THE PERFORMANCE OF STIRLING ENGINE OF THE FREE PISTON TYPE ENHANCED WITH SiC CERAMICS HEATER

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Free piston Stirling engines with integrated linear alternators have the compact size and high conversion efficiency for the sake of the simplicity of mechanical movements. These engines have been developed with the conversion efficiency of 25 %. The material property of ceramics heater is critical in order to achieve such high efficiency. In this paper, the successful design process of the ceramics heater is described. Temperature and stress of the ceramic heater have been calculated by the method of thermo-fluid dynamical analysis and the proper dimensions were decided. Several types of test products have also been designed and manufactured for the evaluation of actual efficiency. Heater efficiency of 63% was estimated from the analysis and the actual test data on free piston engine. It was concluded that the use of ceramics heater in Stirling engine is promising and the high performance of the engine can be realized.

KEYWORDS
stirling engine, free piston stirling engine, ceramics heater, silicon carbide, heater efficiency

1. INTRODUCTION

From 1980, these Stirling engines with high efficiency [Keiji 2005] as shown in Fig. 1, were used as stationary engines in Japan and momentum increased to develop them as a solution for the problem of air pollution caused by exhaust gas from automotive engines. From 1982 to 1987, the "Research and Development into a General-purpose Stirling Engine" project was implemented by the then Ministry of International Trade and Industry as part of the Moonlight Project. This project was implemented by public research organizations led by the New Energy Development Organization (NEDO) and several private companies and concentrated on the development

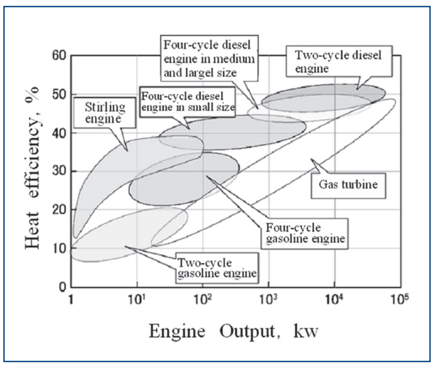


Figure 1. Heat efficiencies of typical engine [Keiji 2005]

of a utilization system concerned with the practical development of engines with 3kW and 30kW outputs and of heat pumps.

In the aforementioned project development, many expensive heat-resistant metal pipes made from inconel and hastealloy were used in the heater section, which is exposed to high temperatures, in order to provide high thermal efficiency and the complex construction was comprised of structures welded to the heater head section, etc. This caused issues from a cost perspective and commercialization proved difficult. In this paper, we describe how we use fine ceramics for the heater section of the engine, which is exposed to high temperatures, to design and develop a ceramic heater with a simple integrated structure that also maintains high thermal efficiency. Further, we provide an example of an actual free piston Stirling engine that uses this heater [Teruyuki 2006] to [Takeshi 2008] and discuss the effectiveness.

2. CERAMIC MATERIAL SUITABLE FOR HEATERS

2.1 BASIC PRINCIPLES OF A STIRLING ENGINE

Fig. 2 shows a schematic of a beta form Stirling engine. A Stirling engine is an external combustion engine with superior characteristics, such as high thermal efficiency and the ability to use a variety of heat sources. From the perspective of achieving the ideal heat cycle including regeneration heat exchange, this thermal efficiency is consistent with the theoretical thermal efficiency of the Carnot cycle represented by low temperature heat sources and high temperature heat sources. However, because a Stirling engine is based on the principle that heat is transferred in an isothermal process, it has the qualities of a high efficiency engine at low output as shown in Fig. 1. In order to utilize the characteristics of the Stirling engine high efficiency heat engine, it is beneficial to increase the temperature of high-temperature reservoir of the working gas.

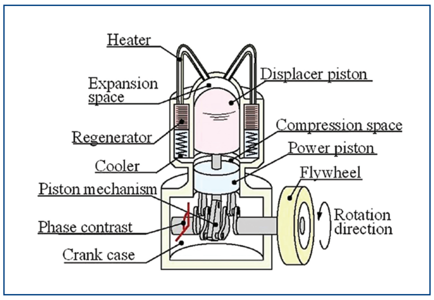


Figure 2. Schematic of Stirling engine

2.2 SELECTING MATERIALS FOR THE CERAMIC HEATER

Ceramic materials can be used under higher temperature conditions compared to general metal materials and therefore it is possible to increase the high temperature heat source by using ceramic materials for the heater material. In so doing, it is possible to increase the thermal ratio of the high temperature heat source relative to the low temperature heat source and increase the thermal efficiency. However, in order that they can be used as heater materials, ceramic materials need to meet the requirements of a high-temperature and high-pressure vessel that is resistant to high pressure and impact at high temperatures and selecting and configuring the shape of the materials is difficult and thus far has not been achieved. Further, because helium gas is used as a working gas for increasing efficiency in the case of Stirling engines, it is also a requirement to select materials that can withstand internal pressure in compact substances and low-strain materials as regards thermal stress. Candidate materials include silicon carbide, silicon nitride, zirconia and alumina, but silicon carbide, which has high thermal conductivity, is the strongest candidate from the perspective of heater heat transfer performance and silicon nitride is the strongest candidate in terms of strength and workability. Because the manufacturing method of both materials is different, two types of material are produced; reaction-sintered body and normally-sintered body. When choosing a material from these candidates, we referred to the paper by Itano *et al.* [Hisao 1987] Other manufacturing methods exist, namely hot press sintering and hot isostatic pressing (HIP), but these were not included as candidates here because of the low degree of freedom in the shape and the high cost. First, we prioritized increasing thermal efficiency and selected silicon carbide as the first candidate material and with the strength and reliability required for future mass production in mind, we chose silicon nitride as the second candidate material. We conducted a basic heating strength test. We discussed our final material selection based on these test results. We decided to use silicon carbide because we found that it exhibited thermal conductivity three times greater than that of silicon nitride, because it can be manufactured using normal sintering at a low cost, and because it meets the required design strength. Hereafter, we describe the performance of a normally sintered silicon carbide product.

2.3 SILICON CARBIDE OXIDATION EVALUATION TEST

A heater is affected by oxidation during use and therefore it is necessary to consider the effect that oxidation has on material strength at the design stage. We conducted an accelerated oxidation test by setting the heater wall temperature higher than the envisaged usage temperature of 800°C. Material strength is evaluated using the bending strength after the oxidation test, but in order to consider the conditions on the surface and inside the heater separately, we cut out and used 4 mm wide, 3 mm thick and 30 mm long test pieces from both the sintered surface and the inside of the material. We conducted oxidation processing for both the ceramic test piece taken from the surface (represents the surface of the heater) and the machined test piece taken from the inside (represents the inside of the heater) and heated the ceramic test piece at 1 200 °C for 2 hours using a gas burner so that the oxidation effect was clearly apparent, and heated the machined test piece in an electric furnace for 2 hours at 1 200 °C and 1 400 °C. The gas burner provides a strong oxidative effect because the flame contains water vapor.

Fig. 3 shows oxidation processing using a gas burner. A reduction in the depth of evenness on the surface of the samples was apparent for both the sample heated by the gas burner and the sample heated in the electric furnace and it was ascertained that oxidation was in process. After oxidation processing, we allowed the samples to cool at room temperature and then evaluated the deterioration using a 4-point bending test with an upper span of 30 mm and a lower span of 10 mm. Tables 1 and 2 show the test results expressed as a Weibull plot using the median rank method. If we compare the strength of the ceramic test piece and machined test piece before oxidation, the average strength (maximum principal stress: 472 MPa) and the Weibull modulus that represents the strength reliability (m:5.9) of the ceramic test piece are both higher than the same characteristics of the machined test piece (343 MPa, m:5.6). It is clear that both the average strength and the Weibull modulus of the ceramic test piece were improved as a result of oxidation processing using a gas burner. Even contrast, even though both the average strength and Weibull modulus of the machined test piece improved as the processing temperature increased to 1 200 °C and 1 400 °C, the increase was small when compared to the ceramic test piece after oxidation processing. If we consider these results, we can conclude that the strength of the machined test piece is inferior to that of the ceramic test piece because of the fine cracks left by machining and the effect of this is particularly significant on silicon carbide, which has low fracture toughness. Therefore, particular care should be taken when machining sintered product in the secondary process. Further, the reason why the strength of both sintered pieces increased after oxidation processing is assumed to be because the shape and size of surface defects are changed by oxidation. It is thought that this change in surface property is dependent on temperature.

We ascertained from the above results that the strength of silicon carbide does not deteriorate due to oxidation, but actually increases. We will advance current ceramic heater design using the data obtained for the material properties.

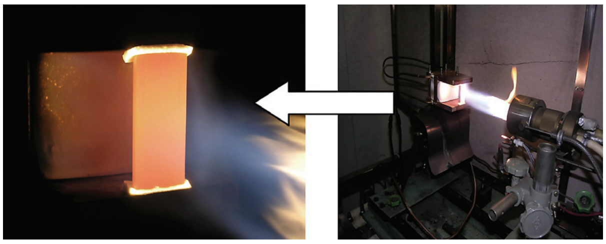


Figure 3. SiC test piece in burner oxidation

Burning temperature: 1 200 °C, Testmethod: Four-points bending test		
Conditions	Before burning	After burning
Average fracture stress (MPa)	427 ± 80	546 ± 45
Weibullum odulus, m	5,9	13,1
Fracture stress at 0,1 % failure probability (MPa)	156	335

Table 1. The effect of burning on the fracture stress of as-sintered test pieces

Testmethod: Four-points bending test			
Temperature	RT	1 200 °C	1 400 °C
Average fracture stress (MPa)	343 ± 67	386 ± 56	394 ± 31
Weibullum odulus, m	5,6	6,6	14,3
Fracture stress at 0,1 % failure probability (MPa)	108	144	251

Table 2. Fracture stress of as-machined test pieces at high temperature

3. PRELIMINARY STUDY OF CERAMIC HEATERS

3.1 DESIGN CONDITIONS FOR CERAMIC HEATERS

Using simulation [Hisao 1987], the combustion gas temperature is converted from a combustion temperature of 2 000 °C to a high temperature housing temperature (helium gas temperature) of an estimated 600 °C via the heater and the average gas pressure is estimated at 2.5 MPa. It is possible to create a thermal design for the target generating output from these research findings and estimated values of efficiency for each section. The pressure resistance design pressure on the ceramic heater was set to 5 MPa with a safety factor of 2. When designing the strength of the heater, it is necessary to estimate the design strength of silicon carbide. Taking into consideration the safety factor including impact load, we set the design strength to the fracture stress at 0.1% failure probability value of 108 MPa shown in Table 2. We set the heater unit target performance to 70 % using the efficiency of converting the combustion gas from the inlet temperature of 2 000 °C to the high temperature housing temperature of 600 °C.

3.2 ENDURANCE TEST THE THERMALLY LOADED HEATER

We conducted a heating test using an engine for evaluation as a test of proof stress against the thermal stress from the heater unit. *Fig. 4* shows the structure of ceramics heater for test. Many conventional metal heaters are comprised of dozens of heat transfer tubes, but this heater is comprised of a combustion gas heat transfer part that receives heat from the combustion gas passing through the fan, a flatplate that manages pressure resistance strength and a working gas transfer part that provides heat to the working gas through a number of small holes. Each part is machined to a complex shape. We checked for defects caused by the thermal stress generated when heat was applied.

Fig. 5 shows the external appearance of the silicon carbide heater after heating for 100 hours at 950°C. We were able to verify that no cracks or fractures had been generated and that the heat had not caused any particular problems as regards the machined shape. [Koichi 2006]

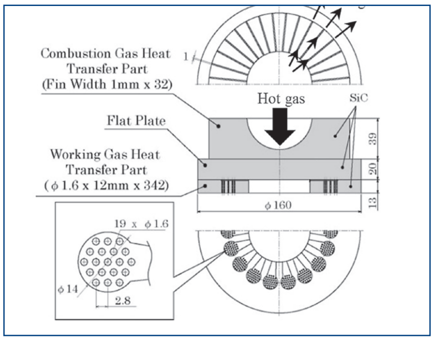


Figure 4. Structure of ceramics heater for test

Figure 5. Ceramics heater

3.3 EFFECT OF FASTENING PARTS TO THE PERIPHERY OF THE HEATER

Although the heating test for the heater standing alone showed the expected result, the heater has the restraint of deformation from contacted other parts. Actually, three component parts are fastened to the periphery of the heater, then bending stress is generated when high gas pressure is applied to the inside of the engine. The bending stress is larger when the thickness of the central part of the heater is smaller. Therefore, we used a convex-shaped structure that has larger thickness in the central vicinity. *Fig. 6* shows the analysis results of ceramics heater.

When the estimated value 5MP was used as the engine pressure (helium gas pressure), and the inlet temperature of 2 000 °C (combustion gas temperature) in the simulation, the temperature of the upper surface wall of the heater was 1400°C, and the temperature of the side walls was 770°C. The maximum principal stress was estimated to 67 MPa at the engine side. The value was below the design strength (108 MPa). But in the pressure test, the heater had some fractures even if at the engine pressure of 3.5 MPa. It would be cased by the asymmetry of the fastening constraint. The heat insulator with ling shape was required to prevent heat loss from the periphery of the heater. We concluded that the insulator brought some uniformity to fastening condition and extra large stress in the heater. Consequently, the fastening method was changed so that the symmetry of stress profile was kept in the heater by adoption of a central integrated columnar insulator.

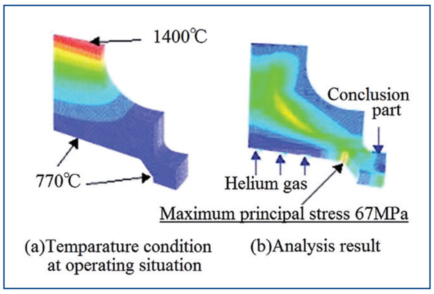


Figure 6. Heat analysis of ceramics heater

4. THERMAL FLUID ANALYSIS AROUND THE HEATER

Fig. 7 shows the configuration of two types (A and B) of the heater, and the heater specifications are shown in Tab. 3. Each configuration for two types of the heater mounted on engines are shown in Fig. 8. In the type A, the expansion chamber is built into the inside of the silicon carbide heater. In the type B, the expansion chamber and ceramic heater are completely separate structures. In this case, it is possible to separate the combustion gas and helium gas (He) and reduce the heater thickness to the working limit.

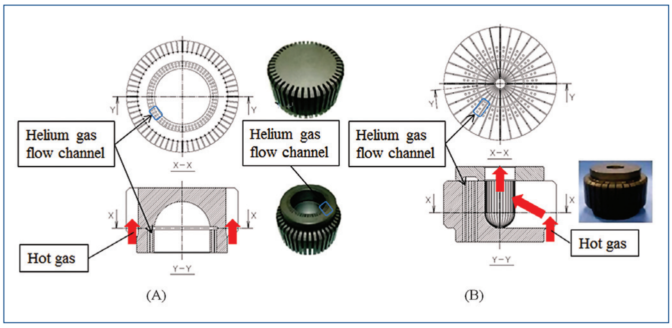


Figure 7. Main configurations of heaters

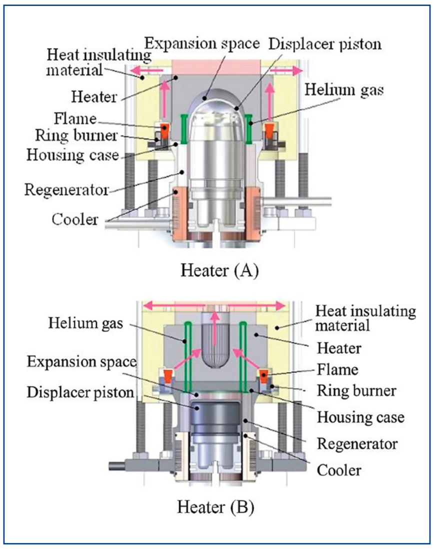


Figure 8. Constructions of heater mounting

Dimension/Shape	Internal Cavity			External Fin			Material
	Bore (mm)	Length (mm)	Number	Width × Height	Length (mm)	Number	
A	2	25	120	1 × 13	50	60	SiC
B	2	65	32	1 × 44	50	32	SiC

Table 3. Main heater dimensions

According to the results of the thermal fluid analysis for the heater unit, the maximum principal stress for heater type (A) is 98 MPa and for heater type (B) is 65 MPa. The maximum principal stress for heater type (B) is 34 % less because the main structure is separate from the expansion chamber. The unit efficiency of the heater compared to the target efficiency of 70 % is 61.2 % for heater type (A) and 63.4 % for heater type (B) and the effect of the small partition wall thickness (approximately 1 mm) of type (B) is apparent. We decided to use heater type (B) based on strength and efficiency [Teruyuki 2005].

Once we had decided on the heater structure, we conducted thermal fluid analysis for the heater including the working gas. We used the ratio of the working gas thermal doseto the amount of heat entering the heater from the high temperature heat source (combustion gas) as a measure of the heater's unit efficiency and evaluated the heater performance using this as an indicator.

We included the heat exchange connected to the heater, the heat insulating material installed to the top of the heater and the holding parts in the simulation model. The analysis results are shown in Fig. 9. The temperature distribution for the solid parts, including engine peripheral parts, and the gas parts are shown separately. According to these results, the heater unit efficiency is 61.3%. This is significantly lower than the efficiency of a heat exchanger used in boilers, etc. but if the temperature of the expansion space is kept below the high-temperature condition of 600°C, this is generally an appropriate value for achieving target performance.

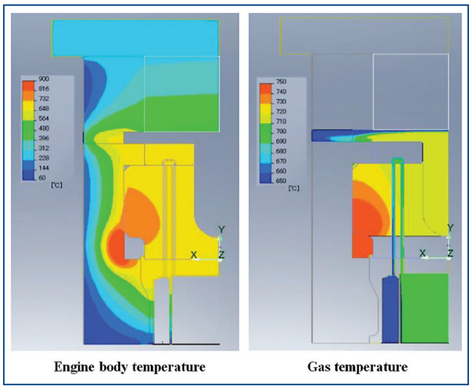


Figure 9. Heat analysis of the engine with B type heater

5. EVALUATION OF THE EFFECTIVENESS USING AN ACTUAL ENGINE

The SiC ceramic heater was installed into an actual free piston type Stirling engine to verify the heater effectiveness (Fig. 10). In a conventional kinematic type Stirling engine, a rotating generator that converts reciprocal motion into rotational motion using mechanisms, such as cranks and cams, which means that the whole machine increases in size and issues such as the generation of mechanical loss in the transfer mechanism arise. In contrast, the free piston type Stirling engine does not need cranks, etc. and therefore the engine generator as a whole can be kept compact and also increased efficiency can be expected because of the reduction in mechanical loss [Teruyuki 2005]. This can be achieved by attaching a direct-drive linear generator [Takeshi 2006] to [Takeshi 2008] to the piston. Howeve there is a chance that efficiency will deteriorate because the phase difference between the displacer and piston cannot be set accurately.

Tab. 4 shows the specifications of the beta-type stirling engine generator and Tab. 5 shows the test conditions. The prototype engine is designed to be equipped with the cogeneration system for the household. For such a purpose the compact engine size is required. Then the engine also has the diameter equal or less than 140 mm, and the rated stroke was16mm(the maxium stroke 20 mm). The operating frequency was designed to 37 Hz from the relation between the displacer piston weight and the spring constant.

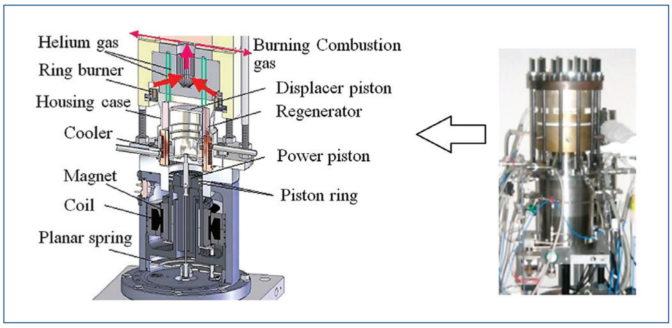


Figure 10. Prototype of Stirling Engine with SiC heater

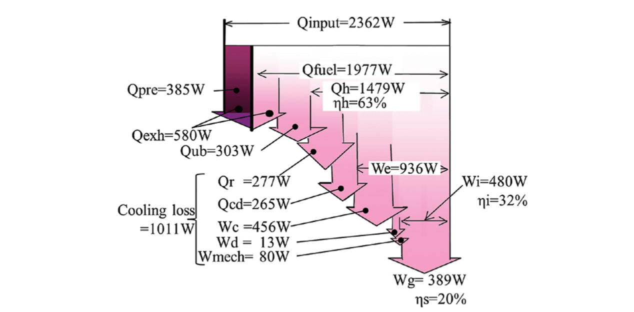
Fig. 11 shows the energy balance of this engine. Qfuel represents the fuel heat input supplied by the town gas thorough the burner, and Qpre represents the heat of preheated air exchanged with the exhaust gas and with the wasted heat of the burner. Qinput denotes

Type	Beta-type
Rated power	400W
Working gas	Helium
Mean Pressure	2.5 MPa
Operating frequency	37Hz
Bore	φ60mm
Stoke	16mm (Piston), 16mm (Displacer)
Regenerator	#100 (Stainless steel matrix)
Generator	Linear Generator

Table 4. Specifications of Beta-type Stirling engine

Mean Pressure	2.55 MPa
Operating frequency	36.8 Hz
Stoke	15.8mm (Piston), 16.0mm (Displacer)
Hot side temperature	547 °C
Cold side temperature	36.9 °C
Cooler inflow temperature	19.8 °C
Cooler outflow temperature	27.7 °C
Cooler flow	1.85 L/min

Table 5. Test Conditions



Qinput	Total energy heat input	We	Expansion space input
Qfuel	Fuel heat input	Wc	Compression space loss
Qpre	Preheated air input	Wi	Indicated horsepower
Qh	Heat input	Wd	Windy loss
Qexh	Exhaust gas heat loss	Wmech	Mechanical loss
Qub	Burner heat loss	Wg	Power output
Qr	Heat exchanger loss	ηh	Heater efficiency.
Qcd	Heat conduction loss.	ηi	Heat cycle efficiency
ηs	Gross thermal efficiency		

Figure 11. Energy balance of engine

the total heat input and is the sum of Qfuel and Qpre. The quantity of heat supplied to the high-temperature reservoir from the heater is defined as the quantity of effective heat input Qh, and the ratio of it to total heat input Qinput is defined as the heater efficiency ηh. As predicted in the thermal fluid analysis, the maximum temperature difference along the heater wall surface was less than 50 °C due to high thermal conductivity of the adopted silicon carbide material. That was one of reason that the ηh was 63 %, which was close to expected value from the simulation. If we adopt a metal heater with high melting point instead of SiC, the burning temperature is limited about 1 500 °C, Although in actual use more than 62 % is required in ηh, realizing that condition is hard because of low burning temperature in the metal heater. In the sense, SiC heater has high competence.

As performance indicators of the Stirling engine, the following losses were evaluated: the total heat of exhaust gas Qexh, the burner heat loss Qub together with cooling loss, the reheat loss within the heat exchanger Qr, and the heat conduction loss Qcd. The calculation of cooler cooling loss decided by cooling performance of the water cooler reached about 1kW. Even in such the situation, the indicated heat cycle efficiency ηi derived from the effective heat input Qh and the indicated power Wi was 32 %, and the fact showed the high performance of this free piston type engine.

The mechanical loss Wmech and the generator loss were subtracted from the indicated power to define power output Wg, and it was measured by wattmeter finally. The power output Wg of 389 W and the gross thermal efficiency ηs of 20 % were obtained in this engine. Those are practical values to operate commercially.

6. CONCLUSIONS

In this study we designed a ceramic heater suitable for a Stirling engine and concluded as follows.

1) A ceramic material (SiC) was proposed as the heater of Stirling engine to increase the input heat without heat damage.
2) As design stress, the principal stress at 0.1% failure probability was used. The value of 108MPa was estimated from the basic test on silicon carbide.
3) In the heat strength test of SiC, no cracks and fractures come out even if under 950°C.
4) A Competence over engines with metal heaters was found, while the particular care for the fastened stress of ceramics was required.
5) A detailed design was prepared, which included the heater shape, using thermal fluid analysis of the heater and peripheral components.
6) In the prototype using a ceramic heater, favorable results were obtained: the heater efficiency of 63%, the indicated efficiency of 32% and the power output of 389W. Our engine had the high performance and potential for commercial use.

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