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Study on a Stirling cycle machine as a household refrigerator - the technical points and prospects for practical use

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Abstract. The greenhouse effect by carbon dioxide issue would make better recognizing the importance of efficient use of energy in terms of high energy conservation measures. Accordingly, attention is drawn to the Stirling refrigerator, which is a perfect Freon free refrigerator. The Stirling cycle has the highest theoretical cycle efficiency corresponding to the value of the Carnot cycle among the proposed thermodynamic cycles. Stirling refrigerators as household refrigerators with high efficiency and high cooling capacity have received limited studies. The authors have designed and developed a 100 W class Stirling refrigerator for household use. This paper presents some thermodynamic characteristics shown by PV analysis and experiments on a Stirling refrigerator with a hybrid regenerator made of copper matrixes and resin matrixes. Then we performed analysis and evaluation experiments using the 100 W capacity prototype refrigerator using the hybrid regenerator, with the aim of applying Stirling refrigerators to household use. These results demonstrate that the Stirling refrigerator is one of the promising candidates as a new refrigeration system or a new generation system. Moreover, this paper proposes the small-size Stirling refrigerator with an active-type regenerator. Then the technical points for practical use were arranged.

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. Development of global warming restraint technology must be promoted still more by Paris protocol. Therefore, 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[1]. 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 that is driven through cylindrical cams. 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. 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. These results demonstrate that the Stirling refrigerator is one of the promising candidates as a new refrigeration system or a new generation system. Moreover, this paper proposes the small-size Stirling refrigerator with an active-type regenerator. Then the technical points for practical use were arranged.

2. Brief description of Stirling household refrigerator

Currently, Stirling refrigerators are practically used as cryo-coolers[2], commercial freezers[3][4][5], and small refrigerators for outdoor use; however, in the case of household refrigerator-freezers, no practical products have yet been developed, although several prototypes have been reported. One reasons for this is the high quality and high performance of the currently-used vapor-compression refrigerators in the temperature range between 253 K and 313 K, which is the operating temperature range of household refrigerators; in addition, these conventional refrigerators are superior in terms of the ease of production and cost. Furthermore, in Japan, high efficiency, low cost, high durability and high quality required for household refrigerators are further reasons preventing the practical application of Stirling refrigerators. However, in addition to the high efficiency that can be expected in Stirling refrigerators, they have many advantages as household refrigerators, as listed in Table 1. For example, with Stirling refrigerators, temperature can be easily controlled via the operating frequency, and a temperature range, such as between 233 K and 193 K, which is lower than the conventional working temperature range of household refrigerator-freezers, can be easily set. In contrast, in the case of vapor-compression refrigerators which use HFC134a (or hydrocarbon) as refrigerant, since the inlet pressure of the compressor is lower than the atmospheric pressure in the temperature range indicated, a 2-step cooling method is required, which makes the equipment very large. Furthermore, the performance of Stirling refrigerators varies depending on the charged gas in addition to the operating frequency; therefore, one model of a Stirling refrigerator can be incorporated in refrigerators with different capabilities, which will make it superior in terms of mass production.

Table 1. Advantages
Freon Free
(Commonly using an inert gas)
Wide cooling temperature region
(even at under 233 K)
High theoretical efficiency
Simple construction
Safety

3. Prototype Refrigerator

Table 2 lists the specifications of a prototype Stirling refrigerator connected to a freezer and evaluated. Since the prototype unit was designed for evaluation, a ball bearing was used for the mechanical section, and sliding parts were basically oil-free. Fig. 1 shows the structure of the prototype unit. The β-type prototype unit minimizes the dead volume, and a regenerator is incorporated into the displacer.

At the cylinder head and the tip of the displacer where the temperature becomes low, interdigitated fins are installed to promote the heat transfer between the cylinder wall and expansion gas.

The measured COP curves are shown in Fig. 2 in order to evaluate the operating characteristics of the prototype refrigerator. When a cooling head temperature were 253 K and 233 K, we obtained maximum COP of 1.05 and 0.70 respectively for the testing conditions of a 0.7 MPa mean pressure of Helium and a frequency of 11.7 Hz. Mechanical parts and performance of the electrical motor is not optimized, and major losses occur in power transmission process accordingly. However, it seems that these results demonstrate that the Stirling refrigerator will be a promising candidate for a household refrigerator.

Table 2 Specifications

Cooling capacity	100 W
Cooler wall temperature	233 K
Radiator wall temperatu	303 K
Working fluid	Helium
Width∗Height∗Depth	260∗320∗130 (mm)
Bore∗Stroke	60∗20 (mm)
Mean pressure	0.7 MPa (Max.1.0 MPa)
Piston speed	16.7 Hz (Max.25 Hz)
Regenerator matrix	Wire mesh (Cu,#100,ϕ50

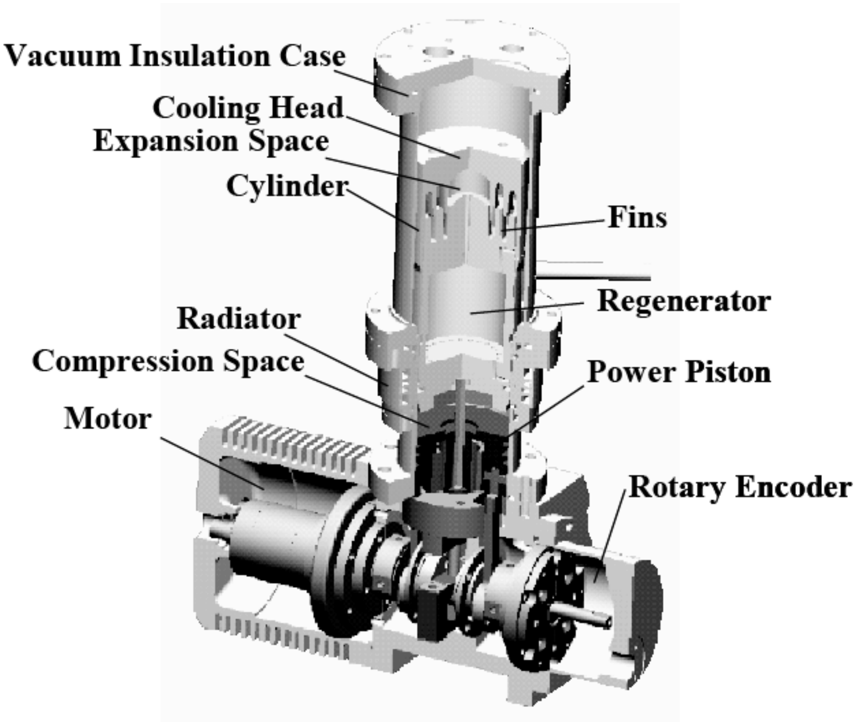

Fig. 1 Schematic view of prototype refrigerator

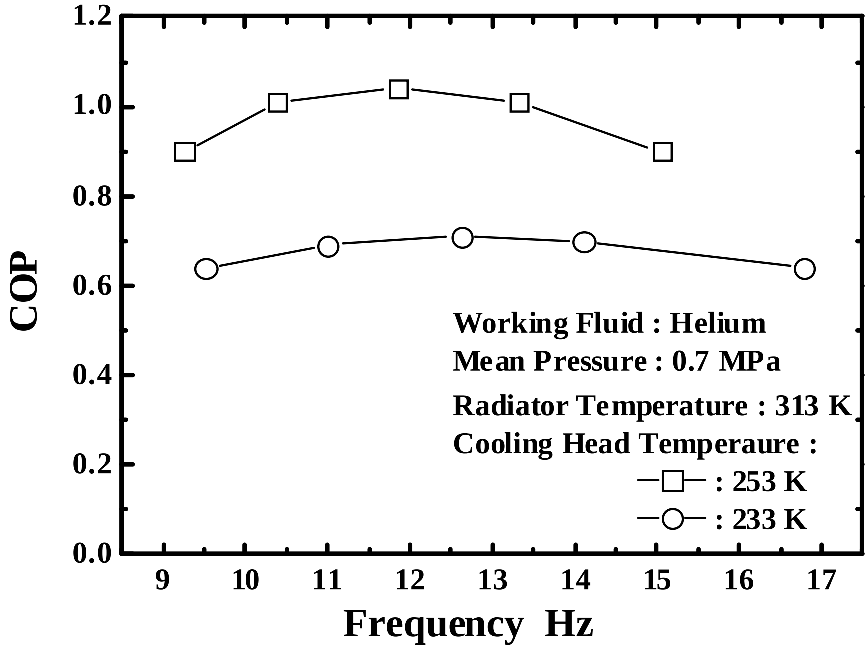

Fig. 2 COP Curves

4. 3rd Prototype Refrigerator

4.1. *Outline of The 3rd Machine*

Figure 3 shows a schematic cross-sectional view of the third prototype refrigerator, and Table 3 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.

Table 3 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
Exp. stroke volume	56.5 cm^3
Comp. stroke volume	56.5 cm^3
Total dead volume	97.99cm^3

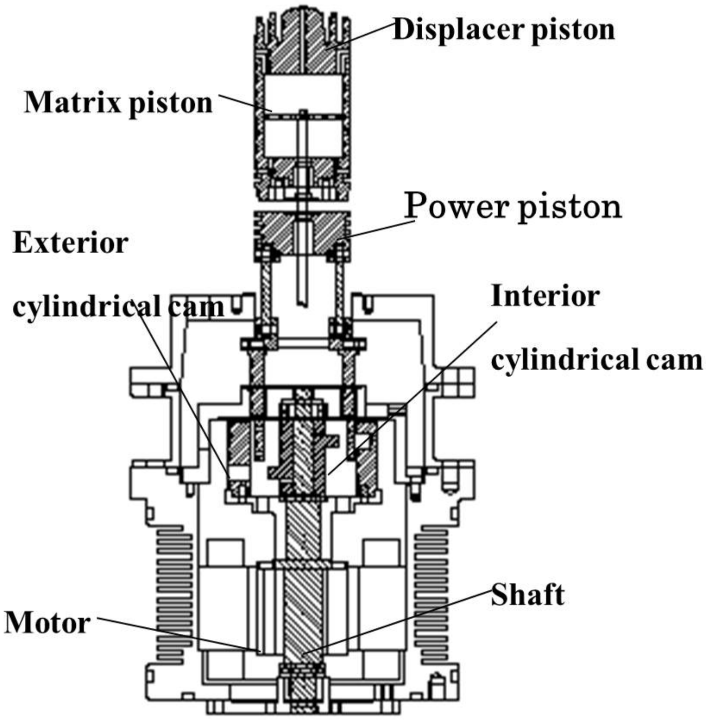

Fig. 3 Schematic view of 3rd prototype refrigerator

Fig. 4 Urethane Matrix

4.2. *Active-type Regenerator*

In the 3rd 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 4, and the geometrical dimension of the urethane matrix is shown in Table 4. 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.

Table 4 Geometrical Value of 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 5 Properties of Copper and Urethane Form

		Copper	Urethane Form
Thermal conductivity	W/(m・K)	400	0.018~0.042
Density	kg/m^3	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

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 5 for reference.

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.

Figure 5and 6 show the experimental results under the respective experimental conditions of a Stirling refrigerator with the active-type regenerator equipped. 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.

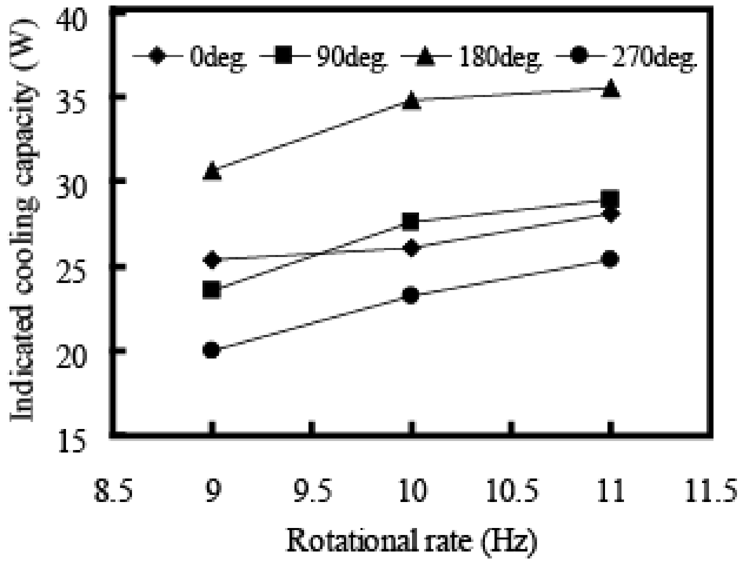

Fig. 5 Effects of Phase Difference on Indicated Cooling Capacity

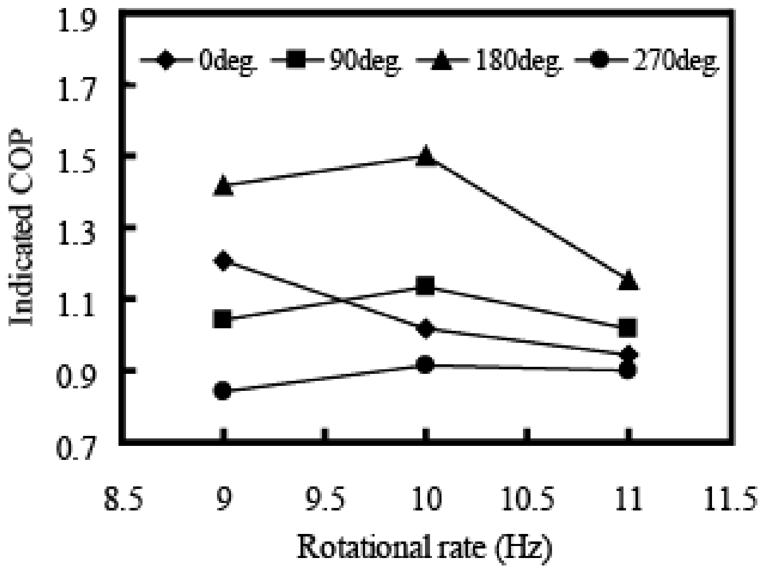

Fig. 6 Effects of Phase Difference on Indicated COP

4. 4th Prototype Machine

The 4th prototype refrigerator is driven with crank mechanism and an AC motor. Design specifications and the schematic view of the refrigerator are shown in Table 6 and Figure 7 respectively. The motor is a standard type AC motor. The input power to the motor can be measured by an ammeter.

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. Then 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.

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 8. 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. This matter is cleared up by intermittent driving for oil return.

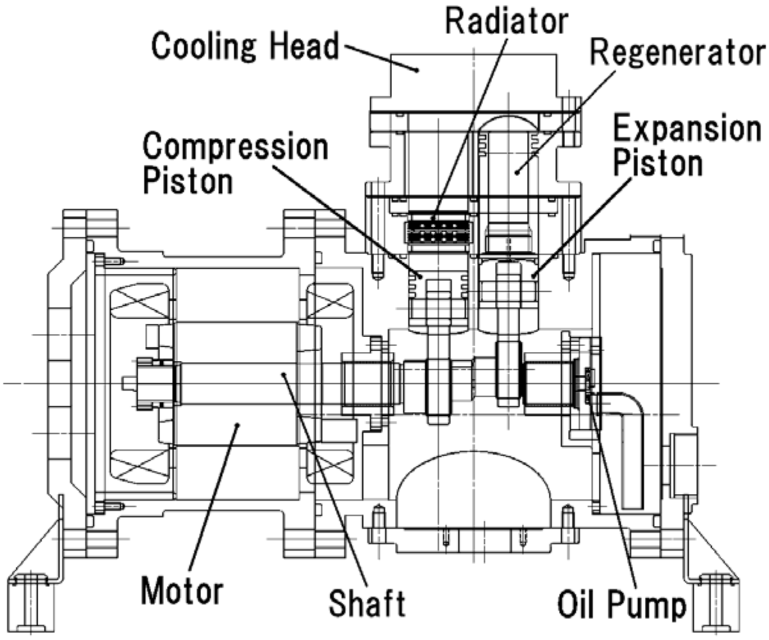

Fig. 7 Schematic View of 4th Stirling Refrigerator

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

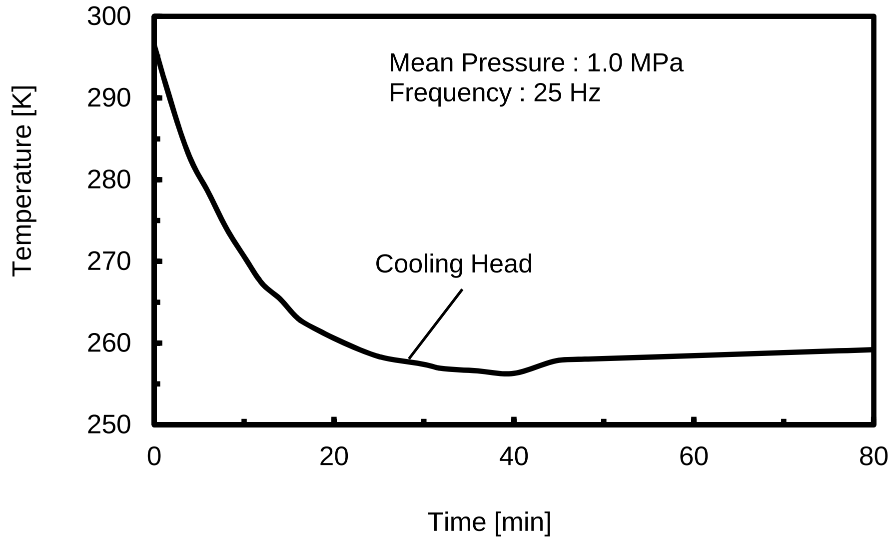

Fig. 8 Cooling Test Results

5. Conclusion

We have designed and developed a 100 W class Stirling refrigerator for household use. Then we performed analysis and evaluation experiments the 100 W capacity prototype refrigerators, with the aim of applying Stirling refrigerators to household use. Moreover, 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 could be verified. These results would promize practical use of the Sterling refrigerator as a new household refrigerator.

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