N O T I C E

NASA TECHNICAL MEMORANDUM NASA TM-76672

EXPERIMENTAL RESEARCH ON THE STIRLING ENGINE

Yoshihiro ISHIZAKI, Yoshio TANI, Narinori HARAMURA

(NASA-TM-76672) EXPERIMENTAL RESEARCH ON THE STIRLING ENGINE (National Aeronautics and Space Administration) 11 p HC A02/MF A01 CSCL 10B N82-22650 Unclas G3/44 09621

Translation of "Nihon Kikai Gakkai Koen Ronbunshu", In: Collected Papers of the Japan Society for Mechanics, No. 790-16, October 1979, pp. 111-113

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, DC 20546 JANUARY 1982

STANDARD TITLE PAGE

1. Report No.: NASA TM-76672
2. Government Accession No.:
3. Recipient's Catalog No.:
4. Title and Subtitle: EXPERIMENTAL RESEARCH ON THE STIRLING ENGINE
5. Report Date: January 1982
6. Performing Organization Code:
7. Author(s): Yoshihiro ISHIZAKI, Yoshio TANI, Narinori HARAMURA
8. Performing Organization Report No.:
9. Performing Organization Name and Address: Leo Kanner Associates, Redwood City, California, 94063
10. Work Unit No.:
11. Contract or Grant No.: NASw-3541
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration Washington, D.C. 20546
13. Type of Report and Period Covered: Translation
14. Sponsoring Agency Code:
15. Supplementary Notes: Translation of "Nihon Kikai Gakkai Koen Ronbunshu," In: Collected Papers of the Japan Society for Mechanics, No. 790-16, October 1979, pp. 111-113.
16. Abstract
17. Key Words (Selected by Author(s))
18. Distribution Statement: UNLIMITED-UNCLASSIFIED
19. Security Classif. (of this report): Unclassified
20. Security Classif. (of this page): Unclassified
21. No. of Pages
22.

EXPERIMENTAL RESEARCH ON THE STIRLING ENGINE /111*

Yoshihiro ISHIZAKI*, Yoshio TANI**, Narinori HARAMURA**
*Tokyo University, Dept. of Engineering
**Aishin Precision Machine Corporation

1. Introduction

The fact that the Stirling engine has such the advantages of high efficiency, fuel variability and low pollution has been discussed in many commentaries and research reports, and development on it is continuing in various countries of Europe and in the United States as a promising candidate of future power. Thus, we have conducted a series of experiments on test Stirling engines of the 50 KW class to clarify the characteristics of the engine and its problems.

Table 1 illustrates the specifications of the test engine while figure 1 illustrates a cross section of the engine. The arrangement is basically Rinia**. Four pistons are arranged at 90° separations circumferentially to promote compactness and uniformity of the temperature distribution in the combustion chamber. Output is removed by a rotating swash plate. Heater tubes of the high temperature heat exchanger are arranged in urceolate form·zig-zag arrangement to effectively recover radiant heat and to increase the surface area facing the flame. Sliding seals for the working gas are divided into numerous stages, and empty spaces inviting gasket-type pressure are installed in the center, promoting uniformity of pressure load on each seal and enhancing durability. A multi-tubular type preheater was installed at the top of the high temperature heat exchanger in

* Numbers in the margin indicate pagination in the Japanese text.
** trans. note. Linear?

this test, but since the total length increases in this layout, the next test device is to have the high temperature heat exchanger installed on the outer periphery as illustrated in figure 1.

表1. スターリングエンジン仕様

1 作動ガス	Heガス 2
3 燃料	白灯油 4
5 ピストン型式	ダブルアクティング 6
7 気筒数	4
8 ボア×ストローク	φ68・49
9 ヒータチューブ温度	750℃
10 冷却水温度	20℃
11 出力取出機構	回転斜板機構 12
13 軸シール方式	スライディングシール 14
15 出力制御方式	最低圧制御方式 16
17 燃焼方式	超音波霧化燃焼方式 18
19 予熱器	多管式予熱器 20
21 高温熱交換器	SUSチューブ壺型 22
23 低温熱交換器	シェルアンドチューブ方式 24
25 蓄熱材料	SUS金網 26

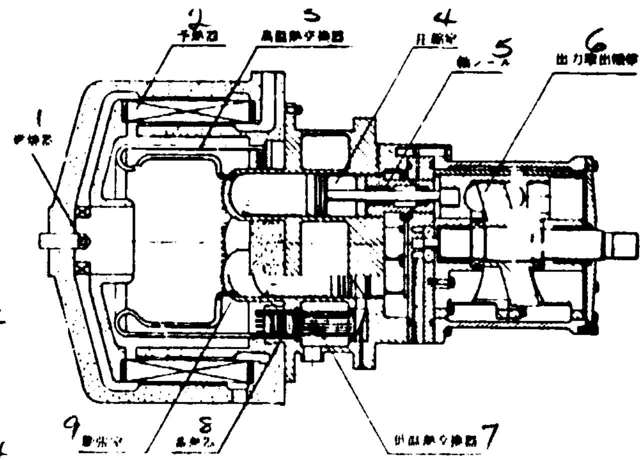

図1 スターリングエンジン概略断面図

Table 1. Specifications of Stirling engine

Fig. 1 Cross section of Stirling engine

1 working gas
2 He gas
3 fuel
4 kerosene
5 piston type
6 double acting
7 number of cylinder
8 bore x stroke
9 heater tube temperature
10 cooling water temperature
11 output removal mechanism
12 rotating swash plate mechanism
13 shaft sealing method
14 sliding seal
15 output control method
16 minimum pressure control method
17 combustion method
18 ultra-sonic atomization combustion method
19 preheater
20 multi tube preheater
21 high temperature heat exchanger
22 SUS tube urceolate shape
23 low temperature heat exchanger
24 shell and tube method
25 heat accumulator material
26 SUS metal mesh

1 combustion device
2 preheater
3 high temperature heat exchanger
4 compression chamber
5 shaft seal
6 output removal mechanism
7 low temperature heat exchanger
8 heat accumulator
9 expansion chamber

3. Test Results

A series of tests, including load tests, starting tests and output control tests, was conducted to determine the characteristics of the Stirling engine. These results are discussed below.

3.1 Output and Efficiency

Figure 2 illustrates the engine performance curve using the working gas minimum pressure Pmin as a parameter. The heater tube temperature is 750°C and the compression ratio is approximately 1.9 to 1. The maximum output obtained in the tests was 51 KW while the maximum efficiency was 27.8% (fuel consumption rate 219 g/psH). The maximum values of shaft output, efficiency and shaft torque in all pressure ranges were set respectively at 2000, 100.0 and 800 rpm. The energy balance and engine of each component are illustrated in figure 3 in the case of working gas minimum pressure of 80 8kg/cm^2 and speed of 1,000 rpm. This energy balance is calculated through measurement of the temperatures and flow rates of the cooling water and exhaust /112
gas. The unknown energy amount is due to measurement errors and heat leaks outside, but based on the assumption that radiant heating from the surface of the heater constitutes the majority of that amount, the total amount of unknown energy was fed into the column of exhaust heat and each component was computed.

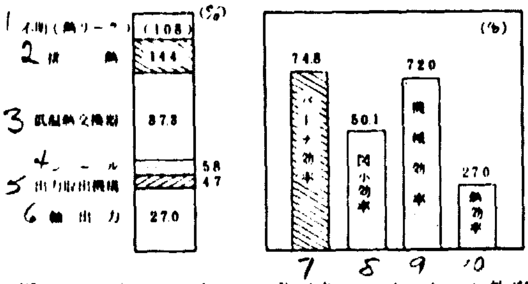

図3 エネルギーバランス及び各コンポーネント効率

(於：P 80kg/cm²、n 1000rpm、TH 750°C)

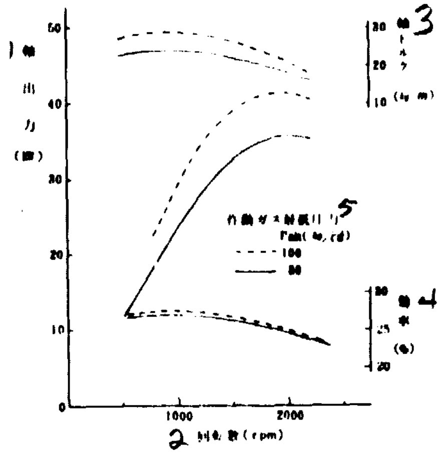

図2 エンジン性能曲線

Fig 3. Energy balance and engine of each component
1 unknown (heat leaks)
2 exhaust heat
3 low temperature heat exchanger
4 seal
5 output removal mechanism
6 shaft output
7 burner efficiency
8 indicated efficiency
9 mechanical efficiency
10 thermal efficiency

Fig 2. Engine characteristic curve
1 shaft output (KW)
2 speed (rpm)
3 shaft torque
4 efficiency
5 working gas minimum pressure

3.2 Starting Characteristics

In this test, the minimum pressure of the working gas was 20 kg/cm^2, and self starting was carried out using an automatic starting device which provided external driving force to the engine shaft when the temperature of the heater tube facing flames reached 750°C and which removed the driving force when the shaft speed reached 250 rpm. Figure 4 illustrates the relation between the initial amount of heating Q_B in relation to time t_1 (starting time) until driving force was provided after burner ignition and time t_2 until removal. The minimum starting time obtained in these tests was 35 sec.

3.3 Output Response

This device uses the minimum pressure controlling method. The response of the internal engine working chamber minimum pressure and of the shaft output is measured when the gas supply valve rapidly opens and pressure from the high pressure vessel (80 kg/cm^2) is supplied to the working chamber since this test involves the warm engine operating state at a working gas minimum pressure of 20 kg/cm^2. The temperature of the heater tube is maintained at 750°C by the fuel control device. Figure 5 illustrates the test results of the acceleration output response using the load torque as a parameter.

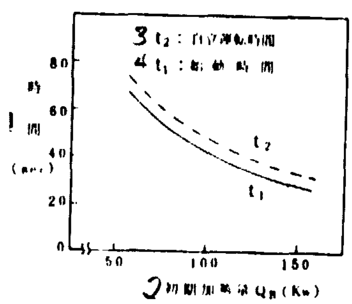

図4 エンジン始動特性

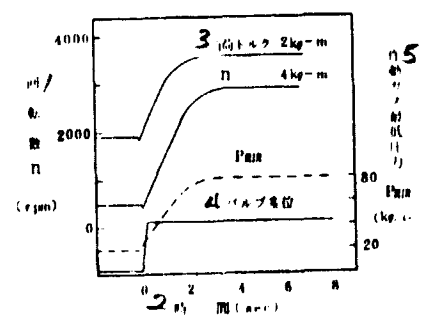

図5 エンジン出力応答性（加速時）

Fig 4. Engine starting characteristics
1 time (sec)
2 initial amount of heating Q_B
3 t_2: self operating time
4 t_1: starting time

Fig 5. Engine output response (during acceleration
1 speed (rpm)
2 time (sec)
3 load torque
4 valve displacement
5 working gas minimum pressure

3.4 Noise, Miscellaneous

During constant operation at a working gas minimum pressure of 80 kg/cm^2 and speed of 1,000 rpm, the noise was 74 dBA (1m distance) and the emissions were approximately 100 ppm of CO and approximately 20 ppm of HC. The vibration was not measured since the amplitude varied with the method of support, but the vibration was confirmed to be very slight since there is no explosion cycle, in contrast to internal combustion engines, and since a rotating swash plate is used in the output removal mechanism.

4. Discussion and Problems

4.1 Output and Efficiency

The maximum shaft output was near 2,000 rpm based on the engine performance curve. This is a very low operating range in /113 comparison to the data from various foreign countries. The cause is surmised to lie primarily in reductions in the indicated efficiency as indicated below.

(1) The pressure loss during the cycle in high speed ranges increases since He is used as the working gas, thereby reducing the indicated efficiency. (In foreign countries, with the exception of Germany, H_2 is used in virtually all cases.)

(2) The working gas temperature within the expansion chamber is reduced with increase in the speed since temperature control of the high temperature heat exchanger is effected through detection of the surface temperature of the heat tubes. This reduces the Carnot efficiency.

Future countermeasures which are required are selection of various specifications to reduce the pressure loss when using He regarding (1) and examination of the means of constant control of the working gas temperature regarding (2). However, the current control method is practical when emphasizing safety of the heater tubes which are exposed to high temperatures and pressures.

Future themes of research are improvement of the burner efficiency and of the mechanical efficiency since the maximum thermal efficiency is only 27.8%. Specifically, the heat tube configuration, preheater structure and adiabatic material must be examined regarding burner efficiency while the seal material-shape and structure of the output removal mechanism must be examined regarding mechanical efficiency. Implementation of the aforementioned measures should easily permit output of 50 KW and efficiency of 30%.

4.2 Starting Characteristics

Since this engine is a closed cycle external combustion engine, the thermal capacity materials such as the heater tubes and cylinders must be heated from without and the working gas must be heated via the internal wall surfaces. Consequently, the starting characteristic depend on the thermal capacity of the working gas heating path, on the total heat transfer coefficient and on the initial amount of heating. These must be examined to promote rapid heating and to reduce friction loss by the seals and output removal mechanism. A starting time of approximately 20 seconds is quite possible.

4.3 Output Response

There are three types of output control methods; phase angle, dead volume and pressure control. The output response in the minimum pressure control method which we used involves how rapidly and uniformly the pressure within the working chamber increases or decreases. Working gas distributors are used as the means of improving the response, and gas is supplied through timing with the isochoric stroke. The output response when the load is great during acceleration should be comparable to that of an internal combustion engine considering that the shaft torque of this engine is great.

4.4 Noise, Miscellaneous

Low noise and vibration are characteristic of the Stirling engine. There is no special problem with emissions either, but EGR etc. must be considered as measures to reduce NOX when the combustion temperature is raised for higher efficiency as the next development step.

4. Conclusion

We have been able to determine the basic characteristics and problems of the Stirling engine through a series of experiments. The basic characteristics are (1) The efficiency is good under partial load. (2) The torque is great. (3) The vibration and noise are low. (4) The exhaust heat is low, but the amount of heat discharged through the cooling water is very great. The problems involve durability of the high temperature heat exchanger (prevention of local heating) which is exposed to high flame temperatures above 1600°C, thermal distortion and high temperature corrosion of the devices near combustion and of the preheater, and further research is required to develop seals which satisfy the three conditions of durability, sealing properties and wear resistance.

Thus, many elements for development remain before the Stirling engine is perfected, but its practical employment does not seem to lie too far into the future considering its advantages of in terms of the problems of environment and energy supplies. Examples which seem most practical include indoor engines and engines used in densely populated residential areas where low vibration and low noise are required; engines applied to heating of cooling water utilizing its great water heating capacity and small engines for recovering waste heat utilizing its characteristics of small size and fuel versatility.

This research was implemented with a research grant from the Ministry of International Trade and Industry. We would like to thank the members of Aishin Precision Machine Corporation, Second Research Group and the Testing Section for the design, trial production and testing of the engine.