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A high pressure and high frequency diaphragm engine: Comparison of measured results with thermoacoustic predictions

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HIGHLIGHTS

- High frequency and high pressure diaphragm engine delivers good power density.
- Engine has no sliding seals and thus no wear or seal leakage leading to long life.
- No high tolerance or exotic parts leading to low cost.
- Good agreement of thermoacoustic model with experimental results.
- Prototype at 500 °C has 21% efficiency and 580 W output.

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ABSTRACT

A novel diaphragm Stirling/thermoacoustic engine has been developed and tested that operates at high pressure and high frequency thereby delivering good power density and efficiency. This engine does not require any high tolerance or exotic parts and may thus be amenable to low cost construction in volume. Given the high frequency (500 Hz) and high working gas pressure (90 bar He) the inertia of the working gas is not negligible and thus traditional Stirling engine analysis fails to properly model such an engine. Instead, the engine is successfully modeled as a traveling wave thermoacoustic engine with a mechanical resonator (the displacer) closing the acoustic power loop. The predictions of the thermoacoustic model are compared with experimental results obtained from a prototype engine.

1. Introduction

Stirling engines have not enjoyed much commercial success to date. One factor in this lack of success is the difficulty of making reliable, low cost, sliding gas seals without the use of lubricants. This problem may be avoided by building an engine based on flexing diaphragms rather than pistons. At least one such engine was built in the 1970s at Atomic Energy Research Lab [1–5]. This engine, called the thermo-mechanical generator (TMG), was however only capable of very modest (~70 W) power output and had very low power density. The low power density was due to a combination of unpressurized working gas and low frequency operation. It did however demonstrate the simplicity and reliability of the metal flexure based approach, running for 100,000 h maintenance free. A later modestly pressurized version produced about 170 W of indicated power [2]. The only other pure metal flexure based Stirling engine found in a literature search was patented by Mechanical Technologies Inc. [6] but no performance details are publicly available. Mechanical Technologies Inc. additionally developed a hybrid Stirling engine with a diaphragm power transducer but with a non-diaphragm, sliding and electrically driven displacer. Published performance data indicate that it produced on the order of 2 kW of mechanical power [7,8]. However, it was not a pure diaphragm engine given the driven, sliding displacer and as such did not realize all the advantages of a pure flexure based engine. In order to make the power density of a pure flexure engine competitive with a piston Stirling engine it is necessary to increase both the operating pressure and frequency by an order of magnitude or more in order to compensate for the inherent small stoke of the flexures. At high pressures and frequencies the inertia of the working gas is no longer negligible, thus a thermoacoustic model is convenient for complete understanding of the engine operation. Thermoacoustic theory has been successfully employed for heat engine analysis by a number of authors [9–13].

A high power density flexure based engine has been designed and built along with a matching thermoacoustic computer model. The engine design is a marriage of a piston-less thermoacoustic engine and a beta free-piston Stirling engine. Flexing diaphragms, akin to the loud speakers used as acoustic drivers in some thermoacoustic machines, replace the pistons of a traditional Stirling

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engine [2] and a mechanical resonator, the displacer, replaces the acoustic feedback network of the traditional traveling wave thermoacoustic engine [10]. The primary distinguishing feature of this engine is the lack of sliding seals. In addition to the obvious disadvantages of leakage, possible wear and losses there are cost disadvantages to sliding seals. Sliding seals without lubricants often require close tolerance fits with the dimension of mating parts matched to on the order of 10 μm. This requires costly precision machining and quality assurance and often manual sorting or polishing of parts to ensure good matches. In comparison, in this flexure engine dimensional machining tolerances are about of an order of magnitude larger and more crucially it is not necessary to closely match one machined part to another so parts may be uses as machined. For example, the power transducer flexure is a steel diaphragm with a specified profile in order to keep bending and pressure stresses as uniform as possible. At the thinnest point near the periphery the transducer has a thickness of about 1 mm. It thickens gradually with decreasing radius reaching about 15 mm at the center. The required thickness tolerance as a function of radius is no more than on the order of 100 μm. Any small deviation in profile leads only to slight changes in stiffness and hence operating frequency but does not have any effect on sealing or wear.

As an additional distinguishing feature in this engine there is no need to contain the linear alternator within the pressure vessel. Due to the small stroke of the diaphragm it is possible to seal the engine with a separate flexure (spring tube 104 in Fig. 1). In addition to hermetically sealing the engine, while allowing transmission of the vibration to outside the pressure vessel, it acts as the primary mechanical spring in the system. Hermetic sealing allows the linear alternator to be outside the pressure vessel without causing working gas leakage and this leads to further pressure vessel size and weight reduction. Since the alternator is outside, and no acoustic resonator is needed, the pressure vessel is very compact.

A flexure based engine of the type described in this paper is likely scalable for powers in the range 100 W to about 10 kW but no detailed modeling or design has yet been done for any engine with greater than 3 kW or less than 500 W of output. Preliminary bottom up costing of the engine taking into account the material and likely manufacturing method of each part in the engine indicates that a 1 kW engine weighing 30 kg can be built for less than 1$/W in moderate volume. The result is a compact engine without the problems associated with sliding seals. The small size of the pressure vessel leads to excellent engine power density. The inherent simplicity of the design, easy manufacturability and small size may lead to extremely high reliability and low manufacturing costs per watt of output.

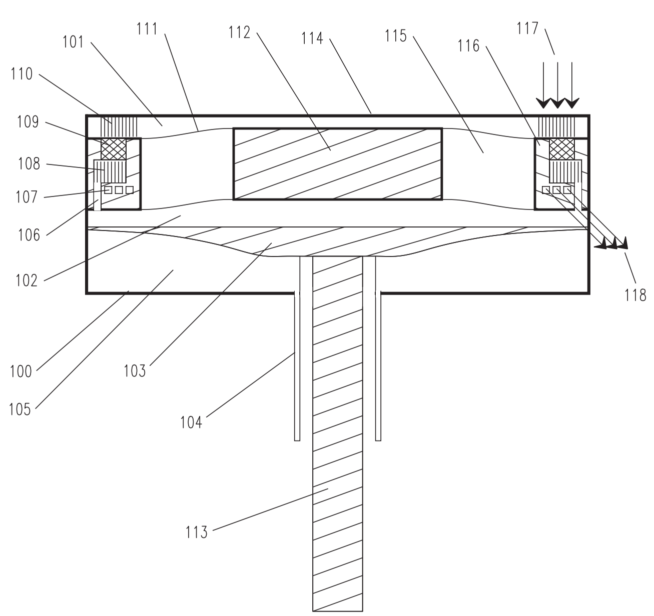

Fig. 1. Diaphragm engine schematic.

2. Design of the engine

A schematic diagram of the diaphragm engine is shown in Fig. 1 and a sectioned rendering of the engine as built is shown in Fig. 2. The engine is filled with 90 bar helium and operates in a beta configuration. The drive shaft (113), depicted at the bottom, is coupled to the (power piston) diaphragm (103) through a folded spring tube (104). The dual flexure structure (111, 112) above the diaphragm acts as the displacer. The action of the displacer is the result of its tuned mechanical resonance interacting with the gas dynamics. Acoustic power is created in the compression space (102) between the diaphragm and the displacer by their out of phase motion. The motion of the displacer leads the motion of the diaphragm by approximately 50 degrees. The acoustic power travels radially along the diaphragm surface and is piped through 48 small access tubes (106) to 24 cylindrical heat exchanger and regenerator (109) units distributed around the outer periphery of the engine. Next the acoustic power flows through the water cooled cold heat exchanger (108) which is made from carbon velvet. It then continues through the glass micro-capillary array regenerator before passing through the hot heat exchanger (110) which is also constructed from carbon velvet. The acoustic power is amplified passing through the regenerator, due to the temperature gradient across the regenerator (maintained by the adjacent heat exchangers), and travels into the expansion volume (101) where it is absorbed by displacer motion and coupled back to the compression volume through the action of the displacer. Due to amplification by the regenerator the returned acoustic power is greater than the initial power and the excess power is transferred to a linear alternator (not shown) by the drive shaft (113).

Below the diaphragm, as shown in Fig. 1, is an enclosed volume called the bounce space (105) which is filled to the same pressure as the engine working volume. The role of the bounce space is to balance the static pressure of the working gas across the diaphragm. This volume is sealed from the atmosphere by a pressure vessel (100) which includes a spring tube that is coupled to the diaphragm. The spring tube is a very stiff spring and is the dominant spring contribution to the mechanical resonance of the diaphragm, drive shaft, and alternator system. The spring tube is of a folded

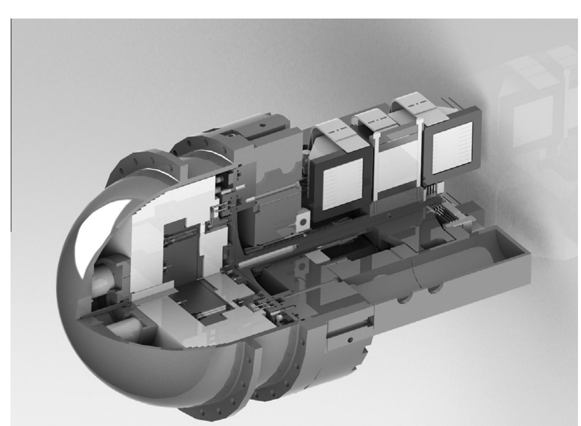

Fig. 2. Cross-sectioned rendering of the diaphragm engine.