Energy Conversion Using Thermoacoustic Devices

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Abstract.

Thermoacoustic engines offer the possibility for simple and efficient energy conversion devices. They can be prime movers where heat produces sound or heat pumps and refrigerators where sound pumps heat. An important element in such engines is the secondary thermodynamic medium, the stack which provides the phasing between heat transfer and pressure changes at acoustical frequencies. Other elements are a resonator, working fluid, usually a gas, heat exchangers and a driver or source of heat. Similar to thermoelectric devices, the engines require a temperature difference for their operation and when run in a conjugate mode they produce a temperature difference. They are interesting because they are simple and they have essentially no moving parts.

Introduction.

Thermoacoustic engines have a history which is possibly older than that of thermoelectric devices and it is only recently that applications for energy conversion have been studied. The first demonstrations of such engines date back to the eighteenth century when glassblowers observed that heating a section of a glass tube can produce sound. In 1777, Byron Higgins [1] investigated sound generation by heat in tubes open at both ends. Some time later, Rijke [2] discovered that a large vertical tube, open at both ends, emitted sound when a heated gauze was placed at about one quarter of the tube's length from the bottom. Sondhaus [3] described how a tube closed at one end produces sound when the closed end is heated. This effect is quite spectacular and it invites an explanation. Many papers were written on the subject but it was Rayleigh [4] who recognized that this is an example of a relaxation oscillator where phasing between heat injection and pressure changes in the tube is critical in sustaining the oscillations. The importance of a temperature difference for driving the acoustical oscillations was recognized with the Taconis [5] oscillations in the common dip-stick used for measuring the level of liquid helium in cryogenic storage dewars. The converse effect, sound producing a temperature difference and even cooling, was observed by Merkli and Thomann [6] in a resonant tube driven acoustically at around 100 Hz. There was cooling, by a few degrees, on a section of the tube where there was a speed antinode. At about the same time, Rott and collaborators [7] presented in a series of papers a theoretical treatment of the observed effects; it is used in essentially all the developments of thermoacoustics.

In 1983, Wheatley and collaborators [8] developed a thermoacoustic refrigerator which produced a temperature difference of around 100° C when pumped with sound at 500 Hz at a level above 185 dB in pressurized helium gas. This opened the field for exploration in a variety of thermoacoustic engines which basically are simple, require essentially no moving parts, and use environmentally safe materials.

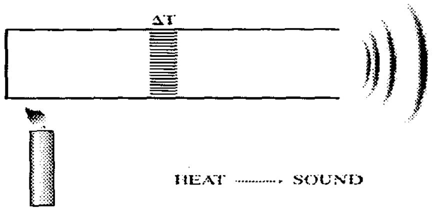
Thermoacoustics deals with the intimate connection between sound and heat as produced in a primary thermodynamic medium, usually a gas, when a solid boundary or a stack of plates interacts thermally with the sound field. The solid material or stack is known as the secondary thermodynamic medium. In a reciprocating action between the primary and secondary medium, the latter provides the correct phasing between heat injection and pressure changes to maintain the engine running.

There are two kinds of thermoacoustic engines:

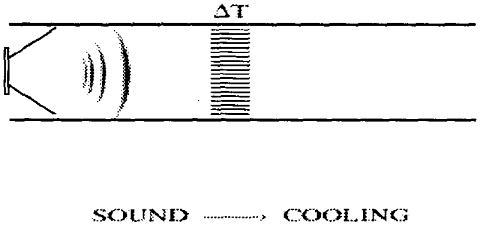
(i) the prime mover, where heat produces sound

(ii) the thermoacoustic heat pump or refrigerator where sound pumps heat or produces cooling.

They are shown in Fig. 1; both provide energy conversion. The basic elements are a source of heat, for the prime mover, a speaker for the refrigerator, a primary thermodynamic medium such as air or helium, an acoustic resonator, and a secondary medium, the stack, with heat exchangers at each end. Such engines are attractive because they have no moving parts, except for the driver, and they are simple.



(a) prime mover



(b) refrigerator

Fig. 1 Thermoacoustic Engines.

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The temperature changes T_1 produced by a sound wave with oscillating pressure changes p_1 are given, for an adiabatic process, by:

$$\begin{aligned} T_1 &= \left(\frac{\partial T}{\partial p}\right)_s p_1 \\ &= \frac{T_m \beta}{\rho c_p} p_1 \end{aligned} \qquad (1)$$

where β is the thermal expansion coefficient, c_p the heat capacity per unit mass at constant pressure, ρ is the density of the gas, and T_m is a mean temperature.

This shows that a sound field has a temperature variation. When a stack is introduced into the sound field, there will be thermal and viscous interaction between the two at the surface of each plate. Heat will flow between each parcel of air in sound field and each plate, the direction of the flow depending on which one is hotter. Such interaction occurs within a characteristic distance from each plate, the thermal penetration depth δ_k ; viscous effects are felt within a viscous penetration depth δ_υ . The depths are given respectively by:

$$\delta_k = \left(\frac{2\kappa}{\omega}\right)^{1/2} \quad \text{and} \quad \delta_\nu = \left(\frac{2\nu}{\omega}\right)^{1/2} \qquad (2)$$

where κ is the thermal diffusivity, ν the kinematic viscosity, and ω the acoustic frequency. The thermal penetration depth will determine the spacing between the plates of the stack, an acceptable spacing [9] being about $4\delta_k$; a small δ_ν is desirable to keep viscous losses low and this occurs with certain gases. An important function of the stack is to provide a thermal delay between heat transfer and the acoustic pressure changes. Since heat conduction is an irreversible process, this type of engine is inefficient by its mode of operation. This can be acceptable in view of the fact that such engines are simple and they have essentially no moving parts; all other types of engines also have inefficiencies. The heat flow occurs within a penetration depth δ_κ around the perimeter Π of each plate, and hence the effective cross-sectional area for heat flux is $\Pi\delta_k$ per plate; a large number of plates is needed to amplify the effect.

Before considering the efficiency of the thermoacoustic engine and comparing it to a Carnot machine, it is interesting to look at the direction of heat flow between gas particles and stack. At some critical temperature changes in the gas due to pressure oscillations cancel the temperature changes at the stack and no heat will flow between the two. The critical temperature gradient establishes a boundary between the direction of heat flow, a heat engine in one case and a heat pump or refrigerator for the other case; it is given by

$$\nabla T_{crit} = \frac{\gamma - 1}{T_m \beta}\frac{T_m}{\bar{\lambda}} \tan\left(\frac{x}{\bar{\lambda}}\right) \qquad (3)$$

at short radian wavelengths $\bar{\lambda}$ it can be quite large. Here γ is the ratio of specific heats and x the distance to nearest pressure antinode. To separate the two types of engines one introduces the parameter Γ which is the actual temperature gradient across the stack normalized to the critical temperature gradient, $\nabla T / \nabla T_{crit} = \Gamma$.

For $\Gamma < 1$, the engine is a heat pump while for $\Gamma > 1$ the engine is a prime mover and at $\Gamma = 1$ there is no heat flux. The efficiency of a prime mover is then the Carnot efficiency divided by Γ and for the heat pump the coefficient of performance is the Carnot COP times Γ . The efficiency here depends only on geometry and fluid parameters.

Prime Mover

This is the simplest thermoacoustic engine requiring no moving parts. Steady heat producing a temperature difference across a stack excites the resonator thus producing intense sound. The topic has been studied extensively covering combustion oscillations in rockets to conversion of heat generated sound waves to electricity. Interesting features of this device are the minimum temperature gradient for onset of oscillations, the thermal phasing of the stack, the intensity of the sound, the role of convection. The temperature gradient across the stack interacts with the Brownian motion of the gas molecules thus causing these to emit sharp pressure pulses at the end of the stack which excite a sound wave in the resonator. The oscillations are sustained by the heat input causing the temperature gradient. There is an onset level temperature gradient which initiates the oscillation while below this level they die away. The stack length Δx is shorter than the radian length $\bar{\lambda}$ but its length does not determine the resonant frequency. It is interesting to note that random thermal motion of gas molecules gets converted by the stack to coherent sound waves.

Possible energy conversion devices using heat to produce sound include a high intensity sound source, a driver for thermoacoustic refrigerators [10] and Stirling refrigerators [11], electric power generators [12]. This engine can be operated at low frequencies making it quite long, 3 m. or more, and up to 5 kHz when the device is about 1.5 cm. long. Studies have concentrated on the stability characteristics and which parameters affect them. [13]

Thermoacoustic Refrigerators

The second type of thermoacoustic engine, the refrigerator, is attracting much attention for applications, especially since it does not use CFC products. High power refrigerators have already been developed; they operate typically at 100 - 500 Hz and hence they are quite large. Performance numbers are impressive as cooling powers at 20% Carnot's efficiency have been achieved

[14] and temperatures of -70°C have been reached. Commercial systems are being considered [15].

In order to illustrate the principles let us consider a small thermoacoustic refrigerator which operates at 5kHz especially because the large low frequency refrigerators have already been covered in various publications [16]. Because it is a resonant system the high frequency device is smaller than the above refrigerators operating at the usual 500 Hz; a half-wave resonator operating in air is ~ 3.4 cm. long. Such small refrigerator shows much promise for applications in computers, modern electronics, and biological samples. It has been designed to be simple, light, and cheap to fabricate; its performance is adequate for many applications requiring a modest ΔT. Figure 2 shows this refrigerator. It is driven by a piezoelectric bimorph driver; with air at 1 atmosphere it can achieve ΔT of ~ 40°C for sound levels of 160 dB. The stack consists of a random mixture of cotton wool fibers, the average diameter being $10 \mu m$. Heat exchangers consist of copper screen; they make direct thermal contact to the stack. The stack provides thermal rectification as the sound field pumps the heat from the cold exchanger up to the hot one, this occurs in a bucket-brigade manner along each plate of the stack until the symmetry is broken at the end of the stack andthen the heat exchangers handle the heat.

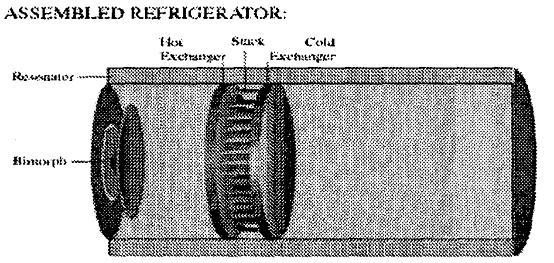

Figure 2. High Frequency Refrigerator.

By pressurizing the air in the resonator the power per unit volume is raised and a better impedance match is provided between air and driver. Moreover the quality factor of the resonator is increased and this leads to higher sound levels in the refrigerator. Since, according to Eq. 2, the penetration depth decreases as the pressure is increased, it is possible to have more stack material and this increase the cooling power. Also, being a small unit it can handle very high pressures on the working gas without exceeding the strength of materials.

A limiting factor in the performance of the refrigerator is the dissipation in the viscous boundary layer. Fig. 3 shows the viscous boundary layer and the thermal boundary layer next to the plate of the stack. The Prandtl number compares the viscous effects relative to the thermal ones; it is defined as the square of the ratio of δ_V / δ_K. For air this number is 0.66 which means that $\delta_\nu = 0.8\delta_\kappa$. This can be reduced by using gas mixtures such as He-Ar; thePrandtl number is cut down by almost a factor of 2 for a concentration of 65% He and 35% Ar

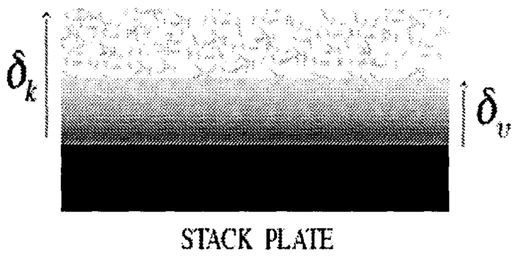

Figure 3. Stack Plate.

Conclusion

The 2 conjugate kinds of engines based on the thermoacoustic effect, the prime mover and the heat pump, provide many examples of devices where energy conversion can be achieved effectively. An interesting one which shows much promise is the use of the prime mover as the driver in a thermoacoustic refrigerator. This composite device has no moving parts and provides a simple way to use heat to produce cooling. Along those lines, another important application of the prime mover is in a Stirling cooler. Very high sound levels can be achieved thus eliminating the need for costly and bulky loudspeakers. [11]

As this conference deals with thermoelectricity it is interesting to point out some of the similarities of the thermoacoustic engines with the thermoelectric devices. They both need a temperature difference for their operation and when run in reverse they produce a temperature difference. In thermoelectric coolers entropy differences betweenthe 2 elements provide the cooling; they are limited to the electrons or holes near the Fermi level in metals and hence large currents need to be used. In semiconductors the situation is different and on e has to deal with the figure of merit. In thermoacoustics, there is also an entropy flow along the stack but it is not limited by the statistics since the gas is used in the classic limit.

The thermal rectification action of the stack is based on the Brownian motion of the gas molecules in the presence of a tilted potential created by a temperature difference. Such behavior is an example of a wider class of engines which have a broad range of applications and which use fundamental aspects of thermodynamics. Some of these aspects will become more evident as the size of the thermoacoustic is reduced for miniaturization.

Acknowledgments

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