prototype engine using hot air as the heat source, which is the simulated waste heat.

CONCLUSIONS

In this paper, we discuss a multi-cylinder Stirling engine as the suitable engine structure for a waste heat recovery system. Also we find the optimal conditions for the multi-cylinder engine using a simple analysis model. Based on the analyzed results, a prototype of the multi-cylinder Stirling engine is designed and built for experiments. The prototype engine consists of three engine units, which have different piston stroke.

As the result of the previous operating tests, it is confirmed that the shaft power of the multi-cylinder Stirling engine is bigger than the sum of shaft power of each engine units. Therefore, we consider that the multi-cylinder Stirling engine is effective for the waste heat recovery system.

On the other hand, it is difficult to design the engine units that are fitted to the optimal points. It is required to develop a high accurate simulation for the multi-cylinder Stirling engine.

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