Waste-Heat-Driven Thermoacoustic Engine and Refrigerator

David L. Gardner (1), Carl Q. Howard (1)

(1) School of Mechanical Engineering, The University of Adelaide, Adelaide, Australia

ABSTRACT

Thermoacoustic engines are a suitable technology for capturing waste heat to perform useful work. These engines utilise a temperature gradient to encourage high amplitude acoustic waves in a resonant chamber. A standing-wave thermoacoustic prime mover and refrigerator combination has been designed and built. The waste heat source is the exhaust gas stream from a common internal combustion engine. The device was designed such that the prime mover harvests approximately 8% of the available waste heat at cruise, and the refrigerator heat load approximates that of two people. The prime mover and refrigerator combination has no moving parts, and uses helium as a working gas.

INTRODUCTION

A thermoacoustic engine (Rott, 1980) is a generic name for a variety of natural prime mover such as devices that deliver acoustic power, natural heat pumps, and devices which absorb acoustic power. However it is more common to differentiate these devices in terms of their operation. Prime movers are commonly called ‘engines’, and generate high-amplitude sound (the ‘work’ in a thermodynamic sense) due to an applied temperature gradient across the device. This is in contract to heat pumps, which are commonly called ‘refrigerators’, and use ‘work’ to create a temperature differential. The term *natural* was coined by Wheatley and Cox (1985), and is used here because the acoustic waves naturally occur as a consequence of a temperature gradient across a heat storage matrix that is loosely-coupled to the gas. Spontaneous acoustic oscillations can also occur when the gas is strongly-coupled to a storage matrix, mimicking Stirling cycle behaviour. In the prime movers, the acoustic oscillations appear spontaneously with adequate temperature gradient.

The thermoacoustic engines and refrigerators utilise high-amplitude acoustic standing or travelling waves confined within a pressurised resonator to do or absorb ‘work’, and have no moving parts. The multi-century history of thermoacoustics and its various incarnations has been described in many publications, but there is no better source than the website at Los Alamos National Laboratory. On this site, the interested reader can open educational and computational resources as well as links to news, publications, and information on research and development of thermoacoustic engines, refrigerators, and gaseous mixture separation. More detailed treatment of the subject is available from Swift (2002), and the computer code DeltaEC (Ward and Clark 2008) used to estimate the thermoacoustic behaviour of systems, can be downloaded from the Los Alamos website. A detailed listing of thermoacoustic references was compiled by Garrett (2004), and is recommended for those seeking a wide range of information sources.

Thermoacoustic devices are often described as being cheap, easy to build, having no close tolerances, and robust (in that they have no moving parts). Many varieties of the devices have been constructed over the past two decades and niche applications exist. But, heat-driven thermoacoustic technology has yet to be embraced; no waste-heat-driven thermoacoustic prime mover or heat pump has yet to be successfully devised, and no heat-driven prime mover has yet to find its way into the marketplace. Orifice pulse tube refrigerators, often thought of as thermoacoustic devices, have been very successfully employed in cryogenic applications and are commercially available (QDrive, Sunpower).

That written, an opportunity for successful implementation of heat-driven thermoacoustic prime movers may now exist. A 2002 study by Lawrence Livermore National Laboratory in the U.S. revealed that approximately 60% of the 103 Exajoules (Exa = 10^{18}) used by the U.S. annually was rejected as waste heat (LLNL, 2002). With the current interest in reducing or harvesting energy waste, thermoacoustic technology might endure renewed scrutiny. Frankly, it seems natural.

Previous researchers have constructed thermoacoustic engines powered by burners, such as Wollan *et al.* (2002). Researchers at the Energy Centre in the Netherland (www.ecn.nl) have also developed a thermoacoustic engine driven by a burner (Spoelstra and Tijani, 2005). As far as the authors are aware, all previous devices have either used simulated forms of waste-heat, by using an electrical heater or used a gas burner. The original contribution of this work is the first design and construction of a combined waste-heat driven thermoacoustic engine and heat-pump system that is directly powered (i.e. not simulated) by exhaust gases from a combustion engine, of which the authors (and colleagues) are aware.

This paper contains descriptions of the waste-heat driven coupled thermoacoustic engine and heat-pump in terms of the mechanical design, instrumentation used on the apparatus, and predicted thermoacoustic performance. Experimental results of the operation of the device will appear in a future publication.

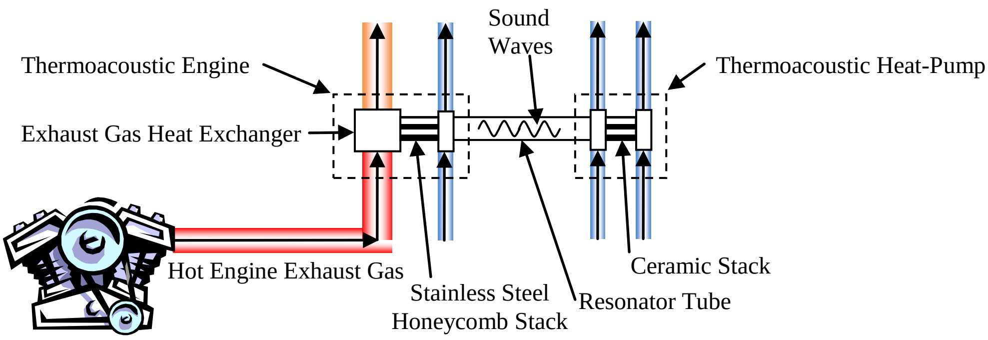

Figure 1: Sketch of the thermoacoustic prime mover and heat pump.

GENERAL CONSTRUCTION

The thermoacoustic refrigeration system comprises two sections namely a prime mover (thermoacoustic engine) and a heat pump, within a pressurised vessel. The pressure vessel contains Helium gas at a mean pressure of 1.6 MPa, and was designed using the appropriate sections of the Australian Pressure Vessel Standard, AS1210. Schedule 40 stainless steel and mild steel pipe components were generally used in the construction, as was the service of a certified pressure vessel welder.

The Prime Mover

The thermoacoustic engine (prime-mover) built in this project is a device that can capture the exhaust-gas waste-heat from an internal-combustion engine, and convert that waste-heat to high-amplitude standing acoustic waves within a resonator. The acoustic waves power a standing-wave thermoacoustic heat-pump, described in the following section. The design of the waste-heat collection system is unique.

Figure 1 is a sketch of the overall system, where the water pumps and tubing for the ambient heat exchangers are omitted for clarity. Exhaust-gas from an internal combustion engine is delivered to the thermoacoustic engine at the left-hand side of the sketch. A heat exchanger is used to extract heat from the gas stream and deliver it to the thermoacoustic engine. Adjacent to the hot heat exchanger within the thermoacoustic engine is the prime mover stack.

The stack is the heat storage assembly that has ‘loose’ thermal coupling to the oscillating gas. It is made of seven stainless steel honeycomb disks of diameter 155 mm and thickness 12 mm. The stack pores are hexagon-shaped with hydraulic radius 0.43 mm. Oscillating gas parcels move heat from the hot heat exchanger to the stack; adjacent parcels absorb the heat causing the parcels to expand, doing work on the surrounding gas, and enhancing the oscillation pressure amplitude. The pressure amplitude and acoustic particle velocity increase in amplitude until reaching equilibrium conditions that are governed by fluidic loss mechanisms.

All ambient heat exchangers are water-cooled.

The pressure vessel is made from 316 stainless steel and has a diameter of 156 mm and wall thickness 6 mm. The pressure vessel is filled with Helium gas, which oscillates as a standing half-wave at the fundamental frequency of the closed-closed tube, at approximately 315 Hz. The resonance frequency of the system is function of the entire thermoacoustic operation of the system that includes the acoustic and thermodynamic impedances, and the length of the pressure vessel. The length of the pressure vessel was selected to be approximately 1.5m long. Based on this design limit, the consequence is that the resonance frequency of the device was calculated to be approximately 315Hz using DeltaEC.

Adjacent to the stack is a water-cooled ambient heat exchanger that maintains a temperature gradient across the stack. The exchanger has copper fins that are 1.5 mm thick and 36 mm long in the direction of the oscillating gas. The fins are separated using 0.8 mm spacers, and were water-jet cut to allow passing fifteen copper tubes (7.92 mm outside diameter) arranged in three rows of five tubes. The stainless-steel shell was similarly bored. The tubes pass through the shell and fins, are silver-soldered to the shell, and are capped with manifolds for water delivery and collection. Care was taken to ensure the tubes did not interfere with the bolts required for assembly of the pressure vessel. The tubes were expanded, using a conventional tube expander, to provide better thermal contact with the fins and spacers. The flow rate of the water through the heat exchanger is approximately 4 litre/minute for each kilowatt of heat rejected by the prime mover.

Penetrations into the shell were made to allow the installation of thermocouples. A recess for an O-ring was machined into the end of the shell to seal the vessel to the next section.

A resonator tube with dimensions of 570mm long by 100mm inner diameter separates the engine and heat-pump. The tube was tapped in three places to allow the installation of pressure transducer to measure the acoustic power (Fusco, 1992). The three transducers span the standing wave pressure node, and are centred 143mm, 243mm, and 343mm from the ambient heat exchanger end of the tube.

The Heat Pump

At the right hand end of the resonator tube shown in Figure 1 is a brass-shelled cold heat exchanger that has fins 1.5mm thick and 15mm long in the direction of the oscillating gas. This heat exchanger constitutes the beginning of the heat pump section. The fins are separated using 0.8mm spacers, and were cut using a water-jet to allow the insertion of three 7.92mm outside diameter copper tubes arranged in one row. The brass shell was bored the same way. The tubes pass through the shell and fins, are silver-soldered to the brass shell, and are fitted with electric cartridge heaters to impose a head load on the heat-pump. As with the previous heat-exchanger, the tubes were expanded using a conventional tube expander to ensure better thermal contact with the fins and spacers.

To the right of the cold heat-exchanger is the heat-pump stack that is made from a ceramic cylindrical substrate, the same material found in automotive catalytic converters. The ceramic cylinders have a diameter of 124mm, length 87mm, 400 rectangular pores/inch^2 with 0.1mm wall thickness between adjacent pores. The stack was surrounded by a 1.5mm thick rubber sheet for protection. The stack and rubber is encased in a 129mm diameter mild steel shell.

After the heat-pump stack is the final heat-exchanger that is held at ambient temperature and removes the remaining heat from the pressure vessel. The heat exchanger has a diameter of 125mm diameter, 20mm long, and has four 7.92mm tubes through which cooling water passes. The construction is identical to the cold heat exchanger, except that the tubes terminate with water manifolds rather than being open for cartridge heaters.

At the end of the final ambient exchanger is a mild steel duct with a diameter of 129mm and 70mm long, which completes the resonator pressure vessel.

THE INSTRUMENTATION

A large number of sensors are used to measure the performance of the system. Three types of sensors were used, namely: rotameter flow meters, Type K thermocouples, and 500psi pressure sensors with Wheatstone Bridge piezoresistive sensing diaphragms. This type of pressure sensor allows measurement of the mean and oscillating pressure.

Two thermocouples are placed in the internal engine combustion exhaust stream, and using the amount of fuel consumed along with measured air fuel ratio stoichiometry, the amount of enthalpy delivered to the thermoacoustic engine is estimated.

The hot duct and hot heat exchanger have four thermocouples at each end, three equally-spaced along the perimeter and one in the centre. Another four thermocouples penetrate the engine ambient heat exchanger to measure temperatures at the cold end of the engine stack, and four more measure the temperature distribution at the engine ambient heat exchanger. A single thermocouple measures the gas temperature 10mm distant from the ambient heat exchanger.

Three pressure transducers enable the measuring of acoustic power passing the resonator pressure node, and another pressure transducer measures the acoustic pressure at the beginning of the heat pump components. A fifth pressure transducer is placed in the resonator boundary; in conjunction with the transducer at the beginning of the heat pump components, the acoustic power consumed by the heat pump can be measured.

The temperature distribution in the cold heat exchanger is measured by four thermocouples, and one measures the gas temperature. A final thermocouple in the engine measures the gas temperature 10mm from the final ambient heat exchanger.

Two thermocouples are used at each ambient heat exchanger to measure the delivered and rejected water temperatures. With the measured flow rate and differential temperatures known, the heat power extracted at these exchangers can be determined.

Table 1 summarises the number of sensors used in the experiment.

Table 1: Number of sensors used in the experiment.

Sensor	Quantity
Thermocouples	25
Pressure Sensors	5
Flow meters	2

COMPUTER MODELLING

The thermodynamic and acoustic performance of the system can be modelled using the software ‘Design Environment for Low Amplitude Thermoacoustic Energy Conversion’ (DeltaEC). This software is suitable for use where the (dynamic) acoustic pressure amplitude is less than approximately 5% of the (static) mean pressure. A DeltaEC model of the system described here was created so that the dimensions of the parts could be determined for the expected operating conditions and desired cooling capacity. The software uses a system of ‘guesses’ and ‘targets’, the former being generally uncontrolled parameters such as frequency or pressure amplitude, and the latter being parameters that can be controlled, such as lengths or boundary conditions.

A Mitsubishi Magna V6 engine was installed in an engine dynamometer test cell facility at the School of Mechanical Engineering. The heat from the exhaust gases of the Mitsubishi engine were used as the source of waste-heat for the thermoacoustic engine. The temperature of the exhaust gas from the Mitsubishi engine is about 700°C and approximately 145kW is rejected from the engine in the exhaust stream at higher engine power levels. The acoustic system harvests approximately 6kW from this exhaust stream.

Table 2 lists the predicted performance of the prime mover and heat-pump described in this paper.

Table 2: Predicted performance for the prime mover and heat pump.

Parameter	Units	Value
Frequency	(Hz)	315
Input Power	(W)	5750
*Hot Metal Temp**	(K)	*860*
*Amb. Metal Temp**	(K)	*311*
Acoustic Power	(W)	500
*Cold Metal Temp**	(K)	230
Cooling Power	(W)	135
Engine % Carnot	(%)	12

The hot metal temperature is limited by the pressure vessel code, and the ambient metal temperature predicted by the heat exchanger design; These are the only DeltaEC targets in the table and are indicated by italics. The remaining parameters are DeltaEC predictions.

The DeltaEC software predicted that the thermoacoustic system would provide 135W of cooling power and the temperature of the cold heat exchanger would be 230K (-45°C), but this is known to be optimistic. Based on the practical experiences at Los Alamos National Laboratories, the expected power of any realised system is less than that predicted by DeltaEC, due to the idealisations of the mathematical models. The more realistic estimates for power and temperature are approximately 120W at 260K (-17°C). This is near the metabolic load imposed by two people. Note that this does not include other heat loads such as radiation or convective loads that occur in passenger vehicles.

SUMMARY

This paper has described the design of a coupled thermoacoustic engine and heat-pump that is powered from the waste heat from the exhaust gas of a reciprocating engine. It is the understanding of the authors that this configuration of thermoacoustic systems has not been previously built and tested. At the time of submission of this paper, the components of the system have been assembled, however testing has not commenced. Experimental data will be presented at the conference.

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