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Study on Design and Performance Prediction Methods for Miniaturized Stirling Engine

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ABSTRACT

This paper shows a design and performance prediction methods for a miniaturized Stirling engine, in order to develop a small portable generator set. First, a 100 W class Stirling engine is designed and manufactured. In order to miniaturize the engine, unique type heat exchangers were applied. A regenerator was located in a displacer piston. For a piston drive mechanism, a Scotch-yoke mechanism which was useful to realize the small-size engine without any lubricating device, was adopted.

Next, an analysis model for the miniaturized engine is developed to improve the engine performance efficiently. The pressure in the working space is analyzed by an isothermal analysis which takes into account a gas leakage through a piston ring and pressure loss in the heat exchangers. To estimate a shaft power, the mechanical loss and the buffer loss, which is caused by a pressure change in a crank case are considered on the analysis model. The calculated results were compared with the experimental data carefully. Then we suggest how to develop practical Stirling engines as a next step.

INTRODUCTION

Recently, the energy and environment problems have become the most serious social problems. So, the low pollution engine is required. The Stirling engine can correspond to such requests. Because, it has excellent characteristics, which are a high thermal efficiency, multi-fuel capability and low pollution.

There are several types of the Stirling cycle machines as shown in Figure 1. They are being researched and developed lively in the world. Especially the Stirling refrigerators are used practically in several fields. Low temperature difference Stirling engines are expected as power sources with a solar or geothermal energy(1). A prototype engine, which is developed in this research is one of the high temperature difference Stirling engines.

As the developments related the high temperature difference Stirling engines, several high performance engines for air conditioners were developed into a Moon-Light project on 1982 in Japan(2). Then, it became clearly that the Stirling engine has high efficient and low pollution characteristics. But the Stirling engine has not reached practical used enough, because It has several problems, which are a high production cost, an endurance of a no-lubricate seal device and a heavy weight.

A purpose of this research is a development of a compact and light weight Stirling engine which is used to drive a portable type generator set.

Problems for developments of the compact Stirling engine are as follows.

1. Development of a high efficient and compact heat exchanger.
2. Development of a compact piston drive mechanism with a small mechanical loss.
3. Estimation of an engine performance and thermal loss accompanied to miniaturize the engine.
4. Accurate estimation of the mechanical loss.

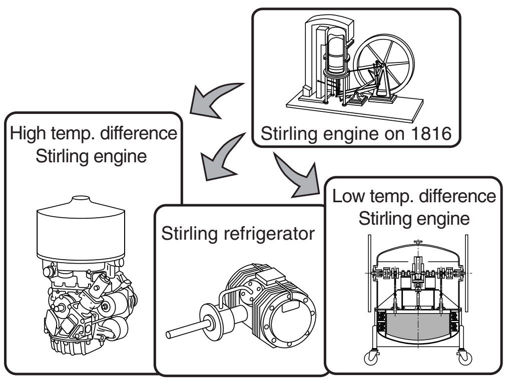


Fig. 1 Stirling cycle machines

This research has suggested as follows in order to solve the problems.

1. Adoption of an original engine structure to miniaturize.
2. Proposal of an unique type heat exchanger for the compact engine.
3. Adoption of a Scotch-yoke mechanism to miniaturize the engine.
4. Estimation of a buffer loss, which is the thermal loss in a crank case.
5. Development of a simple and accurate prediction method for the mechanical loss.

DESIGN OF THE PROTOTYPE ENGINE

DESIGN CONCEPT

The prototype engine aims at compact and light weight. Also it must have a simple structure and a low production cost. Table 1 shows target performance and outline of engine configurations. The target power is 100 W, and the target thermal efficiency is 20 %. These are decided in consideration of a working pressure, temperature and engine weight.

Table 1 Target performance and engine specifications

Output power	100 W
Net thermal efficiency	20 %
Working gas	Helium / Nitrogen
Maximum pressure	1.1 MPa
Max. expansion space gas temp.	650 deg C
Compression space gas temp.	40~70 deg C
Rated engine speed	1000 rpm

In the case of the former high performance Stirling engines, helium or hydrogen has been used as the working gas. But helium is expensive in Japan, and hydrogen is dangerous to explode. On the other hand, it is considered that nitrogen is suitable, because it is low cost and safety. Then the prototype engine uses both helium and nitrogen as the working gas. And it is considered to applicable them after the estimations of the engine performance.

The maximum engine pressure, 1.1 MPa is lower than that of the former engines. It is caused by a portability of the engine. The expansion space gas temperature, 650 deg C is also lower than that of the former engines. In order to reduce the production cost, a general stainless steel is used as a heater material of the prototype engine, though an expensive nickel steel, Hasteloy X is used on many of the former engines.

BASIC STRUCTURE OF THE PROTOTYPE ENGINE

Figure 2 shows a basic structure, which was adopted after considerations about the engine type, a location of the pistons and type of the heat exchangers.

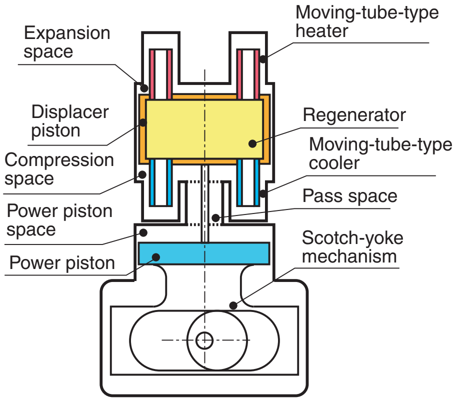


Fig. 2 Basic structure of the prototype engine

A regenerator is located in a displacer piston. The unique heat exchangers named moving-tube-type are located above and below the displacer piston. The heater and cooler consist on inner tubes and outer tubes. The inner tubes move with the movement of the displacer piston. The power piston and displacer piston are located in a line. Then it has been able to realize the compact and light weight engine.

MOVING-TUBE-TYPE HEAT EXCHANGER

Figure 3 shows a comparison of a normal bayonet-type heat exchanger and the moving-tube-type heat exchanger. The moving-tube-type heat exchanger has a simpler and smaller structure than the bayonet-type, though their gas flows are nearly similar. It is difficult to calculate the heat transfer performance of the moving-tube-type heat exchanger, because there are no experimental data for it. So an experimental equation of a shell-and-tubes-type heat exchanger is used the calculation. It is based on the hydraulic diameter of a circular space between the inner and outer tubes.

Figure 4 shows the calculated result of the relation between the engine speed and the number of transfer units, NTU. In the case of the low engine speed, NTU of the moving-tube type heat exchanger is lower than that of the bayonet-type. But in the case of the high engine speed, their difference becomes very small. Then it is considered that the heat transfer performance of the

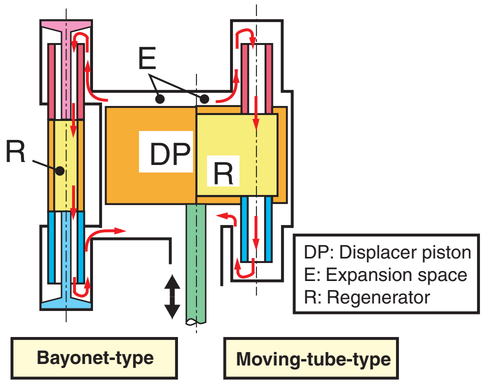


Fig. 3 Comparison of heat exchangers

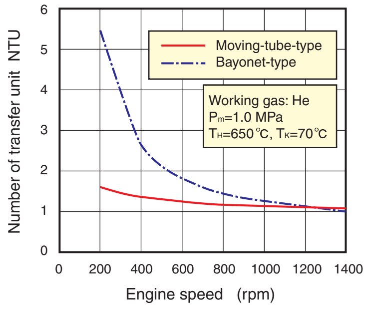


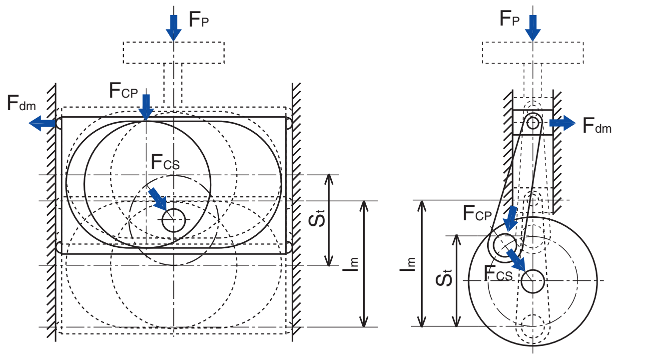
Fig. 4 Number of transfer units function as engine speed

moving-tube-type equals to that of the bayonet-type approximately at the rated engine speed, 1000 rpm.

SCOTCH-YOKE MECHANISM

In order to consider the characteristic of the Scotch-yoke mechanism, it is compared with a cross-head mechanism shown in Figure 5. On their mechanisms, a crank pin force, F_{cp}, a main shaft force, F_{cs} and a guide bearing force, F_{dm} are lead from the piston force, F_p.

Figure 6 shows the calculated results of the relation the standard length, l_m and the mechanical efficiency at the piston stroke, S_T=20 mm. The mechanical loss becomes smaller, when the standard length becomes longer, because the guide bearing force, F_{dm} decreases. This figure shows that the mechanical efficiency of the Scotch-yoke mechanism is higher than that of the cross-head mechanism. Namely, it is considered that the Scotch-yoke mechanism is better than the former cross-head mechanism for the compact engine.



(a) Scotch-yoke mechanism (b) Cross-head mechanism

Fig. 5 Comparison of piston drive mechanisms

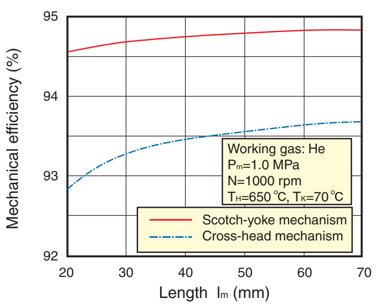


Fig. 6 Mechanical efficiency

CONSTRUCTION OF THE PROTOTYPE ENGINE

After repeats above considerations and the thermal analysis based on an adiabatic model(3), the prototype engine has been manufactured shown in Figure 7. The piston bore and stroke of pistons are each 72 mm and 20 mm.

Figure 8 shows a comparison of the prototype engine and a former high performance engine(4). The prototype engine has been achieved to miniaturize. It is caused that the regenerator is located in the displacer piston. As the result, every space in the engine is used effectively. On the other hand, the former engine is used the cross-head mechanism. The Scotch-yoke mechanism used the prototype engine is effective to miniaturize.

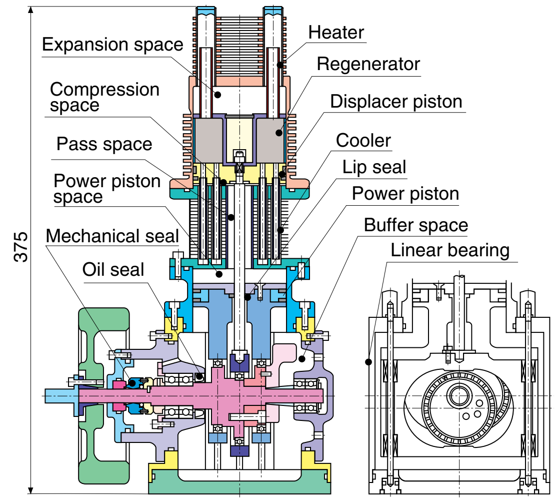


Fig. 7 Schematic view of the prototype engine

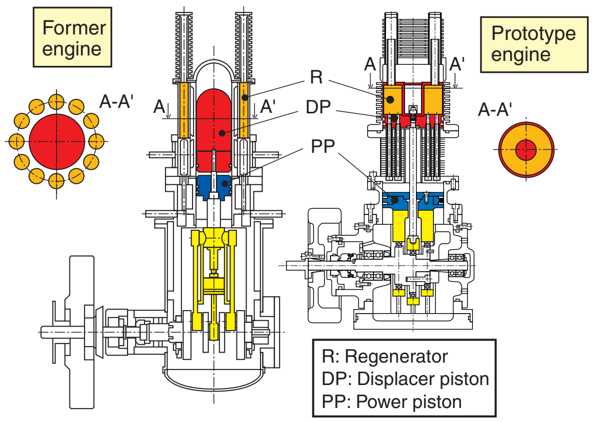


Fig. 8 Comparison of engine types

EXPERIMENTS OF THE ENGINE PERFORMANCE

In order to examine the engine performance and characteristics of the moving-tube-type heat exchangers, the prototype engine is experimented. Experimental conditions are shown in Table 2. An electric heater is used as a heat source, though the prototype engine has been designed using a combustion gas. Because the

Table 2 Experimental conditions

Heat source	Electric heater (~1 kW)
Expansion space gas temp.	490 deg C (±5 deg C)
Working gas	Helium
Mean pressure	0.5, 0.7, 0.9 MPa
Cooling type	Water cooling
Cooling water flux	3 L/min
Cooling water inlet temp.	12 deg C (±0.5 deg C)
Engine speed	500 ~1400 rpm

heat input to the engine can be adjusted easily by the electric heater.

ENGINE PERFORMANCE

Figure 9 shows the experimental result of the relation between the engine speed, the shaft power and the indicated efficiency at the mean engine pressure, P_m=0.5 MPa, 0.7 MPa and 0.9 MPa. The prototype engine can reach the target power, 100 W and indicated efficiency, 22 % at the mean engine pressure, 0.9 MPa and the engine speed, 1100 rpm.

HEAT TRANSFER OF THE HEAT EXCHANGERS

Figure 10 shows the calculated and experimental results of the relation between the engine speed and the number of transfer units, NTU. The calculated results are lead from the experimental equation of the shell-and-tube-type heat exchanger. The experimental results of NTU

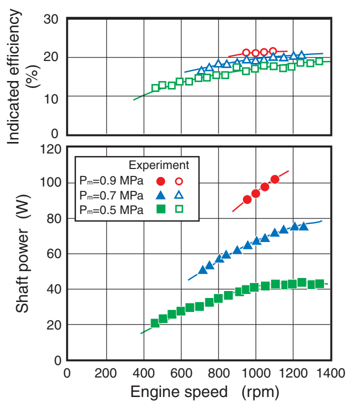


Fig. 9 Engine performance

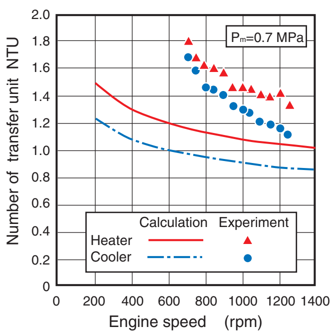


Fig. 10 Number of transfer units as a function of engine speed

are bigger than the calculated results. It is considered that the heat transfer coefficient increases by the complex. Namely, the performance of the moving-tube-type heat exchanger is higher than that of the normal shell-and-tube-type heat exchanger. Then, it is considered that the moving-tube-type heat exchanger is suitable for the compact Stirling engine.

ESTIMATION OF THE ENGINE PERFORMANCE

In order to estimate the detailed engine performance and discuss how to improve the engine performance, it is needed to analyze both the indicated and shaft power accurately. Of course, an accurate analysis method for the indicated power is needed. It also needs to analyze the mechanical loss of the piston drive mechanism and the seal devices, because they affect the performance of the compact engine fairly.

On the other hand, the compact Stirling engine needs to have the buffer space as small as possible, in order to miniaturized the engine. Then it is important that the estimated method for the buffer loss, which is caused by complex thermal changes in the buffer space. Because it also affects the engine performance strongly.

WORKING GAS PRESSURE

Figure 11 shows the analysis model of the prototype engine. The working gas pressure is calculated using an isothermal analysis. As the thermal losses affected to the working gas pressure, a gas leakage from a piston ring and a displacer rod seal, pressure losses in the heater, cooler and regenerator, and effects of sudden expansion and contraction flow in the regenerator are considered.

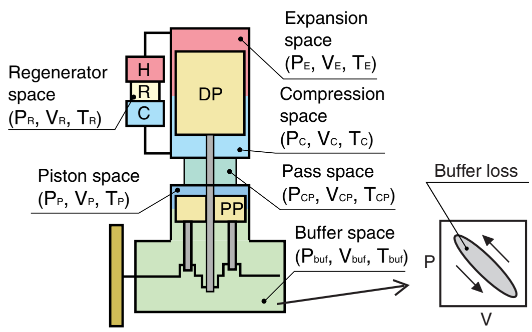


Fig. 11 Analysis model

BUFFER LOSS

In order to determine a suitable analysis method for the buffer space, the buffer loss is calculated with three models as follows.

<u>Isothermal model</u>
The buffer pressure can be calculated easily, under the assumption of constant gas temperature in the buffer space.

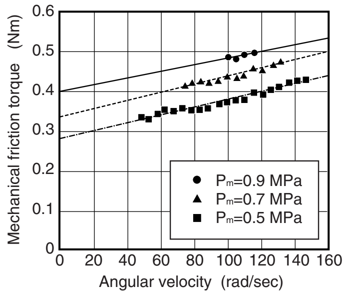
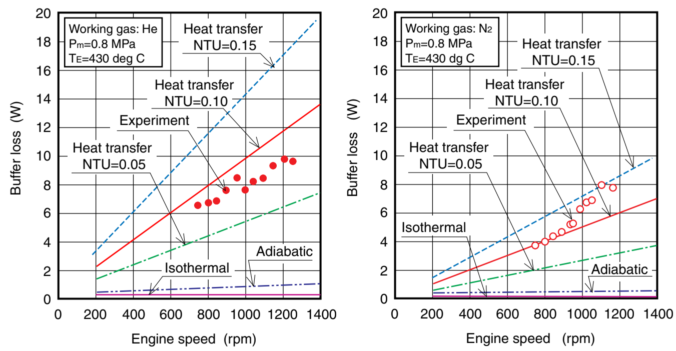


Fig. 12 Friction torque as a function of engine speed



(a) Helium (b) Nitrogen

Fig. 13 Buffer loss as a function of engine speed

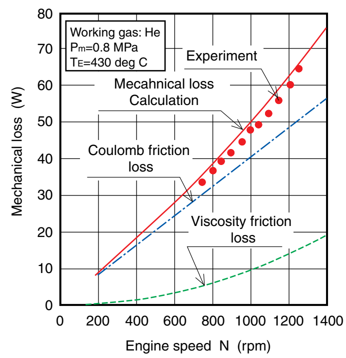


Fig. 14 Mechanical loss as a function of engine speed

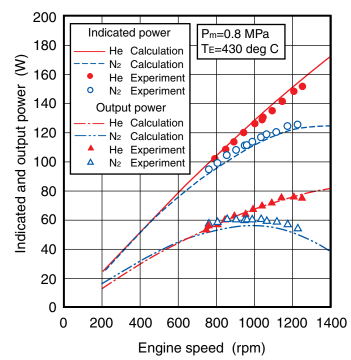


Fig. 15 Power as a function of engine speed

<u>Adiabatic model</u>
The buffer pressure and gas temperature are calculated by a solution of energy equations in the buffer space.

<u>Heat transfer model</u>
As an assumption of the heat transfer model, the wall temperature in the buffer space keeps constant. And the buffer pressure and gas temperature are calculated by the solution of the energy equations. The heat transfer is lead from the number of transfer units, NTU.

MECHANICAL LOSS

As factors of the mechanical loss of the prototype engine, there are piston rings, a lip seal, an oil seal, a mechanical seal and bearings shown in Figure 7. We consider that the mechanical loss can be separate a coulomb friction loss and a viscosity friction loss.

The coulomb friction loss is effected by only vertical force to the mechanical device. So, they can be lead easily by calculations of the mechanical forces.

The viscosity friction loss is effected by velocity of the device. So, it is very difficult to decide a viscosity coefficient analytical, because it is affected the temperature of the working device. Then the viscosity coefficient has been lead by a previous experiment of the prototype engine. Figure 12 shows a relation between the angular velocity and the friction torque. From inclinations of the friction torque, the viscosity coefficient can be lead to 9.0×10^{-4} Nms.

COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

In order to estimate propriety of the analysis method, the prototype engine is experimented with the experimental condition shown in Table 3.

Table 3 Experimental conditions

Heat source	Electric heater (~1 kW)
Expansion space gas temp.	430 deg C (each ±5 deg C)
Working gas	Helium / Nitrogen
Mean pressure	0.9 MPa
Cooling type	Water cooling
Cooling water flux	3 L/min
Cooling water inlet temp.	12 deg C (±0.5 deg C)
Engine speed	500 ~1400 rpm

Figure 13 shows the relation between the engine speed and the buffer loss for both the calculation and the experiment. In this figure, the calculated results of the isothermal model and the adiabatic model are greatly smaller than the experiment results. On the other hand, the results of the heat transfer model correspond with the experimental results, when the number of transfer units, NTU is set to 0.1.

Figure 14 shows the relation between the engine speed and the mechanical loss. This figure shows that the calculation of the coulomb friction loss has a quadratic increasing to the engine speed. This means that effects of piston inertia forces are very small. Also, the mechanical loss can be simulated accurately, when the viscosity friction loss based the previous experiment is considered.

Figure 15 shows the relation between the engine speed, the indicated and shaft power. This figure shows the calculated results agree with the experimental results accurately both the indicated and shaft power. We think that this analysis model is very useful for the design of the compact Stirling engine, because the buffer loss and the mechanical loss are estimated simply.

SUGGESTIONS FOR PRACTICAL STIRLING ENGINE

In this research, the compact Stirling engine for the portable type generator set has been developed. We consider that there are many effective results from the analysis methods to the components' design. In this chapter, we suggest how to develop the practical Stirling engine.

The unique moving-tube-type heat exchanger is developed, and its heat transfer performance is estimated by the simple method. But it has not reached detailed analysis yet. As a next step, we need to construct a database after experiments with the heat exchanger individually.

For the mechanical loss, we confirmed that the analysis method could estimate suitably. But it is very difficult that the viscosity friction loss is predicted before manufacturing the engine. As a next step, we need to construct a database of many Stirling engines.

We confirm that the buffer loss can be estimated by the analysis method using the number of transfer units, NTU. But it is not enough to discuss generalizing. Next step, we need a detailed analysis with the temperature distribution and the gas flow in the buffer space.

As the mechanical device for the pistons, we confirm that the function of the Scotch-yoke mechanism can work enough. But we have not discussed their materials and an endurance performance. An endurance test is needed as next step.

This research has aimed at the development of the portable generator set using the combustion gas. When we consider the energy and environment problems, we should discuss to use the solar and biomass energy like Figure 16.

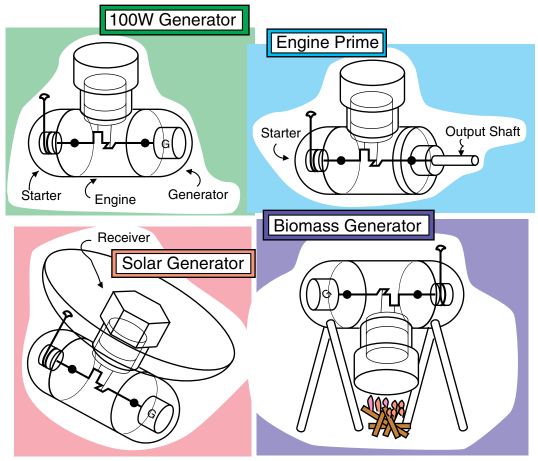


Fig. 16 Major application systems

CONCLUSION

The summary of the results is shown below.

1. The compact and light weight engine is realized by adoption of the unique moving-tube-type heat exchangers
2. The prototype engine is predicted to reach the target performance under the results of the thermal analysis.
3. The prototype engine reaches the target engine power, 100 W and the indicated efficiency, 22 %.
4. The moving-tube-type heat exchanger has the high heat transfer performance.
5. The analysis model which is considered the pressure loss, the gas leakage, the mechanical loss and the buffer loss is presented. It can simulate the engine performance adequately.
6. The buffer loss of the prototype engine is estimated adequately, when it is considered the heat transfer with the number of transfer units, NTU=0.1.
7. The mechanical loss is estimated suitably with the assumption to consist of the coulomb friction loss and the viscosity friction loss.

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CONTACT

The author offers more information related the Stirling engine on the web site. The url is 'http://www.bekkoame.ne.jp/~khirata/'. Any comments are accepted to mail to 'khirata@gem.bekkoame.ne.jp'.

REFERENCES

1. Iwamoto, S., et al., 1997, "Comparison of Low- and High Temperature Differential Stirling Engines," Proceedings, 8th ISEC, p.29.
2. Endo, N., et al., 1988, "Test and Evaluation Method of the Kinematic Stirling Engines and Their Application Systems Used in the Moon Light Project," Proceedings, 4th ICSC, p.315.
3. Kagawa, N., et al., 1995, "Design of Applicative 100 W Stirling Engine," Proceedings, 30th IECEC, p.341.
4. Tsukahara, S., et al., 1988, "Development of 2 kW Stirling Engine," Proceedings, 4th ICSC, p.155.