DESIGN AND CONSTRUCTION OF A THERMOACOUSTIC DEVICE

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Abstract

This paper describes the design and construction of a thermoacoustic engine and fridge. Construction involved in depth design and understanding of the phenomenon. The aim was to produce a device that operates successfully converting heat energy into acoustical power and back. Preliminary design undertaken looked at the 4 main components involved in large scale thermoacoustic devices, the pressure vessel, heater, cooler and stack. The most promising of several main component designs were selected for construction.

Keywords: heater, heat exchanger, stack, thermoacoustics, working medium,

Introduction

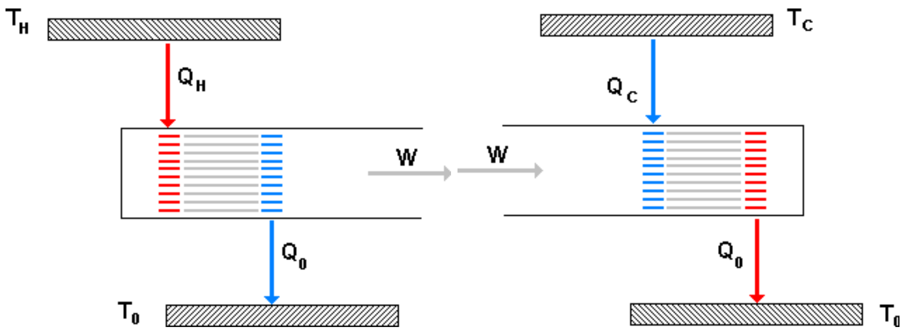
Thermoacoustics as the name suggests is a field, which involves the use of knowledge in both acoustics and thermodynamics. Due to the theoretical complexity of each of these fields on their own, there has been little progress in thermoacoustics, particularly here in Australia. The numerical complexities of thermoacoustic engines are out weighed by the advantages of using the phenomenon. Thermoacoustic devices in operation are "low tech" devices which have no moving parts and hence should require low maintenance. This makes the potential for their application desirable in many fields, applications would include, aerospace, industrial and in the third world. Thermoacoustic devises are currently used by high budget industries but are still able to be constructed from smaller budgets.

During the period of research undertaken by the authors the reference [1] was found to be the most valuable for our understanding of the concepts involved. This reference details the work done at Los Alamos National Laboratory for the United States Department of Energy. The author of [1] has vast experience in the field of thermoacoustics and can be found to be referenced in most journals on the subject.

Thermoacoustic Modelling

Thermoacoustic engines can be categorised into 2 types, namely the standing and the travelling wave type engines. It was decided to construct a standing wave engine due to the relative simplicity of the design. Standing wave engines work by thermal expansion and contraction of a gas between a hot and cold source. The result is a piston-less engine created by the unstable resonance in the system.

A two-stroke engine is analogous to a standing wave thermoacoustic engine as they both develop power every cycle. The actual thermodynamic method of power generation is by a Carnot cycle [1]. By performing a simple ideal energy balance it can be seen (figure 1a) that the power produced is the difference between the thermal input and thermal output [2].



(a) Thermoacoustic engine (b) Thermoacoustic cooler

Figure 1: Schematic Of Thermoacoustic Devices

$$\dot{W} = \dot{Q}_H - \dot{Q}_O \tag{1}$$

$\dot{W}$ denotes work produced, $\dot{Q}_H$ and $\dot{Q}_O$ denote thermal input and output respectively. As with other thermodynamic processes useful work is limited by the Carnot efficiency - η [2]

$$\eta = \frac{\dot{W}}{\dot{Q}} \leq \frac{T_H - T_O}{T_H} \tag{2}$$

T_H and T_O denote the temperature of the hot and cold reservoirs respectively. The design of the thermoacoustic engine was further complicated by the number of conflicting parameters that needed to be balanced to provide an optimal result. Our design started with the modelling of a standing pressure wave that would be produced by a thermoacoustic device. Acoustical wave velocity - c can be calculated by considering the properties of the gas in which the wave is travelling [3, 4].

$$c = \sqrt{\frac{\gamma R T_K}{M}} \tag{3}$$

γ is the ratio of specific heats of the medium, R is the universal gas constant, T_K is the temperature at which the speed is required (in °Kelvin) and M is the molar mass. This general equation allowed the design team to examine the result of using different gases. Knowing the wave speed and that the standing wave engine is half a wave length long it is only a small step to find the resonant frequency produced.

$$f = \frac{c}{2L} \tag{4}$$

L is the entire length of the engine from end to end. For reasons that became ever more apparent throughout the design it was optimal to keep the resonance frequency as low as possible. The main reason for keeping the resonance frequency low was due to the heat transfer required between the thermal sources and the gas. Higher frequency waves required more rapid heat transfer, increasing the complexity and cost of the heat exchangers. A balance however was required as reducing the resonance frequency involved the enlargement of the thermoacoustic engine which also increased the pressure vessel and gas costs.

Other important parameters of the standing pressure wave can be found by modelling the engine as an impedance tube with a standard acoustic driver. The following equations were adapted from [3, 4].

$$P = \frac{P_{max} + P_{min}}{2} \left(e^{j\left(\omega t - \frac{x\pi}{L}\right)} + e^{j\left(\omega t + \frac{x\pi}{L} + 2\pi\right)} \right) + P_{static} \tag{5}$$

P is the pressure at any point x and time t, P_{max} and P_{min} are the maximum and minimum dynamic pressures respectively, ω is the frequency of the standing wave in rad/s found using equation (4) and P_{static} is the static pressure of the engine. Integration and differentiation of (5) yields the particle velocity - U.

$$U = \frac{P_{max} + P_{min}}{2\rho c} \left(e^{j\left(\omega t - \frac{x\pi}{L}\right)} - e^{j\left(\omega t + \frac{x\pi}{L} + 2\pi\right)} \right) \tag{6}$$

ρ is the density. Finally, dividing the velocity by the frequency yields the particle displacement - X for later use

$$X = \frac{P_{max} + P_{min}}{2\omega\rho c} \left(e^{j\left(\omega t - \frac{x\pi}{L}\right)} - e^{j\left(\omega t + \frac{x\pi}{L} + 2\pi\right)} \right) \tag{7}$$

The results from this modelling were then used in the design of the thermoacoustic devices.

Thermoacoustic Design

From our work we have found that the heat exchangers required are the main difficulty in the design and construct of thermoacoustic engines. Generally there are three heat exchangers in thermoacoustic engines being the heater, cooler and stack. The stack is a heat exchanger that sits in between the heater and the cooler. Its purpose is to produce a temperature gradient along its length that is in thermal communication with the gas. A property called hydraulic radius - r_h was used to calculate the thermal communication distance of the stack.

$$r_h = \frac{A}{\Pi} \tag{8}$$

A is the cross sectional area for the gap and Π is the perimeter. To utilise the entire cross section of the gas the hydraulic radius of the stack must be of the same order as the thermal penetration depth of the gas - δ_κ.

$$\delta_\kappa = \sqrt{\frac{2k}{\omega\rho c_p}} \tag{9}$$

k is the gas thermal conductivity and c_p is the coefficient of specific heat of the gas. This equation shows the importance of gas conductivity and keeping the frequency low in relation to stack gap size. Due to the influence of gas conduction some time was spent looking at the feasibility of using gases other than air.

Gas	Ar	Air	CO	CO_2	H_2	He	N_2	O_2
$k \times 10^3$	42.71	67.21	64.44	68.05	428.1	362.2	63.06	71.79

Table 1: Gas Conductivity (W/mk at 1000°K) (adapted from [5] and [6])

As can be seen in table 1 air has only one sixth the thermal conductivity of Hydrogen. It can be said that generally small light molecules provide the best thermal conductivity. Being the lightest element and very cheap the use of Hydrogen was an option however its inflammability made it unsuitable for our purposes. The next best gas was Helium which is non-inflammable [7] but quite costly. It is planned that our thermoacoustic engine will be run on Helium after initial trials in air.

The thermal penetration depth of Helium worked out to be 0.16mm in our device. This meant that with Helium as the working medium the size of the gaps required between consecutive stack layers was 0.3mm. Obtaining this small gap proved difficult with our limited technology and budget. Several different methods were proposed and the most promising of these prototyped. Trial construction further reduced the number of options that were viable. The final design was a spiral stack utilising 0.3mm thick Aluminium sheet and 0.3mm nylon fishing line which was later removed to provide the air gap. While not as fine as similar stacks produced at Los Alamos we hope that it will provide good performance considering the cost savings.

The heat energy required will be provided to our system by Nickel-Chromium resistance wire. Electrical power has many benefits over other heating techniques. Electrical means seemed the easiest and cheapest way to provide heat into the confined space where the heater resides. Power requirements have been approximated at about 1000 Watts. This amount of power is easily obtainable from a wall socket hence 240 Volt mains operation of the heater element was decided. As the actual requirements and heater element output can only be approximated, it was decided early on to use a control system which is easily done with mains power. This control circuit utilises a thermocouple to sense the internal temperature and govern the power input using phase clipping techniques with a triac.

To produce the required cold reservoir thermal energy will be removed from the gas and stack by a finned heat exchanger. This will work by passing a fluid at a temperature lower than that of the heated gas. We designed our cooler to extract enough power using mains pressure water at ambient temperature, through 4 small Copper tubes in the engine's cross section. We could have used larger Copper tubes to increase the power extraction however this would have increased the impedance presented to the acoustical flow. In the event that insufficient power is extracted by mains water there is an option of using different cooling mediums. Fins added to increase the contact area with the gas and stack, reducing thermal resistance which in turn improves power extraction. Analytical analyses of this part proved very difficult requiring some erroneous assumptions about power extraction and final water temperatures. The intended design was checked with dimensional analyses of a picture in [1] before manufacture.

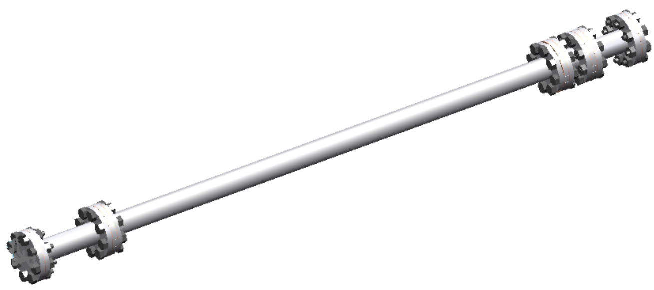


Figure 2: Thermoacoustic Device

The working parts of the thermoacoustic engine are all contained within a pressure vessel (figure 2) that holds the pressure in the engine. This pressure consists of two parts the static internal pressure of 3 MPa and the induced standing pressure wave created. For an assumed acoustic level of 180dB the induced pressure wave will have 20 kPa peaks. Stresses in the pressure vessel were considered in its design to allow for safe operation with assistance from the Australian standards [8, 9]. It was desirable to produce a pressure vessel with no internal protrusions that may impede the flow of the sound wave and in turn reduce the efficiency. To reduce the cost and difficulty of manufacture we chose to use standard American National Steel Institute DN80 (nominal bore) tubing [10]. The overall design of the engine was highly modular making construction easier and increasing the number of experimental options.

Up to this point we have only been discussing the thermoacoustic engine. There is another part to thermoacoustics and that is the thermoacoustic fridge (figure 1b). To create a thermoacoustic fridge all one has to do is replace the heater with a cooler and run the thermoacoustic engine in reverse by driving it with an acoustical source. This produces a refrigeration type cycle extracting heat from the cold side of the refrigerator stack. We hope to create a lower than ambient temperature in operation.

The performance of our engine will be judged by its output efficiency. G. Swift [1] has made several thermoacoustic devices and claims efficiencies in the order of 23% of the Carnot efficiency. As this is the university's first attempt at building a thermoacoustic engine utilising reduced technology it is not expected that such high efficiencies will be achieved. Efficiencies of 23% of the Carnot are still poor, relative to current mechanical technology. It is hoped that efficiencies of thermoacoustic devises can be improved with further development. Still, thermoacoustic devices have real world applications due to their low maintenance and lack of environmentally harmful gases.

Conclusion

Production of the thermoacoustic engine and fridge has started after long periods of design work. Large portions of time were spent understanding the complex behavior and interaction between the thermoacoustic elements of the engine. Of this time, much was spent modelling the processes using Matlab in an attempt to optimise performance and output. When a costing was done on this optimal design we required a budget on par with the high technology research industries. Using cheaper materials and lower tolerances for thicknesses of the stack we should have an engine that is near enough to the optimal design and significantly cheaper. With our new understanding of thermoacoustics we now appreciate the relative simplicity of important elements irrespective of the mathematical complexity. In light of this we still believe that our engine, once constructed, should be able to produce sufficient energy to produce some form of cooling and hopefully start a legacy of thermoacoustic excellence at Adelaide University.

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