NEW CONCEPT, HERMETICALLY SEALED STIRLING ENGINE

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ABSTRACT

In this report a new concept, hermetically sealed Stirling engine will be presented, in which the engine is intended to combine the compactness and high power density of kinematic Stirling engines with the advantage of hermetically sealed free-piston Stirling engines. The new Stirling engine concept is of single cylinder, so called beta displacer type, with a swept volume of 68 cubic cm, an electric power of 2-3 kW at the speed of 3000 rpm and a mean helium working gas pressure of 12.5 MPa. The first prototype, called the demonstrator Stirling engine, uses rotating electric machinery, although equally well linear generators are applicable. The whole unit is hermetically sealed and pressurized. As a consequence the number of seals inside the engine is limited to piston rings and the displacer piston rod seal, neither of which need to be absolutely gas tight.

BACKGROUND

In a continuous effort to simplify and make more reliable Stirling engines for different commercial applications and specially for Stirling-electric generator sets the principal components of the Stirling engine have been analysed and brought to their most functional shape. Such components involved are:

- o preheater
- o heater
- o regenerator
- o cooler
- o mechanism
- o seals

Important improvements and simplifications also can be made in the control system and in the necessary ancillaries. In different applications of Stirling engines considerable gains can be made by a better integration of the engine function in the actual application system.

In this report specifically improvements and simplifications in the Stirling engine mechanism and seals will be covered as well as a better integration with electric generators, all in an effort to create competitive Stirling-electric generator sets. A range of suggested ways to achieve this goal will be presented, some of which will be tested in a demonstrator unit. The results will be evaluated in order to find the optimal configuration for Stirling engines and specially Stirling-electric generator sets.

GENERAL PRINCIPLES

For certain applications of Stirling engines, such as driving electric generators, a convenient way to integrate the components of such a system is to pressurize the complete system including the mechanism and the electric generator. In order to realize such an integration and pressurization and creating a totally hermetic unit a number of design steps must be taken, as will be described in the following.

Pressurized Crankcase

The basis for a hermetic Stirling engine is the pressurized crankcase. By selecting suitable geometries, like cylindrical and spherical shapes of nodular iron castings, the weight and wall thickness penalty will be quite small. A certain amount of material is anyhow needed in order to obtain the necessary stiffness of the structure. This is valid for mean cycle pressures of at least up to about 12 MPa and for cast structures.

One important consequence of selecting a pressurized crankcase is, of course, the improved situation for the piston rod seals. On one side of these seals there is the cyclic variation of pressure in the Stirling cycle and on the other side the mean gas pressure.

A small gas leakage is acceptable because there is no loss of gas to the outside. A considerable gain in simplicity, cost reduction and reliability is achieved. The need to lubricate the gas seal, which is indispensable, when a crankcase with atmospheric pressure is used, disappears and the problems of the oil seal can be relieved with limited lubrication of the mechanism, as will be described below.

Anti-Friction Bearings

While journal bearings require a plentiful of lubrication oil for their good function, anti-friction bearings work better, with less friction, if lubrication is limited. Anti-friction bearings are also desirable because the friction losses in absolute terms always are lower than for journal bearings. However, special care must be taken in the design of mechanisms with anti-friction bearings in order to get sufficient bearing life.

Balanced Piston Side-forces

Another consequence of the choice of limited lubrication is the need to avoid the traditionally used cross-head, which also requires abundant lubrication with oil. There are several ways to replace the cross-head, the rhombic drive is one well-known way. In some cases the rhombic drive could be a good solution, but for the Stirling-electric generator set another, simpler mechanism has been found. Eliminating the cross-head often will result in a lower engine envelope.

Linear or Rotary Electric Generators

It has been found that the use of a linear electric generator would allow a considerable reduction in bearing loads, because the piston forces can be directly transmitted to the power absorbing electric generator instead of being first transformed into rotary motion. In a way a semi-free piston engine would be created, the bearings would only be used to drive the displacer piston and for the purpose of transferring energy from one part of the cycle to another. The lightly loaded bearings would result in extended life for the engine.

The present demonstrator Stirling engine has still rotary electric generators for the reason that they are more easily available.

Based on these four general principles a demonstrator engine will be tested and evaluated. The results of the evaluation will then be used for the design of an application prototype, that will be tested under actual user conditions. See figure 1.

LIMITED LUBRICATION

The simplification of the piston rod oil seal will demand some type of limited lubrication system. As it has already been

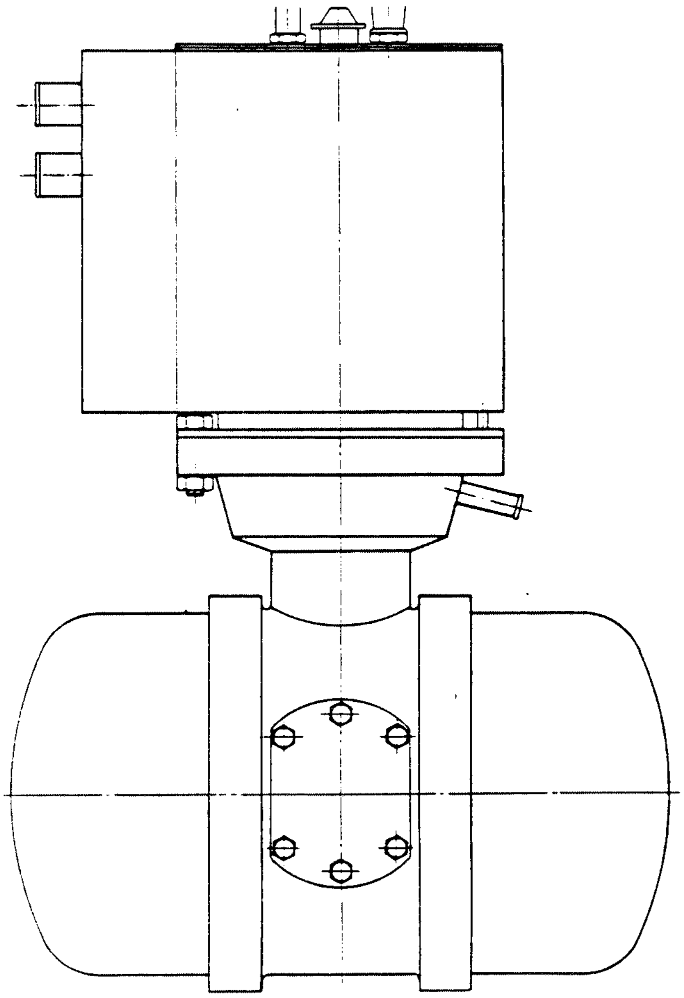

Figure 1: Outside View of Application Prototype

mentioned, also the application of anti-friction bearings favors a system with only a limited amount of free oil. Several types of limited lubrication systems have been evaluated. The most promising are the following.

Oil Mist Lubrication

This is the favored system for anti-friction bearings. It gives a continuous supply of small amounts of oil to the elements of the bearings. Thus optimal life and very low friction losses can be achieved.

An additional space between the cycle and the crankcase has to be arranged, a buffer space with cycle mean pressure, and a wall with three piston rod seals, one for the displacer piston rod and two for the power piston. Sliding seals or even metal bellows seals can be used.

Grease Lubrication

Sealed, grease lubricated anti-friction bearings of roller, ball and needle type also operate with very low friction and, if the load is reasonably low, they will have very long life.

A distinct advantage with sealed, grease lubricated anti-friction bearings is that only a limited amount of grease will over the life of the bearings leak out, thus allowing a very simple piston rod seal to be used.

The use of sealed, grease lubricated needle bearings was considered enough promising, that the demonstrator unit will be provided with such bearings.

Another advantage with sealed, grease lubricated needle bearings is the small dimensions, which makes them easy to integrate in the drive mechanism. The pressurized helium will act as a cooling medium, that effectively transfers the friction energy to the walls of the crankcase. If necessary water cooling can be arranged.

Dry ceramic bearings

The advent of ceramic dry bearings of anti-friction type will, of course, be very wellcome as the ideal application in a helium pressurized crankcase.

When such a solution of the bearing requirements can be realized, then there will obviously be no need at all for a piston rod oil seal. This then constitutes the ultimate solution to the oil contamination problem in kinematic Stirling engines, because no liquid lubrication will be needed in such an engine.

The presently selected solution on the demonstrator Stirling-electric generator unit with sealed, grease lubricated needle bearings will be evaluated, whereupon the final choice of bearings will be made.

GEOMETRY OF THE MECHANISM

A number of requirements will be posed on a mechanism, that retains all the favorable characteristics of kinematic Stirling engines, such as high power density, high efficiency and reliability and at the same time add such properties as eliminated risk for oil contamination and hermetic design, all properties, which generally characterize free piston Stirling engines.

Requirements

These are the requirements that should be demanded and fulfilled:

- o The piston side forces should be balanced out, thus eliminating the need for a crosshead.
- o Allow the use of optimal cycle phase angle, that favors good performance.
- o Allow an almost complete balancing of inertia forces.

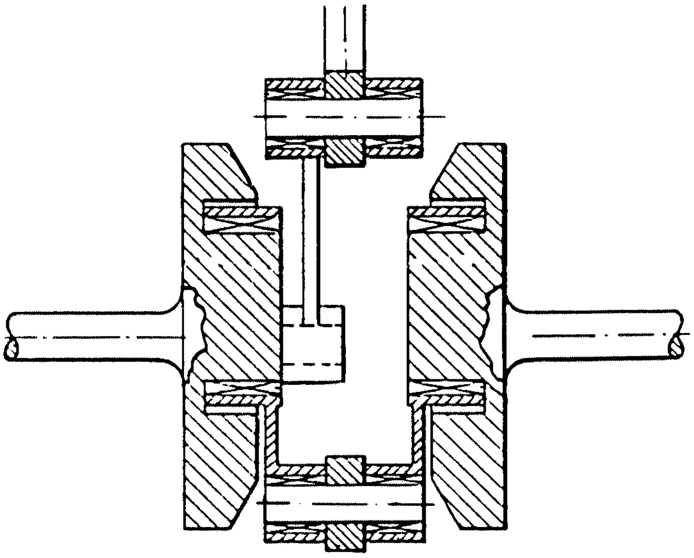

Figure 2: Vertical Section of Mechanism

- o Subdivide piston forces on several bearing elements for a minimum of bearing load and a maximum of bearing life.
- o If gears are necessary for synchronization purposes, then they should have no or very light load, in order to allow operation under limited or no lubrication conditions.

The Rhombic Drive

It is evident that the rhombic drive fulfills these requirements. For certain applications the rhombic drive can be recommended, specially if it is designed in such a way that linear electric generators can be used.

One disadvantage of the rhombic drive as applied with rotating electric generators, one for each shaft in order to avoid gear loading, is that the shafts have different center-lines, thus creating a nonsymmetrical shape of the unit.

Another disadvantage is that the rhombic drive is fairly complicated, although a large amount of design experience exists.

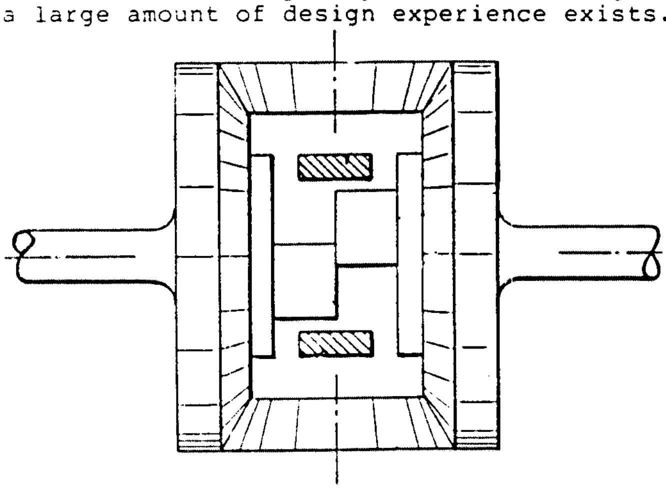

Figure 3: Horizontal Section of Mechanism

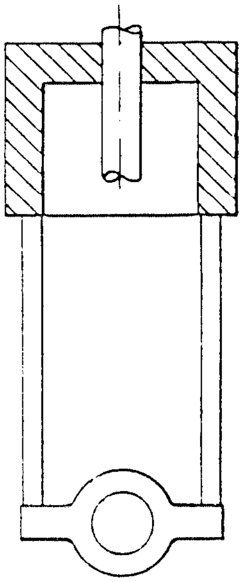

Figure 4: Lower Yoke with Rods

THE SIMPLIFIED MECHANISM

To avoid these disadvantages a simplified drive with all the stated requirements fulfilled, and the two shafts along the same center-line. With two contra-rotating electric generators the synchronizing gears will operate without load. Figure 1 shows a Stirling-electric generator set using this type of mechanism. As can be seen the unit will be very compact and fully symmetric.

<u>The Function of the Mechanism</u>

The function of the simplified mechanism can be explained with the help of figures 2-5. The two gear wheels in figure 2 are connected to counter-rotating electric generators positioned on the same center-line. In each of the two gear wheels there is one connecting rod with a big, sealed, grease lubricated needle bearing. This connecting rod is attached to a yoke below the gears. Equally on each gear wheel there is another connecting rod attached on a pin in the gear wheel and connected to a yoke above the gear wheels.

The lower yoke with its two counter-rotating rods is attached via two rods to the power piston as can well be seen in figure 4. The upper yoke with its two counter-rotating connecting rods is attached to the piston rod of the displacer piston.

The engine is a beta-type displacement Stirling engine with two pistons in the same cylinder, one power piston and one displacer piston.

In figure 3 it can be seen how the two gear wheels are synchronized by one or two smaller gear wheels, so called synchronizing gears, preferably made of plastic material.

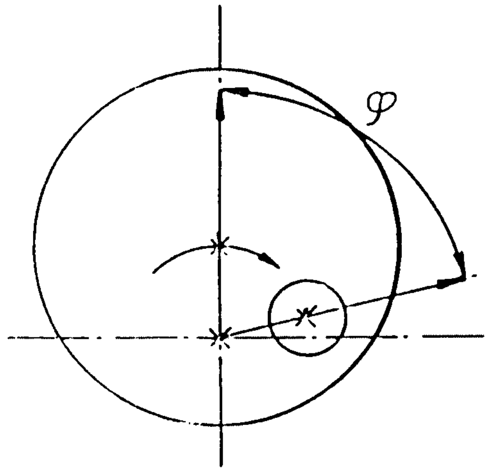

Figure 5: Cycle Phase Angle of the Pistons

With contra-rotating electric generators no gear forces are needed, because no energy is transferred via the gear wheels. It can also be seen that the big gear wheels can be provided with counterweights so as to almost completely balance all inertia forces.

All bearings presently are sealed, grease lubricated needle bearings, a guarantee for a minimum of friction losses.

Finally figure 5 shows how the attachment of the big ends of the connecting

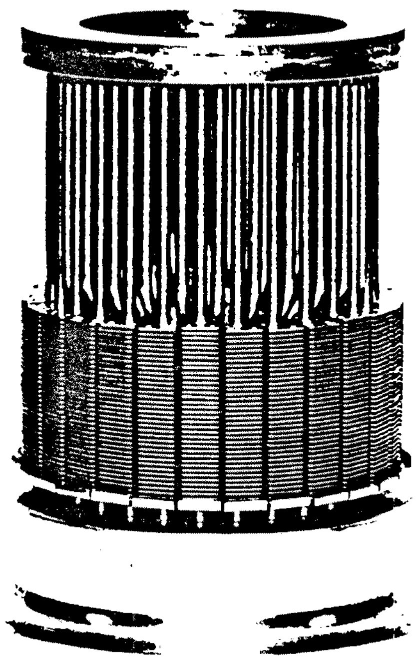

Figure 6: Demonstrator Prototype Heater

rods in the gear wheels allows the selection of any cycle phase angle that is considered optimal. Due to the two contra-rotating shafts the piston forces can be subdivided on several bearings so as to limit the bearing loads and give long bearing life.

The two contra-rotating gear wheels use the same bearings as the rotating electric generators, preferably sealed, grease lubricated ball bearings.

BEARING LIFE

With the proper dimensioning of the bearings the life with rotating electric generators is sufficient for most applications i.e. 3000-10000 hours of operation at full load.

For very long life, i.e. up to 60000 hrs linear electric generators are preferred. Then the driving forces of the piston can to a great extent be balanced by the absorbing forces of the linear electric generator. In such a way the bearing loads will be very light resulting in extended life of the bearings.

A linear, electric generator will conveniently be attached to the lower yoke of the mechanism, which is connected to the power piston.

Almost complete balancing of the inertia forces can still be made by attaching counterweights on the counter-rotating gear wheels.

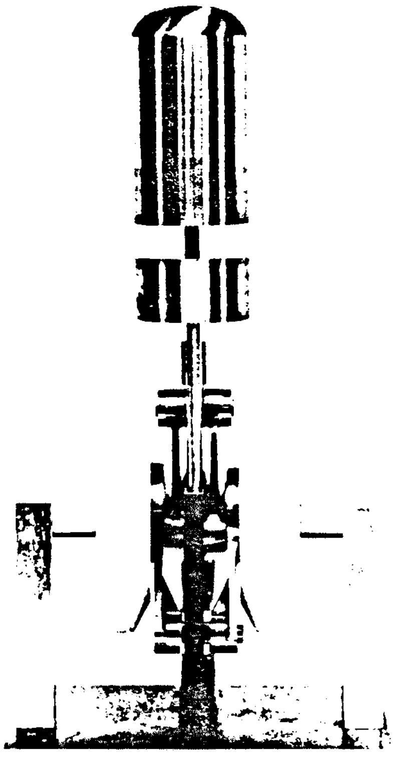

Figure 7: Model of the Mechanism

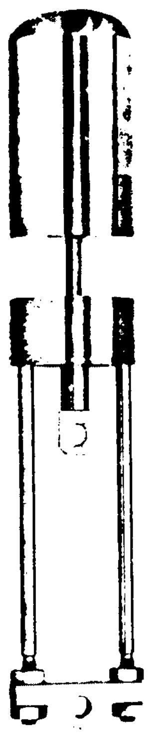

Figure 8: Lower Yoke with Rods

DEMONSTRATOR AND APPLICATION PROTOTYPES

The evaluation of the new mechanism with its limited lubrication bearings in a pressurized crankcase will be made in a test bed, where precise measurements can be made under actual operating conditions. The main data for the first experimental unit, the so called demonstrator prototype, can be seen in table 1.

Table 1: Principal Data for the Two Prototypes of Hermetically Sealed Stirling-Electric Generator Set

Demonstrator Prototype:

Bore, mm	60
Stroke, mm	24
Swept Volume, cm^3	68
Electric Power, kW	2-3
Speed, rpm	3000
Mean Cycle Pressure, MPa	12.5

Application Prototype:

Estimated Size:

Height, mm	565
Length, mm	365
Width, mm	225

The heater and the cooler are of conventional tube type and the regenerator is annular. The rotating electric generators can be used both for motoring the Stirling engine, to start the engine and finally to measure the performance of the engine. A photograph of the demonstrator heater is shown in figure 6.

In figure 7 a model of the mechanism can be seen, where all three gear wheels are made of plastic material, whereas in the operating prototype the two counter-rotating gear wheels will be made of metallic material and the small, synchronizing gears of plastics. The lower yoke for the power piston and the upper yoke for the displacer piston can be seen.

Figure 8 presents the lower yoke with its push rods to the power piston. The lower yoke can be connected to a linear electric generator for direct transfer of the piston forces to the generator, thus creating on alternative to the counter-rotating electric generators.

Finally one of the two connecting rods for the power piston is shown in figure 9. The small end and the big end sealed, grease lubricated needle bearings are mounted.

The calculated power of the demonstrator prototype for different mean working gas pressures can be seen in figure 10.

In the next prototype, the so called application prototype, the performance, size and weight of the unit will be optimized so as to give a small, light-weight and high performance mobile unit. The estimated size of the application prototype can be seen in Table 1.

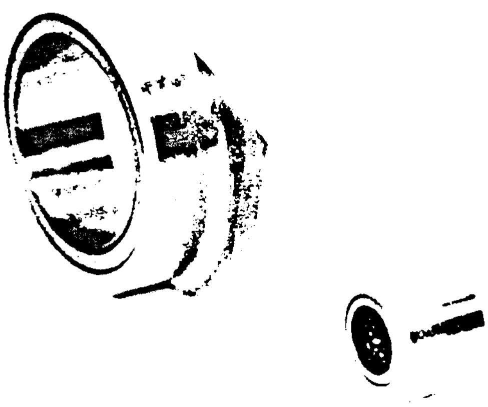

Figure 9: Connecting Rod for Power Piston

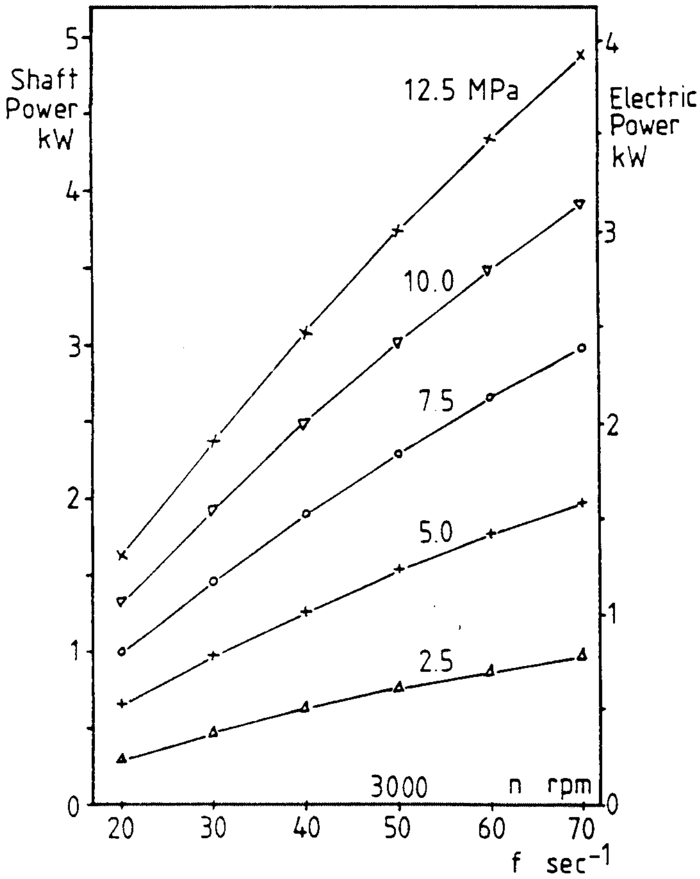

Figure 10: Calculated Demonstrator Prototype Power

CONCLUSION

A new concept, hermetically sealed Stirling engine is under development. Specifically the limited lubrication mechanism will be evaluated with regard to simplification of internal gas and oil seals. Other components successively will be simplified in order to arrive at an economically competitive unit without sacrificing the attractive characteristics of the Stirling engine.

ACKNOWLEDGEMENT

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