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# REFRIGERATOR AND THERMOACOUSTIC ENGINE

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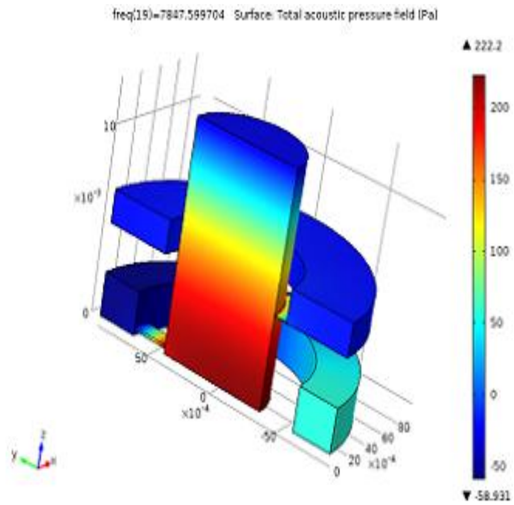
***Abstract-*** **Thermoacoustic heat engines provide a practical solution to the problem of heat management in microcircuits where they can be used to pump heat or produce spot cooling of specific circuit elements. There are basically two types of thermoacoustic engines, a prime mover where heat is converted to acoustic energy and a heat pump or cooler where sound can pump heat up a temperature gradient. Such devices are relatively simple, they can be efficient, and they are readily adaptable to microcircuit interfacing. Since this type of engines is usually operated in a resonant mode, the operating frequency determines its size. The devices presented here are pumped at frequencies ranging from 4 to 24 kHz. They have been developed for interfacing with microcircuits as heat pumps or spot coolers.**

***Index Terms-*** **Heat management, Thermoacoustic, Miniaturization, Acoustic heat pump, Engine**

## I. INTRODUCTION

It is, for example, necessary to include the thermal and viscous losses when modeling the response of small transducers, like condenser microphones, MEMS microphones, and miniature loudspeakers (i.e. receivers). Other applications include analyzing feedback in hearing aids and in mobile devices, or studying the damped vibrations of MEMS structures.

A good example for us to investigate here, which relates to an engineering application, is the transfer impedance of the standard IEC 60318-4 occluded ear canal simulator (sometimes referred to as the 711-coupler), as depicted in the figure below. In the graph to the right, the response is modeled including and excluding thermoacoustic losses. It is evident that these types of losses need to be included in order to capture the correct behavior when comparing their curves to the standard simulator's data




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 success-fully 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).

## II. PHYSICS OF THERMOACOUSTICS

*Governing Equations*

The procedure to derive the governing equations in the frequency domain is to assume small harmonic oscillations about the steady background properties. The dependent variables take the form:

where $p$ is the pressure, $\mathbf{u}$ is the velocity field, $T$ is the temperature, and $\omega$ is the angular frequency. Primed (') variables are the acoustic variables, while variables accompanied with the subscript 0 represent the background mean flow.

In thermoacoustics, the background fluid is assumed to be quiescent so that $\mathbf{u}_0 = \mathbf{0}$. The background pressure $p_0$ and background temperature $T_0$ need to be specified (they can be functions of space). Inserting the above equation into the governing equations and only retaining terms linear in the first-order variables yields the governing equations for the propagation of acoustic waves including viscous and thermal losses.

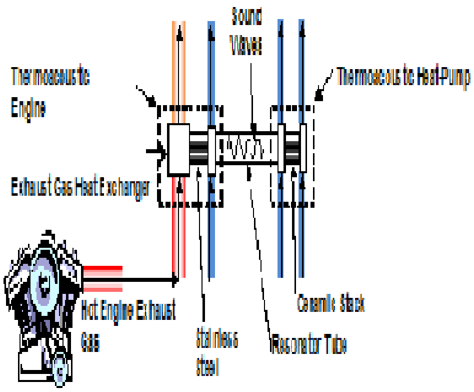



**Figure 1: Sketch of the thermoacoustic prime mover and heat pump**.

## GENERAL CONSTRUCTION

The thermoacoustic refrigeration system comprises two sec-tions namely a prime mover (thermoacoustic engine) and a heat pump, within a pressurized 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 omit-ted 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 ther-moacoustic 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.

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 pres-sure transducer to measure the acoustic power (Fusco, 1992). The three transducers span the standing wave pressure node, and are centered 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.

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.

## III. THE INSTRUMENTATION

A large number of sensors are used to measure the performance of the system. Three types of sensors were used, namely: rotmeter 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.

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.

Table 1 summarizes 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 |

## IV. COMPUTER MODELLING

The thermodynamic and acoustic performance of the system can be modeled using the software Design Environment for Low Amplitude Thermoacoustic Energy Conversion (Delta EC). This software is suitable for use where the (dynamic) acoustic pressure amplitude is less than approximately 5% of the (static) mean pressure. A Delta EC 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 target, 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.

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 |

*Bulk Losses and Attenuation*

It is important to note that viscous and thermal losses also exist in the bulk of the fluid. These are losses that typically occur when acoustic signals propagate over long distances and are attenuated. One example of this is sonar signals. These types of losses are, in air, only dominating at very high frequencies (they can be neglected at audio frequencies). The bulk losses are, of course, also described by the governing equations for thermoacoustics as they include all the physics. However, modeling large domains with the thermoacoustics equations is very computationally expensive. In the Acoustics Module, you should instead use the Pressure Acoustics interface and select one of the available fluid models: *Viscous*, *Thermally conducting*, or *Thermally conducting and viscous*.

## V. CONCLUSION

Now that you know the theory behind thermoacoustics and the associated equations, we can move on to tips and tricks for setting up a thermoacoustic model using COMSOL Multiphysics and the Acoustics Module. We will discuss that as well as examples and applications in the next blog post of this series.

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