Study on a Displacer Type Stirling Refrigerator as a Household machine

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Abstract

Environmental concerns are causing commonly used chlorofluorocarbon (CFC) refrigerants to be phased out of production. The less ozone-depleting HCFC's will be regulate in the near future. The green house effecting HFC's are also likely to be regulated and banned in the next 10-20 years. Accordingly, attention is drawn to the Stirling refrigerator, which is a perfect a freon free refrigerator. Moreover, The Stirling cycle has the highest theoretical cycle efficiency corresponding to the value of the Carnot cycle among the proposed thermodynamic cycles. The green house effect by carbon dioxide issue would make better recognizing the importance of efficient use of energy in terms of high energy conservation measures. Stirling refrigerators have been put to practical use in the fields of super conduction and space engineering. In general, it has been applied to low cooling capacity cryo-coolers, in order to obtain temperatures in the 10-15K range. However, Stirling refrigerators as household refrigerators with high efficiency and high cooling capacity have received limited study. A 100 W class Stirling refrigerator as a household refrigerator has been designed and constructed that operates. The operating characteristics of this refrigerator have been evaluated and are presented in this paper.

A prototype household Stirling cycle refrigerator employing helium as working fluid has been investigated whether a freon free machine be a viable alternative for a current household refrigerator. Attention is focused on the effects of a light, nylon mesh regenerator integrated in the displacer on performances of the prototype refrigerator. The nylon matrix has approximately 80 % of refrigeration capacity of copper matrix. The findings suggest that a refrigerator better optimized for the nylon matrix regenerator would be highly competitive to the HFC based refrigerators currently available as well as a base-line Stirling cycle refrigerator.

1 Introduction

There is increasing global concern regarding environmental issues such as green house effect and depletion of ozone layer. With respect to chemical substances including freon refrigerants which contribute to global warming, their reduction in a step-like manner is being carried out based on an international agreement. In addition, the regulation of the production and use of specified freons that contribute to the mechanism of ozone-layer depletion has already been realized. Under these circumstances, interest directed toward safe and highly efficient new cooling systems which use naturally available refrigerants instead of artificial chemicals which may induce unknown problems in the future as in the case of freon refrigerants, has been increasing.(1)

Stirling refrigerators employ a gas cycle which uses natural refrigerants such as helium and nitrogen, and have superior characteristics in that their theoretical efficiency is equal to the

Carnot efficiency . Therefore, high efficiency can be realized. However, in terms of practical application, while cryo-coolers [2] and commercial-use freezers[3] exist, the use of Stirling household refrigerators which operate with a lower temperature difference than engines and cryo-coolers is limited and only several research reports exist;[4] in these Stirling household refrigerators, the cooling capacity is 50-200 W and the operating temperature range is ±50 K. A major reason for the limited application of Stirling refrigerators is that, vapor compression-type refrigerators which are already spreading in household refrigerators are close to perfect conditions, and the necessity to develop other refrigeration systems is low.

Aiming at the development of a Stirling refrigerator as a new alternative for the vapor compression-type refrigerators for household use, we experimentally fabricated a β -type Stirling refrigerator prototype model (hereafter called the prototype refrigerator) with 100-W cooling capacity, and also constructed its operation simulation model using a quasi-steady-flow model. Then, we examined the basic performance of the refrigerator using the simulation model and operation speed and inclusion pressure as parameters.[5] The results revealed that the application of Stirling refrigerators to household use is promising. In household refrigerators, efficiency is one of the most important factors. Detailed optimal design should be applied to improve refrigerator efficiency. However, analyses of household Stirling refrigerators in terms of the efficiency are not sufficient. Therefore, in this study, we investigated parameters that significantly affect the efficiency such as the type of dead space and regenerator materials.

2 Household Refrigerator

In household refrigerators, efficiency is one of the most important factors in Japan. The changes of the consumption electric power in Japanese typical refrigerators is shown in figure 1. The amount of consumption falls right down from 1976 to 1982. The main reason is that the efficiency of the refrigerator is increasing. There is a leveling out from 1982. From this year, the typical type refrigerator has 4 or 5 doors. From 1986, Japanese manufacturer began the change of

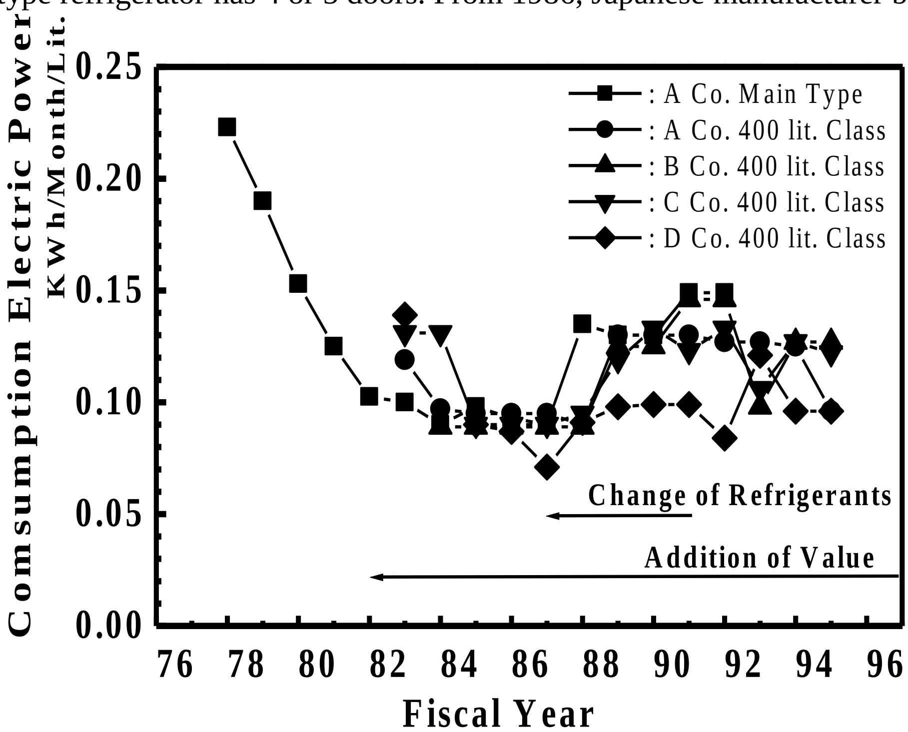

Figure 1 Changes of the consumption electric power

refrigerants. Table 1 lists the efficiencies. Stirling refrigerators have superior characteristics in that their theoretical efficiency is equal to the Carnot efficiency . Therefore, high efficiency can be realized. However, actual efficiency of prototype Stirling refrigerator is lower than the vapor compression refrigerator.

Table 1 Theoreical efficency

	Theoretical Efficency	Actual Efficiency
Vaper Compression refrigerator Refrigerant:HFC134a	About 390%	150〜170%
Stirling Refrigerator Refrigerant:Helium	490%	Prototype About 110%
Cooling Capacity : 100W Conditions : 253〜303K		

3 Description of The Prototype Refrigerator

We evaluated the performance of a Stirling refrigerator using the prototype refrigerator which was designed and fabricated for experimental use. In this section, the specifications and structure of the prototype refrigerator are described.

3-1 Specifications

Table 2 lists the specifications of the prototype refrigerator used for the evaluation experiments. First, the cooling capacity and operating temperature range which are the basic specification parameters of refrigerators are described. The cooling capacity was set to be 100 W in the experimental use so that a large-capacity power source for driving the motor would not be required. This value corresponds to the cooling capacity for a 200l-class small refrigerator, which is suitable for the evaluation experiments. The operating temperature range was set to be between 233 K and 303 K. We define the operating temperature range for household refrigerators to be from room temperature to the temperature necessary to freeze foods, and the range for the prototype refrigerator was set as above. As a working fluid, we used helium gas

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,ϕ5

which is used fairly frequently for Stirling engines and refrigerators, because we consider it to be appropriate for clarifying basic operating characteristics of the prototype refrigerator. The sealing pressure is 1.0 MPa at the maximum. In general, as the sealing pressure of a refrigerator increases, and as the operating frequency increases, the output increases. Overseas, there is a design of a Stirling refrigerator which operates with high-pressure sealing of over 1.0 MPa.[(6)] However, we determined the sealing pressure used in this study considering legal issues in Japan.[(7)] Investigations should be conducted from the viewpoint of determining the future increase in the pressure of refrigerators considering the legal and technological aspects. Based on these parameters for the prototype refrigerator, we determined the general operation frequency of the refrigerator and operation space volume, and dimensions of the regenerator and the heat exchanger. The usual operating frequency of the refrigerator was determined to be 16.7 Hz, based on a detailed survey on the diameter and stroke distance of the piston; in this determination, we took into consideration the sliding limit velocity and safety margin of the Teflon piston ring used in the prototype refrigerator. In addition, during the basic design of the refrigerator, we partially adopted the numerical analysis code[(8)] developed for Stirling engines. We used a copper material having good thermal characteristics in the operating temperature range as the matrix of the regenerator; 200 units of No. 100 wire mesh with element wires of ϕ 0.1 diameter were installed. The dead volume ratio was 1.3.

3.2 Structure

Figure 2 shows the structure of the prototype refrigerator. In order to optimally minimize spaces other than the working space (compression room and expansion room), i.e., so-called dead volume, and to reduce the deterioration level of the performance due to a decrease in compression ratio, the β-type is adopted, in which the displacer with a built-in regenerator and the power piston are connected in serial configuration in the cylinder. Inside the cylinder of the cooling head which becomes a low-temperature tip, coaxial fins are placed so that they are mutually interlocked with the tip of the displacer, in order to promote the transfer of heat to the expansion gas. The displacer is made of glass-fiber-reinforced phenol resin, aiming at the suppression of the thermal loss at both tips of the displacer and at reducing the weight. An electric heater is attached to the cylinder head; the cooling capacity is determined by the power

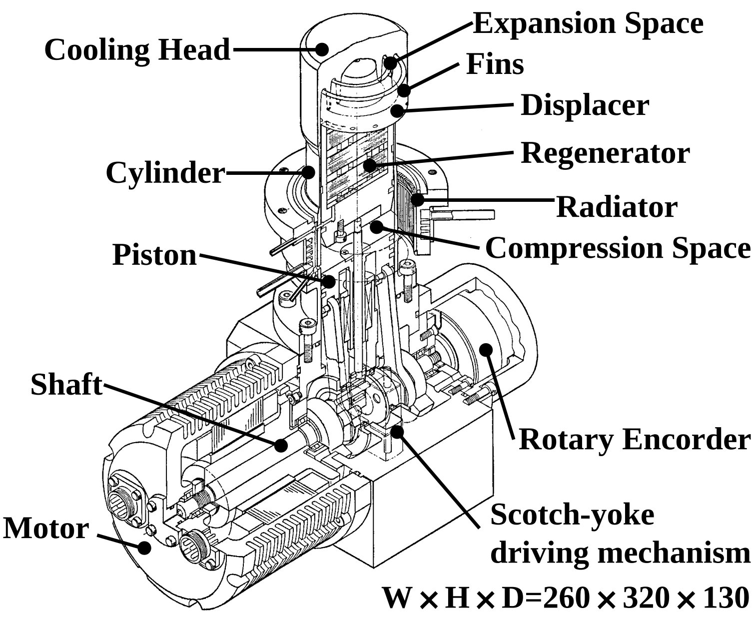

Figure 2 Schematic view of prototype refrigerator

insulator container and irradiation shield sheet. A water-cooling-type radiator is installed around the cylinder with consideration given to the ease of experiments. A DC 200 W servomotor is equipped to provide sufficient output for evaluation of the basic operating characteristics; the power is transferred via the piston using a scotch-yoke mechanism. As a driving mechanism, there is an example of a setup adopting a free-piston system;[9] however, in our study, we adopted a crank driving system equipped with the scotch-yoke mechanism from the viewpoint of simplifying the operation control and reducing the weight of the refrigerator. In the refrigeration unit installed in a household refrigerator, high efficiency, small size and light weight are the important factors to consider. To improve the efficiency of free-piston system refrigerators, a reduction in the weight of the piston is essential, however, the accompanying operating control procedure becomes complex; we adopted the scotch-yoke system to avoid these technological problems.

4 Effects of Dead Volume

Dead volume is one of the factors which significantly affects the performance of Stirling refrigerators. Large dead volume promotes reduction in the efficiency caused by a decrease in the compression ratio. In the case of Stirling refrigerators, since dead volume resulting from essential elemental components such as a heat exchanger and regenerator exists, how to reduce the dead volume is an important consideration for the design. We investigated the effects of an increase in the dead volume on the performance.

Figure 3 shows dead volume of prototype Stirling refrigerator which is analytic result used *"Pro/Engineer"* as high-end 3D-CAD. Table 3 lists the breakdown of the dead volume inside the working space of the prototype refrigerator. The regenerator accounts for most of the dead volume, 66.0%. However, since the filling density of a regenerating material which generates the dead volume inside the regenerator is closely related to the thermal efficiency of the regenerator and the flow resistance of the working fluid, these factors should be sufficiently taken into consideration when designing a regenerator. Similarly, a radiator should have a

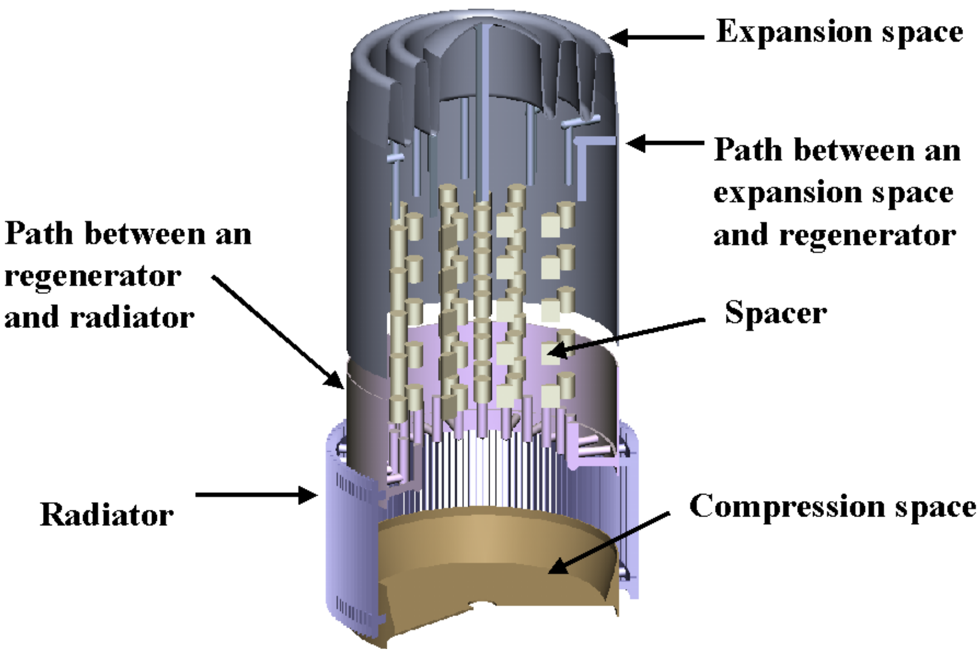

Figure 3 Schematic view of dead volume of prototype refrigerator

Table 3 Dead volume of working spaces [×1

Expansion space	7.847 m^3
Expansion spase-Regenerator pipes	1.498 m^3
Regenerator	41.485 m^3
Radiator	3.241 m^3
Radiator-Compression space pipes	3.960 m^3
Compression space	4.847 m^3
Total	62.878 m^3

minimum amount of dead volume to ensure the specified thermal-exchange performance. The dead volume of the expansion space is approximately three times that of the compression space; this is due to the fins installed at the tip of the displacer and inside the cooling head. The volume of the connecting pipes which connect the compression and expansion spaces and the heat exchanger and regenerator, and account for approximately 8.7% in the prototype refrigerator, should be minimized.

The effects of the dead volume on the performance differ depending on the location of the dead volume. This is because dead volume is closely related to the flow resistance of the working fluid and thermal efficiency of the heat exchanger and regenerator, and these factors influence the refrigerator performance. Therefore, we evaluated the effects solely of the dead volume, irrespective of these factors, on refrigerator performance, through the addition of dead volume by adding a branch pipe to the connecting pipe. The branch section at the connecting pipe is located between the compression space and the radiator, and the dead volume ratio is increased to 2.1 through the adjustment of the length of the branch pipe. Figure 4 shows the relationship between the dead volume ratio and the cooling capacity/indicated work, under the constant-temperature condition. As the dead volume ratio increases, the cooling capacity decreases and the indicated work increases. This is mainly due to a decrease in the compression ratio with increasing dead volume. In the design of a refrigerator, we must reduce the dead volume as much as possible.

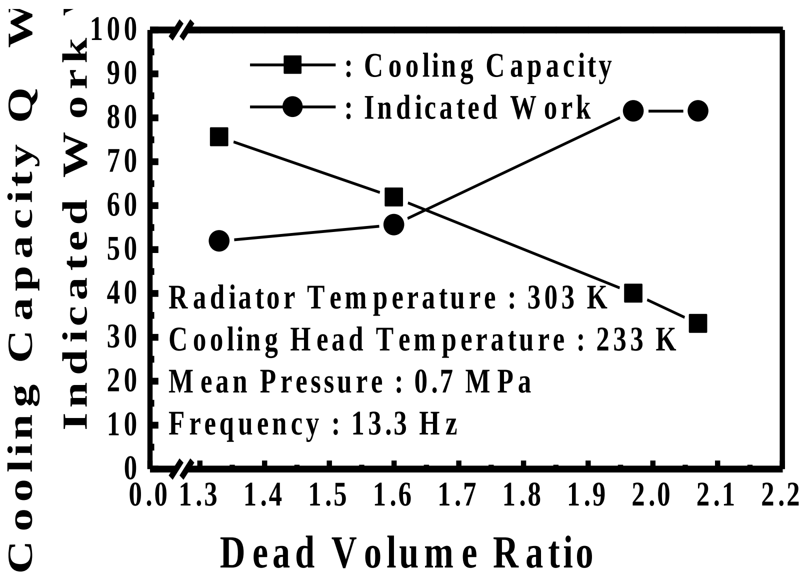

Figure 4 Effects of dead volume on performance

5 Performance using nylon mesh as regenerator matrix

Figure 5 represents the heat balance example of a prototype refrigerator using copper mesh as a regenerator matrix at operating conditions of 0.7 MPa mean pressure, piston speed of 16.7 Hz, and temperature difference between the cooling head and the radiator of 51.1 K. It is clear from this figure that the difference between the indicated work and input power is large. The main reason for this is that a significant amount of work was lost in the power transmission mechanism between the motor and the piston. The mechanical loss was reduced by replacing the copper mesh matrix in the regenerator with the nylon mesh. As expected, the light material reduced the inertia of the integrated displacer in motion, thus leading to an improvement of mechanical efficiency.

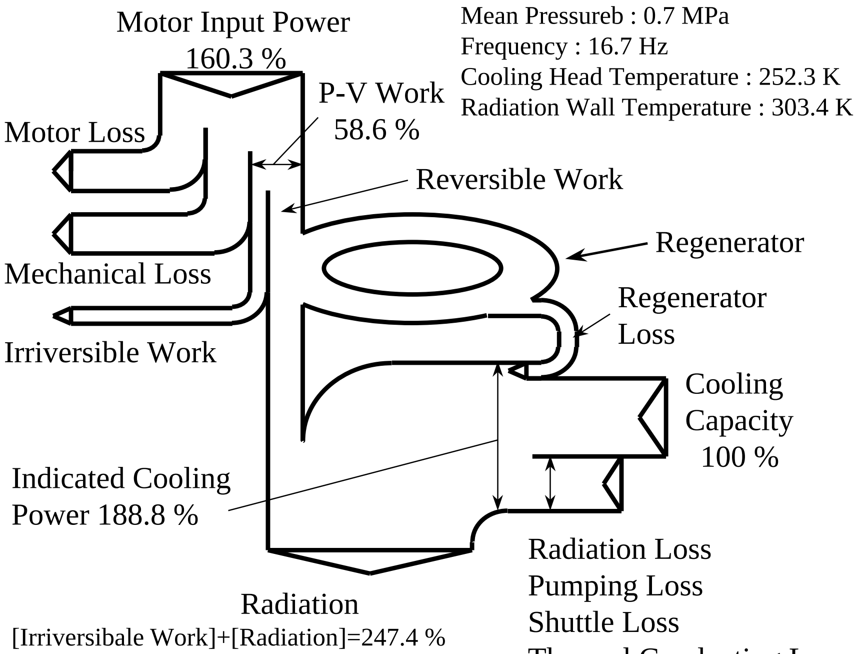

Figure 5 Heat Balance

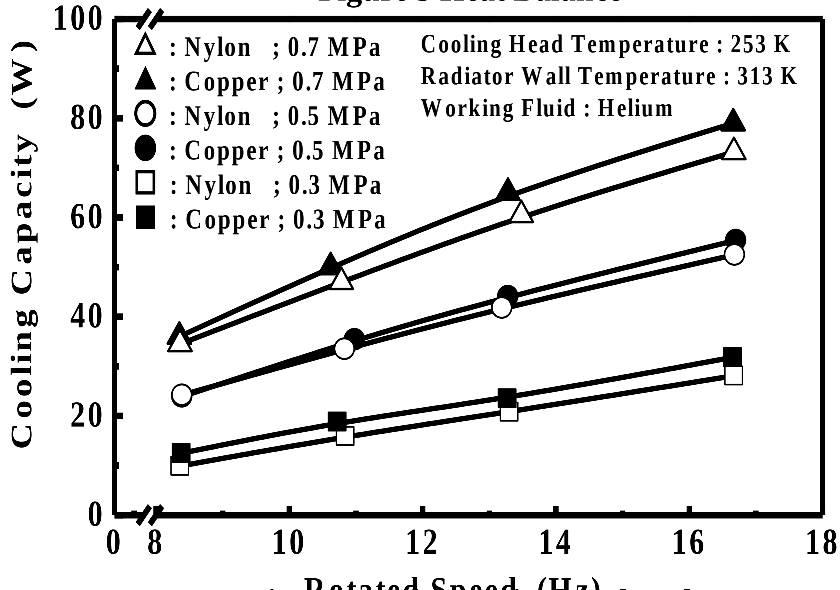

Figure 6 Refrigeration produced

Refrigeration was measured for a prototype refrigerator with different regenerator matrices made of different amounts of nylon mesh. For the regenerator using nylon matrix, no special modifications were made to the base-line refrigerator using copper mesh as the regenerator matrix. In order to determine effects of nylon mesh on performances, data were compared with base-line data for the refrigerator with a copper mesh. Figure 6 shows the cooling capacity. As can be seen from Figure 6, the refrigerator with the nylon matrix produces approximately 80 % of the refrigeration produced by the base-line refrigerator at a 253 K cold head temperature. The refrigeration of both machines increases at a consistent rate as the piston rotation speed and helium pressure increase, although in the high-speed region, the rate drops slightly for the refrigerator with the nylon matrix. The main reason for this is that the energy losses, such as pressure drop, occurring in the nylon matrix are larger than the cooper matrix. It seems that the flow area is decreased by the compression of the nylon meshes. Although there is a need to fine-tune the refrigerator using a nylon matrix, it seems reasonable to assume that the refrigerator using a nylon matrix is useful for the household Stirling refrigerator. The mechanical loss was reduced by replacing the copper mesh matrix in the regenerator with a nylon mesh. As expected, the light material reduced the inertia of the integrated displacer in motion, thus leading to improved mechanical efficiency.

6 CONCLUSION

The performance of the β-type household refrigerator of 100 W capacity has been fine-tuned by the analytic or experimental approach. The results are summarized below.

(1) Cooling performance as a function of the dead volume ratio were measured with varying pressure, piston speed and temperature lift. We verified that the dead volume ratio significantly affects COP.
(2) Cooling capacity of the nylon mesh machine exhibit good performance for household use. The refrigerator using a nylon matrix realized approximately 80 % of the refrigeration of the refrigerator using cooper matrix.

7 REFERENCES

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