# STUDY ON A STIRLING CYCLE MACHINE OF 100W DESIGN CAPACITY

*Toshio Otaka, Associate Professor, Department of Science and Engineering, Kokushikan University, Tokyo, 154-8515, Japan*
*Masahiro Ota, Professor, Department of Science and Engineering, Tokyo Metropolitan University, Tokyo, 192-0397, Japan*

**Abstract:** This Stirling refrigerator only imparts a light load to the global environment because it does not use fluorocarbon gas refrigerants. Additionally, it can be said that its theoretical efficiency is identical to that of the Carnot, with this refrigerator being a sustainable refrigerating system. To put the Stirling refrigerator into practical use at room temperature, a smaller sizing, higher durability and higher efficiency are essential. The authors have designed and developed a 100 W class Stirling refrigerator for household use. And the operating characteristics of the machine have been evaluated. In addition, to investigate the possibility of the practical application of Stirling refrigerators to household use, we have designed and fabricated on an experimental basis a 4th prototype Stirling refrigerator which uses a sealed oil-lubrication mechanical section, and we are currently evaluating its performance. As a result, the operational characteristics of the Stirling cycle machine have been clarified with respect to design factors. These results demonstrate that the Stirling cycle machine is one of the promising candidates as a new refrigeration system or a new generation system.

**Key Words:** ***Stirling refrigerator, regenerator, coefficient of performance***

## 1 INTRODUCTION

In recent years, global environmental destruction represented by global warming has become a major issue. The Kyoto Protocol, which was adopted on the basis of international consent to prevent global warming, became effective in February 2005. The development of refrigerators and air conditioners which use refrigerants that do not add to global warming has been urgently called for. Stirling refrigerators use a gas cycle with high theoretical efficiency in which hydrogen, helium or nitrogen, which do not contribute to global warming, are used as a working gas; therefore, such refrigerators are attracting attention for their effectiveness in the fight against global warming.

To date, we have designed and experimentally fabricated a prototype Stirling refrigerator for household use, and have clarified that its performance is equivalent or superior to vapor-compression refrigerators, which are widely and conventionally used, on the basis of performance–evaluation experiments and analyses of a refrigerator (Otaka et al. 2002). To put the Stirling refrigerator into practical use at room temperature, a smaller sizing and higher efficiency are essential. For this purpose, the authors have repeatedly studied the displacer-type Stirling refrigerator (hereinafter, referred to as the “second prototype refrigerator”) that is driven through cylindrical cams (Otaka et al. 2006). However, using the light-weight, flexible matrix in the regenerator to make it more efficient, it reciprocates within the regenerator’s housing, so that the problem will occur wherein a volume fluctuation in residual gases and change in flow loss within the regenerator adversely affect the refrigeration capacity.

In this study the authors have thus contrived an active-type regenerator provided with a matrix piston that deforms the matrix according to the reciprocating motion of the displacer piston, and have actually designed and manufactured a new experimental model (hereinafter, referred to as the “third prototype refrigerator”). Additionally, we have conducted the same experiments as those for the second prototype refrigerator by using a polyurethane foam matrix (hereinafter, referred to as a “urethane matrix”) as the material for the regenerator. This urethane matrix has never been used as the material for a regenerator, and is flexible and restorable if deformed. In addition, to investigate the possibility of the practical application of Stirling refrigerators to household use, we have designed and fabricated on an experimental basis a 4th Stirling refrigerator which uses a sealed oil-lubrication mechanical section, and evaluated its performance.

In these experiments, the authors have grasped the operating characteristics of these Stirling machines and will then report them herein.

## 2 EXPERIMENTAL REFRIGERATOR

### 2.1 3rd Prototype Machine

#### 2.1.1 Outline of Experimental Model

Figure 1 shows a schematic cross-sectional view of the third prototype refrigerator, and Table 1 shows its specifications. The third prototype refrigerator is constructed based on the structure of the second prototype refrigerator, and has the feature that it uses two cylindrical cams. It is hence designed to be able to separately use the cams for the power piston and displacer one through the matrix piston. The matrix piston is driven through its interior cylindrical cam protruding outside. At the same time, the exterior cylindrical cam is a grooved one. The power piston and displacer one are driven through the latter cam. The phase difference between the matrix piston and the displacer piston can be changed in an incremental or excremental angle of 15 degrees.

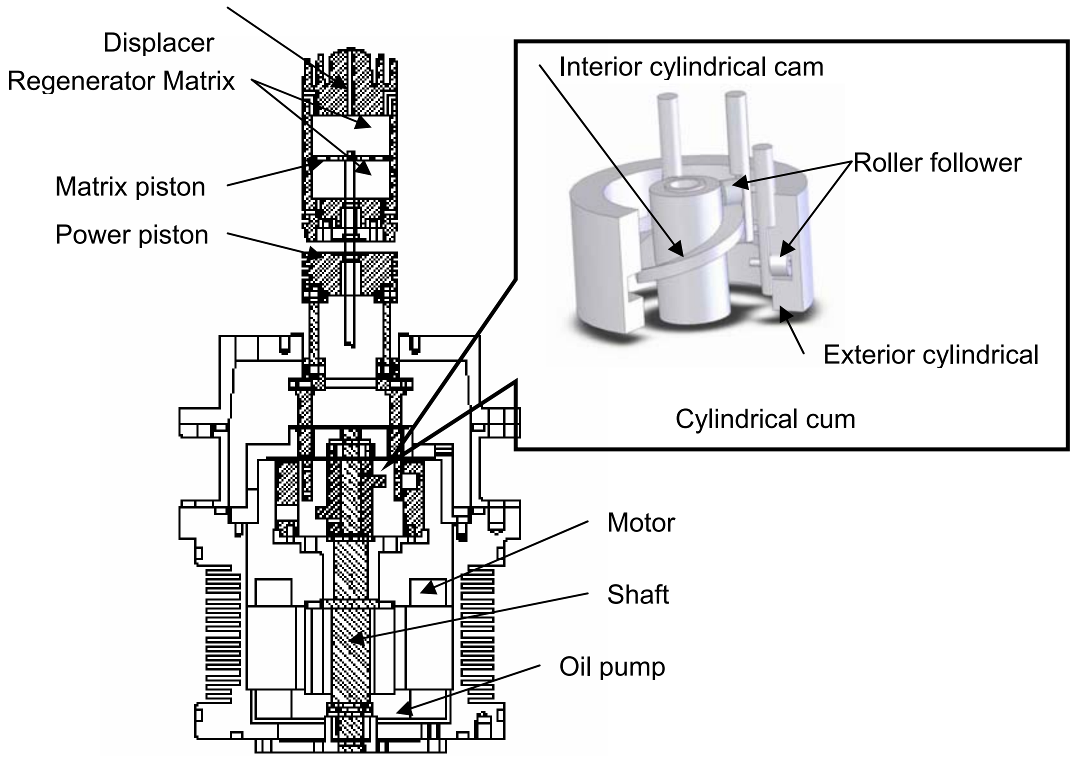



**Figure 1: Schematic Drawing of Stirling Refrigerator with Active Type Regenerator**

**Table 1; Design Specifications**

| Basic form | Displacer type (β-type) |
|---|---|
| Driving system | Cylindrical cam |
| Working gas | Helium |
| Cooling capacity | 100 W |
| Cold side temperature | 233 K |
| Warm side temperature | 313 K |
| Mean pressure | 700 kPa |
| Rotational rate | 16.6 Hz |
| Expansion stroke volume | 56.5 $cm^3$ |
| Compression stroke volume | 56.5 $cm^3$ |
| Total dead volume | 97.99$cm^3$ |

### 2.1.2 Active-type regenerator

In the third prototype refrigerator, the volume of operating gases (helium), which is calculated by the displacement volume of the power piston that compresses and expands the operating gases, is 56.5 cc. On the other hand, the dead space volume is approx. 98.0 cc in total and, out of this, the volume of resident gases within the matrix pore space is 71.4 cc. It is believed that the efficiency of compression and expansion is improved by moving the resident gases within the pore space which occupies the majority of this dead space respectively to the compressing pore space and expanding one. It is the purpose of this active-type regenerator to conduct this movement efficiently. The urethane matrix is compressed and filled one by one in the upper and lower portions of the matrix piston constructed within the displacer piston. In this state, compression and expansion processes are conducted by the matrix piston that can change the phase difference according to the motion of the displacer piston, thus changing the volume of resident gases within the matrix pore space. This structure enables an increase of the efficiency of the regenerator.

The urethane matrix which is used as a thermal storage medium for the active-type regenerator is shown in Figure 2, and the geometrical dimension of the urethane matrix is shown in Table 2. The common multipurpose material is cheap, easy to get, and made of etherate urethane foam (Everlight FLG made by Bridgestone Corp.), with this being used as the material. The common urethane material was processed by stamping with punch dies.
Since the detailed thermal property of the urethane matrix is necessary to identify in the future, both the generic physical property of the urethane foam and for comparison, its physical property in case of 200 of laminated copper mesh generally used as a matrix for the regenerator are shown in Table 3 for reference.

**Figure 2: Urethane Matrix**

The urethane matrix has low thermal conductivity and a high porosity, so that low pressure loss can be expected. The heating storage capacity of the matrix is apt to be lower than that of copper metal because of its
lower density, but the capacity can be compensated for by changing the degree of compression and filling the urethane matrix. Also, it is flexible and has restoring force even after deformation, so it is suited to materials for the active-type regenerator which conducts compression and expansion processes by the matrix piston.

**Table 2; Values of Geometrical Various Urethane Matrix**

| | |
|---|---|
| Diameter | 51 ( mm ) |
| Height | 52 ( mm ) |
| Density | 20±2 ( $kg/m^3$ ) |
| Number of cell | 60 ( number/25mm ) |
| Weight | 2.12 (g) |

**Table 3; Properties of Copper and Urethane Form**

| | Copper | Urethane Form |
|---|---|---|
| Thermal conductivity W/(m･K) | 400 | 0.018~0.042 |
| Density kg/㎥ | 8800 | 12~100 |
| Specific heat J/(kg･K) | 400 | 1800~2800 |
| Porosity | 0.728 | 0.90~0.98 |
| Weight of matrix g | 244.3 | 1.23~10.21 |
| Thermal capacity of matrix J/K | 97.61 | 2.21~28.59 |

## 2.2 4th Prototype Machine

The 4th prototype refrigerator is Type β with Scotch-Yoke Mechanism. Design specifications and the schematic view of the refrigerator are shown in Table. 4 and Figure 3 respectively. The motor is a standard type AC motor. The input power to the motor can be measured by an ammeter.

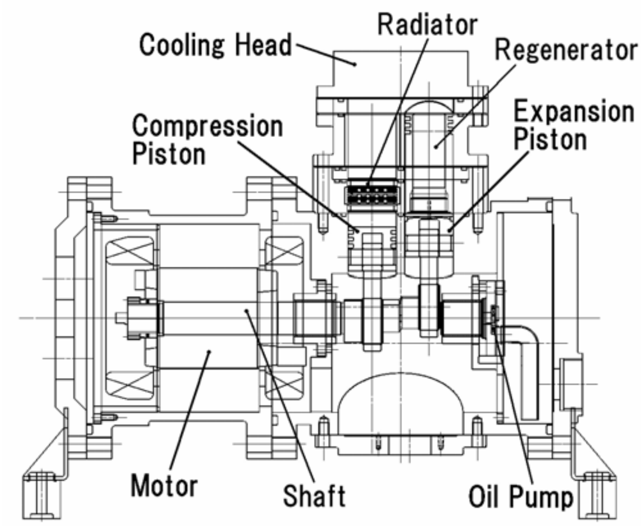



**Figure 3: Schematic View of 4th Stirling Refrigerator**

**Table 4; Specifications of 4th Stirling Refrigerator**

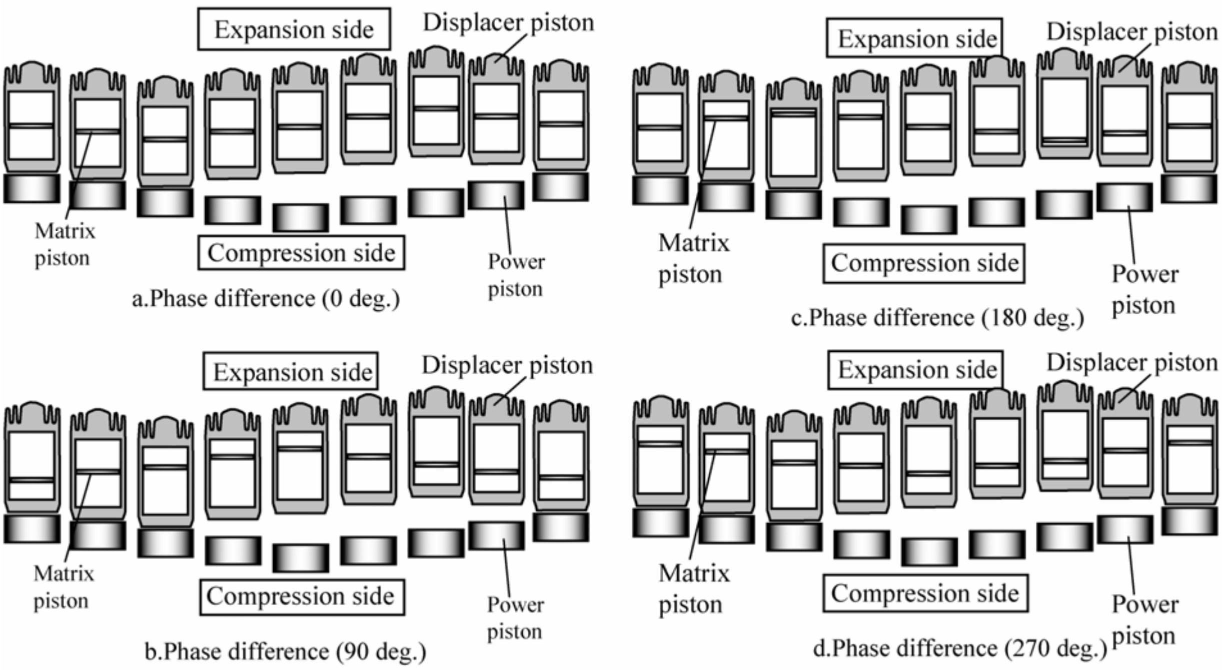
| | |
|---|---|
| Cooling capacity | 100 W |
| Cooler wall temperature | 233 K |
| Radiator wall temperature | 303 K |
| Working Fluid | Helium |
| Width×Height×Depth | 430×380×230 mm |
| Mean pressure (MAX.) | 2.0 MPa |
| Operated speed (MAX.) | 2000 rpm |
| Bore×Stroke | 39×18 mm |

The type of matrix in the regenerator is laminated metallic mesh type. The laminated metallic mesh consists of #100 copper wire mesh and stainless wire mesh. And to decrease the dead volume, it was integrated to the heat exchanger. The wall of the regenerator is made of phenol resin. The hot part of the heat exchanger is water-cooled to keep flowing water at constant temperature. The lubrication oil is ester oil. The lubrication oil at the bottom of the refrigerator is circulated by a positive displacement pump fixed to a motor-driven-shaft through the center of the shaft to the bearing and connecting rod at constant volume rate. The lubrication oil fed to each part returns to the bottom by gravitational drop. In addition, to prevent the lubrication oil from entering the regenerator, an oil guard is applied adequately.

## 3 EXPERIMENTAL RESULTS

### 3.1 Performances of Active-type Regenerator

This section shows the experimental results under the respective experimental conditions of a Stirling refrigerator with the active-type regenerator equipped. The general description of the motion under the respective experimental conditions of the matrix piston and the displacer one and power piston are shown in Figure 4. Also, Table 5 shows experimental




conditions such as the inclusion gas pressure and the operating frequency.

**Figure 4: Phase Difference of Matrix Piston**

**Table 5; Experimental Conditions**

| | |
|---|---|
| Mean pressure kPa | 300 |
| Rotational rate Hz | 9~11 |
| Radiator temperature K | 303 |
| Cooling head temperature K | 273 |
| Working gas | Helium |

In Figure 5, the impact of the phase difference on refrigeration capacity is shown. In Figure 6, the impact of the phase difference on COP is shown. According to Figures, the highest performance is seen at a phase difference of 180 degrees, and the value of the refrigeration capacity is at its maximum approximately 1.3 times higher than that at the phase difference of 0 degrees, and the value of the shown COP is at its maximum approximately 1.5 times higher than the same. It is believed that the reason for this is as follows: if the phase difference of the matrix piston is 180 degrees and when the isothermal compression process of the Stirling cycle is performed during the operation of the third prototype refrigerator (the position or phase of the displacer piston: 0-90 degrees), the urethane matrix filled in the lower portion of the matrix piston is compressed toward the compression space side and thereby largely deformed. As such, the gases cannot resultantly pass through the urethane matrix, which will serve as a valve that temporarily isolates the compression space from the resident gasses within the pore space of the urethane matrix filled in the upper portion of the matrix piston, with its compression efficiency acquired. When the isothermal expansion process of the Stirling cycle is performed during the operation of the third prototype refrigerator (the position or phase of the displacer piston: 180-270 degrees), gases expand efficiently, so it is believed that performance has increased.

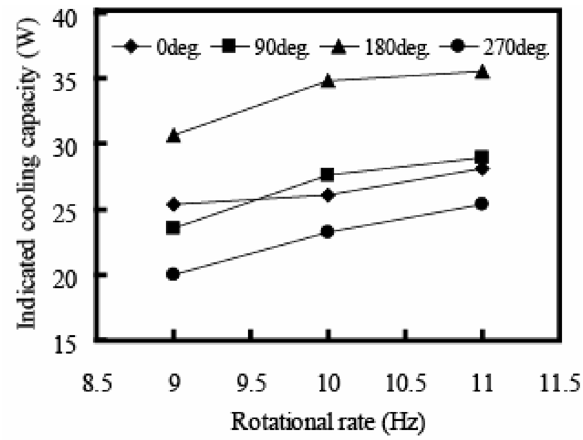



**Figure 5: Effects of Phase Difference on Indicated Cooling Capacity**

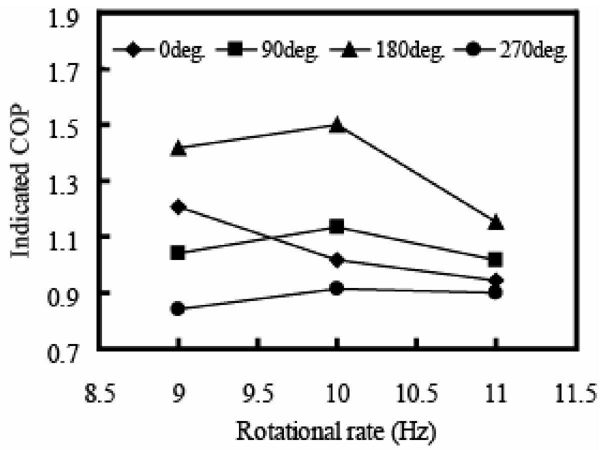



**Figure 6: Effects of Phase Difference on Indicated COP**

### 3.2 Performances of the 4th Prototype Regenerator

At first, the cooling experiment was conducted on the experimental model. At the starting of this experiment, the temperature of the cooling head was 297K. The temperature variation with time is shown in Figure 7. The wall temperature of the cooling head falls immediately after the operation starts and the cooling speed is accelerated. The trend slows down after 20 minutes and finally after 40 minutes the temperature 256K is attained. After that, however, the temperature gradually rises. This is supposedly caused by a lot of oil entered into the regenerator which decreases operating space and results in decrease of cooling capacity, and by the transmitted heat from the motor through the oil.

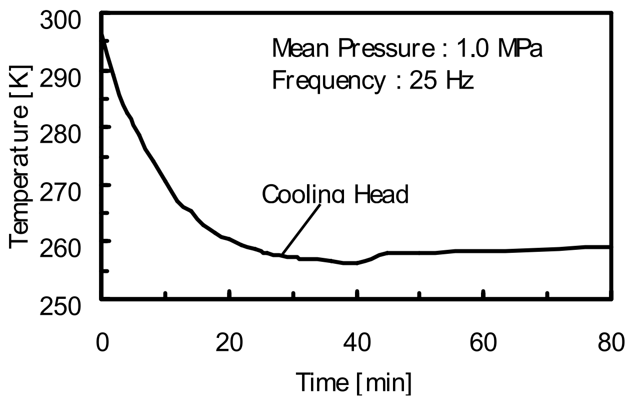



**Figure 7: Cooling Test Results**

Then, to evaluate the effect of oil, a comparative P-V analysis was conducted on the enclosed matrix and nothing matrix in the regenerator. The crank angle being detected by a gap sensor, the pressure in the expansion room and compression room was measured by sensors and the data were transmitted to the pressure amplifier. The detected crank angles and the outputs from the pressure amplifier were recorded in the computer. The pressure conversion from outputs of the pressure amplifier and calculation of crank angle into the operation space volume were performed in the computer using prearranged conversion formula. Using the calculated data, the P-V diagram was illustrated.

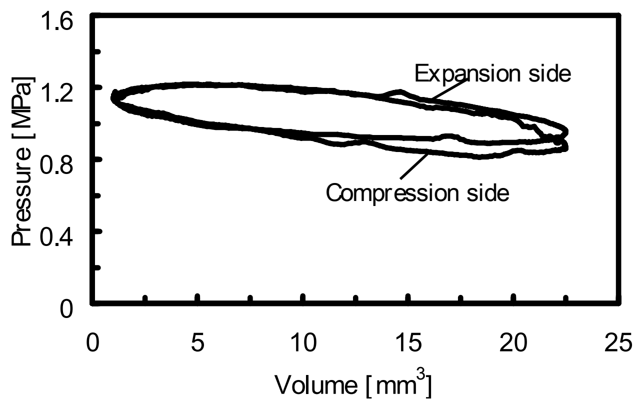



**Figure 8: P-V Diagram of Nothing Matrix**

Figure 8 shows the measurements with the nothing matrix in the regenerator. The pressure variation amplitudes on both of the compression side and expansion side are very close, which means the pressure loss is almost nil.

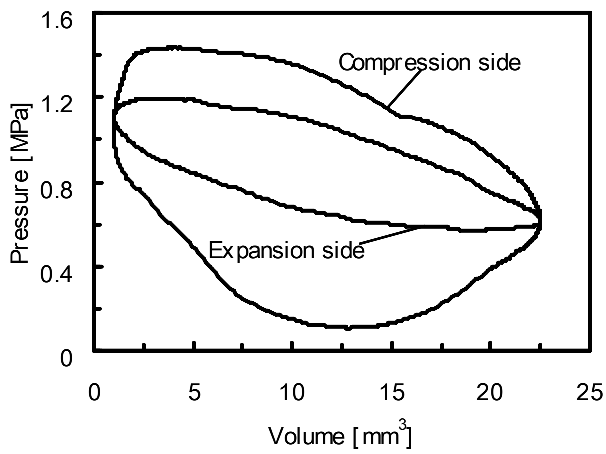



**Figure 9: P-V Diagram of Enclosed Matrix**

Figure 9 shows the measurements with the enclosed matrix in the regenerator. The pressure variation amplitude of the expansion side is smaller than the compression side, which means that the pressure loss is larger. The result of this experiment shows the pressure ratio of the expansion side to compression side is 1:2. This is supposedly caused by oil clogging in the regenerator matrix. It was confirmed that when the cooling head was disassembled after the experiment, the existence of contaminated oil in the regenerator was visually found.

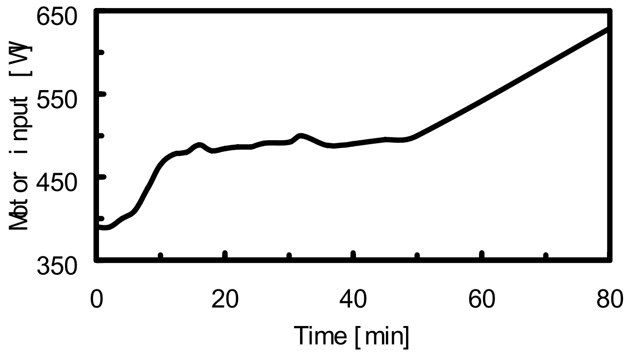



**Figure 10: Motor Input**

Figure 10 shows the trend of the motor input with time. At the start of the experiment, the motor input is 390W. After 10 minutes, it rises to 465W. The increase shows the motor workload for abrupt increase of cooling work. After that it is gradually rising up to 50 minutes, which shows the motor load is in a stable and semi-regular condition. During this stage, however, the oil, little by little, enters into the regenerator and the motor input gradually increases. After 50 minutes, the motor input rapidly increases, and at 80-minute point, it records 629W. In addition, the time when the motor input starts rising is nearly equal the time when the temperature of the cooling head starts rising. This may be caused by a lot of oil entered into the regenerator resulting in creation of considerable resistance.

## 4 CONCUSION

We have contrived an active-type regenerator provided with a matrix piston that deforms the matrix according to the reciprocating motion of the displacer piston, and have performed experiments after mounting the urethane matrix on that. At that time, the availability of a regenerator for a Stirling refrigerator as a new system can be verified. Moreover, the operating characteristics of the Stirling refrigerator with an oil-lubrication mechanism were evaluated by its experiment. Our resultant conclusions are as follows:

(1)It has been confirmed on the Stirling refrigerator with the oil-lubrication not having any sealing mechanism that when a lot of oil enters into the operation space, the operation space reduces and causes lower cooling capacity.

(2)It has been clarified through the experiment that when the oil enters into the regenerator, the regenerator matrix is clogged with the oil resulting in larger pressure loss. In this experiment, the pressure ratio between the expansion side and compression side is approximately 1:2.

In the future, adequate oil volume is to be studied for further improvement of performance.

## 5 REFERENCES

Otaka,T., Ota,M., Murakami,K., Sakamoto,M., Study of Performance Characteristics on a Small Size Stirling Refrigerator, Heat Transfer - Asian Research, Wiley Periodicals, Inc.31 (2002-5), pp.344-361.

T. Otaka et al., Thermodynamics Characteristics of Hybrid Regenerator for Stirling Refrigerator, Proc. The 3ed Asian Conference on Refrigeration and Air-conditioning, (2006), pp.753-756. Gyeongju