A hot air driven thermoacoustic-Stirling engine

Presented at the Heat Powered Cycles Conference 2012,
ECN, Netherlands, 10 -12 September 2012

M.E.H. Tijani
S. Spoelstra

September 2012
ECN-M--12-044

A HOT AIR DRIVEN THERMOACOUSTIC-STIRLING ENGINE

M.E.H. Tijani*, S. Spoelstra

Energy research Centre of the Netherlands (ECN), PO Box1, 1755 ZG Petten, The Netherlands, email: tijani@ecn.nl

Significant energy savings can be obtained by implementing a thermally driven heat pump into industrial or domestic applications. Such a thermally driven heat pump uses heat from a high-temperature source to drive the system which upgrades an abundantly available heat source (industrial waste heat, air, water, geothermal). A way to do this is by coupling a thermoacoustic engine with a thermoacoustic heat pump. The engine is driven by a burner and produces acoustic power and heat at the required temperature. The acoustic power is used to pump heat in the heat pump to the required temperature. This system is attractive since it uses a noble gas as working medium and has no moving mechanical parts. This paper deals with the first part of this system: the engine. In this study, hot air is used to simulate the flue gases originating from a gas burner. This is in contrast with a lot of other studies of thermoacoustic engines that use an electrical heater as heat source. Using hot air resembles to a larger extent the real world application. The engine produces about 300 W of acoustic power with a performance of 41 % of the Carnot efficiency at a hot air temperature of 620°C.

1. INTRODUCTION

Conventional engines generate work from heat by driving a piston or turning a turbine. Thermoacoustic engines in contrast have no mechanical moving parts or sliding seals involved in the power cycle which makes them very reliable. They have also the advantages of using only environmentally friendly working medium (noble gases), simple implementation, and the use of common materials. The thermodynamic cycle used by a thermoacoustic traveling-wave engine is similar to the Stirling cycle. In 1979, it was recognized that the time phasing between the pressure and velocity of the gas in the regenerator of a Stirling system is the same as in a traveling acoustic wave (Ceperly, 1979).

In an attempt to eliminate the moving mechanical parts in a conventional Stirling engine, Ceperley built a traveling-wave thermoacoustic engine which consists simply of a regenerator sandwiched between two heat exchangers placed inside an air filled looped tube. However, the engine did not function due to large viscous losses in the regenerator and to mass streaming in the tube. It is only in 1999 that the first efficient thermoacoustic-Stirling engine is built by Backhaus et al. (Backhaus, 1999). This engine converts heat into acoustic power with an efficiency of 30 %, corresponding to 41 % of the Carnot efficiency without moving mechanical parts. In 2009, Tijani et al. developed a thermoacoustic-Stirling engine which achieved an even higher performance of 49 % of the Carnot efficiency (Tijani, 2011). These efficiencies are considered high enough to allow commercial applications. However, these efficiencies are obtained using electrical heaters as a heat source. This is not realistic for real worlds applications. The challenge is to achieve these efficiencies using industrial heat sources like hot flue gases from a gas burner or industrial waste heat.

This paper presents the design, construction, and test of a hot air driven thermoacoustic heat engine. The remaining of this paper is organized as follow: Section 2 describes the working principle, design, and construction of the engine. Section 4 is devoted to the measurements procedure. Section 5 presents the experimental results. In section 6 some conclusions are drawn.

2. DESIGN AND CONSTRUCTION OF THE THERMOACOUSTIC ENGINE

The engine uses heat Q_h from hot air at a high temperature T_h to generate acoustic power W. Part of the acoustic power is dissipated in the acoustic resonator (tube) and the rest (useful) is dissipated in a variable acoustic load. The remaining heat (Q_a) and the dissipated acoustic power (Q_r and Q_l) are rejected to the environment (T_a) as shown in Figure 1. In this study the engine operates between a high temperature and the ambient temperature.

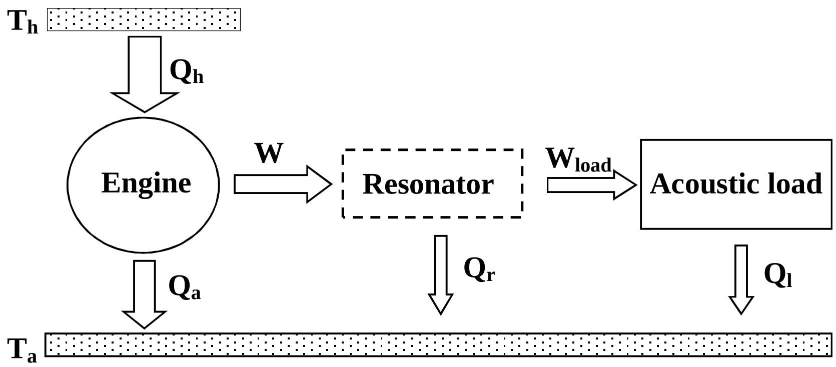

Figure 1 – Thermodynamic illustration of the thermoacoustic heat engine.

A schematic illustration of the thermoacoustic engine is shown in Figure 2. The thermoacoustic computer code DeltaEC (Ward, 1994) is used to design and optimize the engine. The engine uses helium at 40 bar and the operation frequency is 120 Hz. Air driven by a blower and heated by an electrical heater is used as hot heat source and water flow chilled by a thermostat bath is used as a heat sink for the engine. The different components of the engine as incorporated in the DeltaEC-model are as indicated in Figure 2. The engine consists of a torus-shaped section attached to a quarter-wavelength acoustic resonator and to a variable acoustic load. The torus-shaped section contains the thermodynamic active part consisting of a regenerator (REG) sandwiched between two heat exchangers AHX1 and HHX. The regenerator is the core of the engine where the thermoacoustic conversion processes takes place. The thermoacoustic-Stirling heat engine functions like an acoustic amplifier. The application of heat to the HHX and anchoring AHX1 to ambient temperature creates a temperature difference across the regenerator which generates spontaneously an acoustic wave (Ceperly, 1979; Backhaus, 1999). The acoustic wave is amplified by forcing the helium gas in the regenerator to execute a thermodynamic cycle similar to the Stirling cycle. The acoustic wave takes care of the compression, displacement, and expansion of the

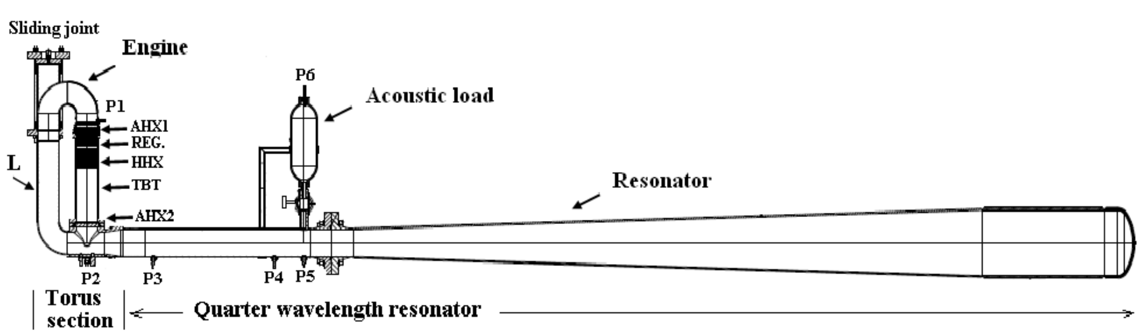

Figure 2– Schematic illustration of the thermoacoustic Stirling-engine. An acoustic load is placed on the resonator to control the power output of the engine. The pressure sensors are indicated by "P's".

gas, and for the timing necessary for the Stirling cycle. To keep the process on going, part of the acoustic power is fed back through the feedback tube (L) to the ambient side (AHX1) of the regenerator to be amplified. The remainder of the acoustic power is available as useful power at the junction to the resonator. The gas column in the thermal buffer tube (TBT) provides thermal insulation for the HHX. A secondary ambient heat exchanger (AHX2) is placed at the end of the TBT to intercept the heat leaking down the TBT. A CAD-drawing of the torus part of the engine is shown in Figure 3.

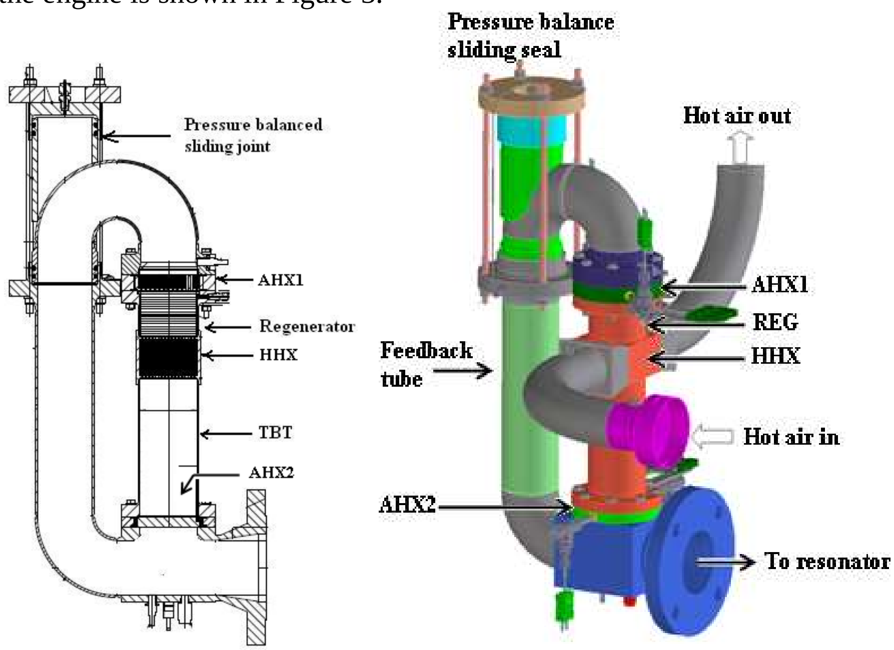

Figure 3 – A schematic- (left) and a CAD-drawing (right) of the torus part of the engine

The regenerator consists of a 6 cm long stack of 180-mesh stainless steel screens with a diameter of 6.7 cm. The diameter of the screen wire is 40 μm. A volume porosity of 78 % and a hydraulic radius of 35 μm are calculated using the mesh-number and wire diameter.

The regenerator holder, the HHX, and TBT are made from the same high temperature steel block (AltempHX) as illustrated in Figure 4 (middle). The first ambient heat exchanger (AHX1) is of cross-flow type and consists of a cylindrical brass block with a length of 2 cm and a diameter of 6.7 cm. Copper fins are used at the helium side to increase the heat transfer area. The water-side consists of rectangular channels (slits) 1 mm high and 15 mm wide. A picture of AHX1 is shown in Figure 4 (left). The hot heat exchanger (HHX) is the most crucial component of the engine. It is designed to exchange 2 kW of heat between hot air and helium gas. The length in the acoustic direction is 5 cm and the diameter is 6.7 cm. It is chosen to use a fin-fin cross-flow heat exchanger. The optimization of the heat exchanger consists of transferring the needed heat with minimal pressure drop and temperature difference. Slits are made in the block for both helium- and air-side using EDM technique. However, because of the length of the slits and the difficulty to access them this process took a long time and the cost were proportionally high. Stainless steel fins are brazed in the slits to improve heat transfer between helium and air. For the helium side 50 fins/in are used with a length of 5 cm and a height of 1 mm. For the air side 20 fins/in are used with a length of 7.5 cm, a width of 4.5 cm, and a high of 2 mm. The second ambient heat exchanger consists of a

Figure 4 – (Left) Picture of the AHX1; (middle) the block consisting of the regenerator holder, HHX, and TBT; (Right) picture of AHX2.

cylindrical brass block with a diameter 6.7 cm, a length of 1 cm, and containing 782 holes with a diameter of 1.5 mm through which the helium gas oscillates. Water flows around the perimeter of this block to carry away the heat leaking down the TBZ. A picture of AHX2 is shown in Figure 4 (right). The thermal buffer tube consists of a thin-walled cylindrical tube with an inside diameter of 7 cm, a wall thickness of 1.6 mm, and a length of 17 cm. The feedback inertance consists of cylindrical tube with a length of 73 cm and diameter of 6.7 cm. The pressure balanced sliding joint is used to compensate the thermal expansion of the hot parts of the engine. This will avoid the building of mechanical stress in the hot walls and hence the damage of these parts. The variable acoustic load consists of a 1 liter-tank and an adjustable valve. The resonator consists of two straight tubes connected by a cone. The first straight tube has an inner diameter of 8.3 cm and length of 86 cm, the conical tube has a start inner diameter of 8.3 cm, a length of 210 cm, and a final inner diameter of 21.3 cm. The last tube has an inner diameter of 21.3 cm and a length of 50 cm terminating in ellipsoidal cap. An elastic membrane is placed at the ambient heat exchanger to suppress Gedeon streaming (Backhaus,1999).

3. CHARACTERIZATION OF THE ENGINE

The characterization of the performance of the engine requires the measurement of thermal and acoustic powers. The system will be instrumented so that these different quantities can be measured. The thermal power input to the engine delivered by hot air flow or the thermal power extracted by flow water from the AHX1 or AHX2 is given by

$$\dot{Q} = \rho c_p U(T_o - T_i) \tag{1}$$

Here is ρ the density of hot air or water c_p is the specific heat of air or water, U is the volume flow rate of air or water, and T_i and T_o are the input and output temperatures of the stream flowing through the heat exchanger. The volume flow rates of air and water are measured with flow meters and the temperatures are measured by K-type thermocouples placed at the inlet and outlet of the heat exchangers.

The acoustic power produced by the engine is measured by the so-called two-microphone method. By reference to Figure 2, the acoustic power flowing past the midpoint of the two pressure sensors p_3 and p_4 is given by (Fusco, 1992)

$$\dot{W}_{2mic} = \frac{A}{2\omega\rho_g \Delta x}\left[\left(1-\frac{\delta_\nu}{r}\right)p_3 p_4 \sin\alpha + \frac{\delta_\nu}{2r}\left(p_3^{\,2} - p_4^{\,2}\right)\right]. \tag{2}$$

Here p_3 and p_4 are the amplitudes of the dynamic pressures measured by the two pressure sensors, Δx is the distance between the two transducers along the resonator, α is the phase angle by which p_3 leads p_4, ω is the angular frequency, ρ_g is the average density of the gas, and δ_v is the viscous penetration depth. The acoustic power dissipated in the load is given by (Fusco, 1992)

$$\dot{W}_{load} = \frac{\omega V_c}{2\gamma p_m} p_5 p_6 \sin\beta , \tag{3}$$

where p_5 and p_6 are the amplitudes of the dynamic pressures measured at the entrance of the load and in the compliance of the load respectively, β is the phase difference between p_5 and p_6, ω is the angular frequency, V_c is the volume of the tank of the load, p_m is the average pressure of the gas, and γ is the ratio of the isobaric to isochoric specific heats. The power, measured by the two-microphone method is the sum of the acoustic power, dissipated in the resonator section to the left of the midpoint of the two-microphones and the acoustic power, dissipated in the load

$$\dot{W}_{2mic} = \dot{W}_{res} + \dot{W}_{load} . \tag{4}$$

It is worthwhile to note that the two-microphone method is quite difficult due to its sensitivity to the microphone position, the phase difference, and flow conditions. The performance of the engine η is given by

$$\eta = \frac{\dot{W}}{\dot{Q}_h}, \tag{5}$$

where $\dot{W}$ is the acoustic power produced by the engine (entering the resonator) which is deduced from $\dot{W}_{2mic}$ by extrapolation using the DeltaEC model of the system. The Carnot efficiency of the engine is given by

$$\eta_C = \frac{T_h - T_a}{T_h} . \tag{6}$$

Here T_h is the temperature of the hot air and T_a is the average temperature of the cooling water flowing through the ambient heat exchanger. The performance relative to Carnot is defined as the ratio

$$\eta_r = \frac{\eta}{\eta_C} . \tag{7}$$

4. EXPERIMENTAL RESULTS

The accuracy of the acoustic power measurements is first checked by plotting Expression 4 for several drive ratio’s. The drive ratio is the ratio of the acoustic pressure and the average pressure. Linear fits to experimental results show a slope of about 1 which gives confidence in the two-microphone method measurements (Backhaus, 1999).

Figure 5 shows the measured performance of the thermoacoustic engine as a function of the temperature of the hot air for two drive ratio’s. The acoustic power output and the performance relative to Carnot increases as function of the hot air temperature. At a given hot air temperature the acoustic power produced by the engine at a dive ratio of 6 % is higher than at 4 %. The engine produces about 300 W of acoustic power with a performance of 41 %

of Carnot efficiency at a drive ratio of 6 % and a hot air temperature of 620°C. This relatively good performance is obtained in spite of a considerable heat leakage due to streaming in the TBT. As explained before, an elastic membrane is placed at the ambient heat exchanger to

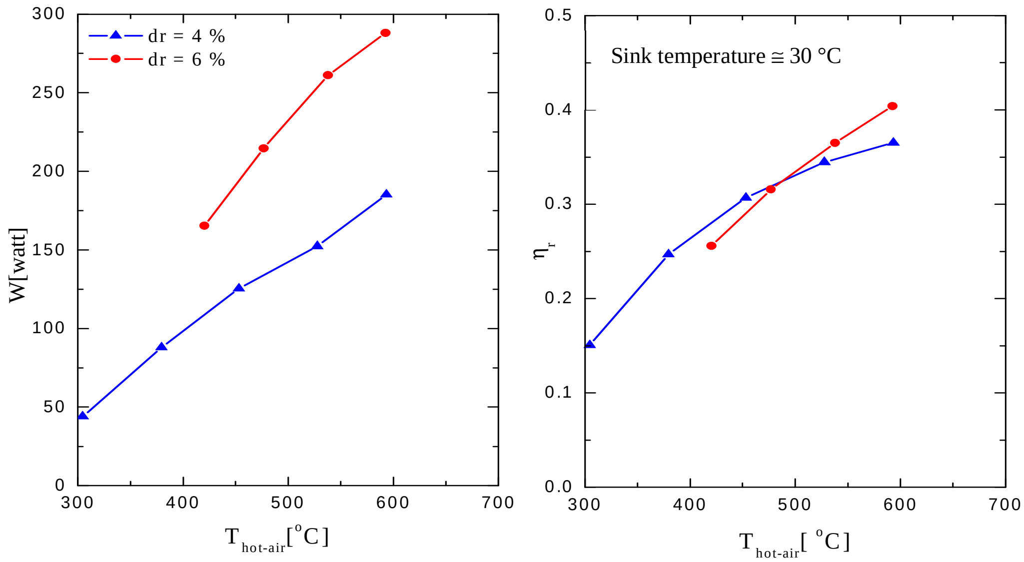

Figure 5– Measured acoustic power and performance relative to Carnot (η_r) as a function of the hot air temperature for two drive ratios 4 and 6 %.

suppress Gedeon streaming. However, Rayleigh and/or jet-driven streaming in the TBT causes a heat leakage down the TBT. Another point is that the HHX is designed to exchange 2 kW of heat between hot air at 800°C and helium gas at 550°C. To this end a hot air flow of 80 m^3/h is required. However, the experiments show that the hot air flow is 80 m^3/h at room temperature but decreases with the temperature of hot air to about 40 m^3/h at 600°C. The result is that only 1 kW of thermal power can be transferred to the engine and thus only about half of the expected acoustic power is produced. An improvement of the performance might be expected by suppressing the heat leak and improving the heat transfer in the HHX.

5. CONCLUSION

A hot air driven thermoacoustic-Stirling engine is designed, built, and tested. The engine produces about 300 W of acoustic power with a performance of 41 % of the Carnot performance at a hot air temperature of 620°C. The performance of the engine can be improved by suppressing the heat leak down the thermal buffer tube and improving the heat transfer in the HHX. The results of this study can be considered as encouraging for possible industrial applications of the thermoacoustic technology. However, an extended study is required for the ways efficient heat transfer between the thermoaocustic engine and different industrial heat sources might be achieved. To this end compact heat exchangers especially conceived for oscillating flow heat transfer might be considered.

References

Backhaus, S., Swift, G.W, Nature **399,** 335-338 (1999).
Ceperley, P.H., *J. Acoust. Soc Am.* **66,** 1508-1513 (1979).
Fusco, A.M., Ward, W.C. & Swift, G.W. *J. Acoust. Soc. Am*. **91,** 2229-2235 (1992).
Tijani, M.E.H., Spoelstra, S., *J. Appl. Phys*. **110**, (2011)
Ward, W.C., Swift, G.W *J. Acoust. Soc. Am.* **95,** 3671 (1994).