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OPTIMIZATION OF THERMOACOUSTIC ENGINES FOR CONVERSION OF HEAT TO ELECTRICITY

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ABSTRACT

Thermoacoustic heat engines show much promise for the conversion of heat or waste heat to electricity. This paper presents developments that lead to optimization of such devices for a variety of applications needing thermal management. Heat engines in the mid-audio, at 2 kHz, and the low ultrasonic range, 24 kHz, were developed. Studies were made of heat transfer within the engines, thermal coupling to outside sources and power density. In some applications it would be beneficial to have arrays, especially when the devices are small; their synchronization can lead to increased power output. The generated sound is converted to electricity by piezoelectric devices.

INTRODUCTION

Thermoacoustic engines can convert heat to sound. Such devices are important because the generated acoustic energy can be simply converted to electrical energy. That is the goal of the work presented here. The introduction of this subject raises questions as to the how and why of converting heat to electricity using thermoacoustics; at the same time this topic brings forward a variety of applications which can benefit from the approach presented here. A thermoacoustic engine is a heat engine [1] where a temperature gradient along a stack of large surface area material in an acoustic resonator can generate an intense sound when the temperature gradient exceeds a threshold value, the critical temperature gradient. The acoustic oscillations are sustained by a steady heat input, by positive feedback from the resonator, and by thermal interaction between the sound field and the elements of the stack. The device is a self-sustained oscillator [2] whose behaviour is determined by parameters of the system and not by the external input. It is a resonant system whose frequency is basically determined by the resonator. Because of the wide range of applications for this type of device, a practical size was selected to meet some of the requirements. Hence devices operating in the range of 2 kHz and 24kHz will be discussed here.

NOMENCLATURE

T	[K]	Absolute temperature
Pr	[-]	Prandtl number
$\dot{Q}$	[W]	Heat flow
a	[m/s]	Speed of sound
P_1	[Pa]	Acoustic pressure
ω	[rad/s]	Angular frequency
ρ_m	[kg/m^3]	Average density
γ	[-]	Ratio of specific heats
β	[$1/^0C$]	Thermal expansion
κ	[m^3/s]	Thermal diffusivity
ν	[m^2/s]	Kinematic viscosity
δ_κ	[m]	Thermal penetration depth
δ_ν	[m]	Viscous penetration depth
Γ	[-]	Temperature gradient normalized by critical temperature gradient
η	[-]	Efficiency

The trend toward miniaturization, as featured here, is very important for many applications. Consequently, the devices presented here will be from the mid-audio to the low ultrasonic range.

In scaling the devices in size, certain parameters and characteristics have to be carefully considered. One such dimension in the thermal penetration depth δ_κ which determines the distance over which a sound field interacts thermally with an object, such as a stack element near it; there is also a distance which relates to the viscous losses, it is the viscous penetration depth δ_ν. Both distances are defined as:

$$\delta_\kappa = \sqrt{\frac{2\kappa}{\omega}} \qquad [1]$$

$$\delta_\nu = \sqrt{\frac{2\nu}{\omega}} \qquad [2]$$

and they are related by the Prandtl number:

$$Pr = \frac{\delta_\nu^2}{\delta_\kappa^2} \qquad [3]$$

which is 0.7 in air. Both distances are important in determining the spacing between the elements of the stack for efficient performance of the engine. [3]

The efficiency of a thermoacoustic heat engine is given as the sound output/heat input. It can be related to Carnot efficiency by:

$$\eta = \left(\frac{\Delta T}{T_h}\right)\left(\frac{1}{\Gamma}\right) \qquad [4]$$

where Γ is the ratio of temperature gradient along the stack normalized by the threshold temperature gradient for oscillation. ΔT is the temperature difference across the stack and T_h is the hot heat exchange temperature. The diffusion of gas parcels along the stack elements from the hot part of the stack to the cold end generates pressure pulses there which excite the resonator at its resonant frequency. Positive feedback from the resonator maintains the acoustic oscillation.

The generated sound is converted in situ to electrical energy using a piezoelectric transducer. It is possible to use also electromagnetic or electrostatic converters; the piezoelectric approach was chosen here because of its potential for high power density especially in small systems [4]. The electrical output is at the frequency of the heat engine. It can be rectified or down shifted in frequency.

There are several applications of thermoacoustic heat engines, mostly on large scale devices. Probably the oldest one is the helium dipstick device used for measuring the level of liquid helium in a vessel. The change in resonant frequency and amplitude in oscillation occurs at the interface between liquid helium and its vapour [5]. A recent application of this type of heat engine is in the generation of sound waves of high amplitude for acoustic pulse tube refrigerators for liquefaction of natural gas with no moving parts [6].This is a large scale application using pressurized helium gas. Because of the importance of thermoacoustic heat engines to a variety of applications, there has been many studies covering the fundamental aspects of this type of acoustic oscillator [7,8].

OPTIMIZATION OF DEVICE FOR ENERGY CONVERSION

The problem studied here is twofold, the development of this type of device for converting heat to electricity, and its interfacing with sources of heat or waste heat. As the device described here has many applications, it is important to develop such devices for the expectations of the various applications. Issues that are addressed in this work are power density, device efficiency, power output, and in particular thermal coupling to the source of heat, for large ΔT or small ΔT. Possible applications of this technology are in power plants, waste heat recovery, automotive waste heat [9], server farms for computer thermal management, solar energy harvesting, and other systems in need of thermal management. Each application with its own specific needs has a range of optimal temperature differences ΔT, and structural configurations.

EXPERIMENTAL DETAILS

Two types of acoustic energy converters were studied, one operating in the mid-audio at 2 kHz, and one working in the low ultrasonic range at 24 kHz. Fig. 1 shows the basic unit and the approach used in this work. It shows how heat can generate sound. At the bottom of the acoustic cavity the generated sound is converted to electricity by means of a piezoelectric device.

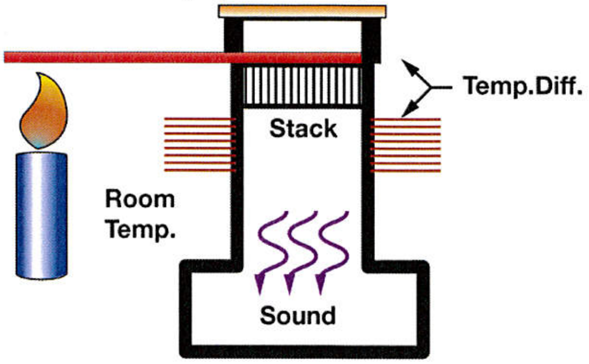

Figure 1 Basic thermoacoustic energy converter.

Heat was injected to the hot side of the device by means of an electric wire heater wound next to the hot heat exchanger or by direct contact of the hot side of the device to a hot plate. The cold side was maintained at room temperature. Temperature was monitored at specific locations in the engine: the hot side of the stack, the cold side of the stack, the cold side of the resonator, and the hot side of the resonator. All measurements were made with copper-constatan thermocouples. The temperature was monitored continuously.

On the 2 kHz engine, the temperature at specific locations was measured at constant heat input to the engine. The sound level was monitored by a piezoelectric device located inside the engine. This study was conducted on two thermal modes of operation, a constant heat flow through the engine, and a constant temperature difference across the engine. This made it possible to follow the thermal behaviour of the engine when generating acoustic energy. This was achieved by changing the thermal conductance in parts of the engine, and by switching on or off mechanically the acoustic intensity.

The 24 kHz engine was studied in continuous operation using a thermocouple, and a piezoelectric microphone. The engine had a volume of ~3mm^3. Although its power density could be high, the sound level was relatively low. In order to increase the sound power output, an array of engines would raise the sound level. This led to an investigation of thermoacoustic engine coupling and synchronizations for possible use in an array of such kHz engines [10].

RESULTS: 2KHZ ENGINE

The device resonator, a ¼ wave resonator, was 3.12 cm in diameter and 4.24 cm long; its volume was 32.4 cm^3, and it operated at 1.930 kHz. The stack consisted of steel wool pressed between a hot and a cold heat exchanger, a temperature gradient was established along the stack. The heat exchangers were fine copper wire screen with an open area of 36%. The working fluid was air at one atmosphere. The piezoelectric device, a PZT monomorph, was located at the bottom of the acoustic cavity which attached to the acoustic engine resonator. In order to study the performance of the engine, a special shutter was incorporated to switch the engine off or on while the heat input was on. This is shown in Fig.2; a steel wool plunger was pressed in or out of the cold side resonator opening.

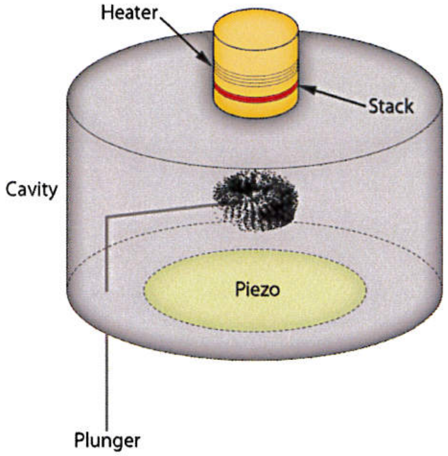

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Figure 2 Thermoacoustic energy converter with plunger to switch off or on the sound output.

The engine could be activated by means of a heater wound on the resonator or by thermal contact to a hot plate (this simulates a real application with contact to a source of heat). Above a threshold temperature gradient along the stack, intense sound was generated; its intensity depended on the magnitude of the temperature gradient. Constant heat was applied to the engine. It was switched off by using the plunger to block the resonator; removing the plunger allowed sound to be generated again. During the sequence of sound on, sound off intervals, the temperature was monitored at the 4 locations shown in Fig. 3.

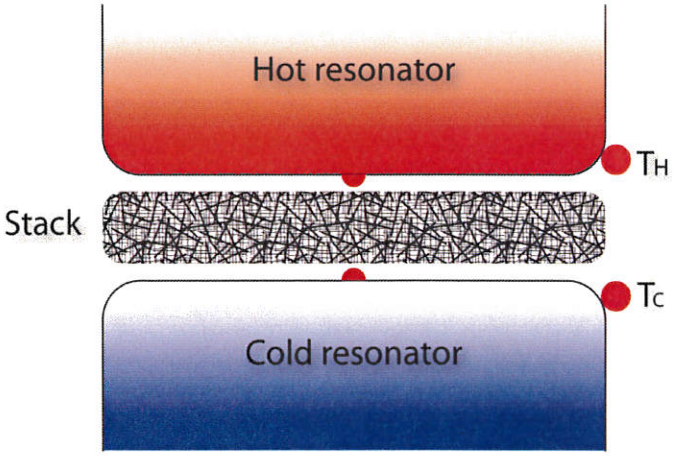

Figure 3 Temperature sensors at hot resonator, cold resonator, and each side of the stack.

The results show the time dependence of the thermal behaviour of the active part of the engine. With constant heat input to the engine, the temperature profile varies with the sound output. When sound is on, there is a temperature drop across the hot side of the resonator and stack. During this part of the cycle, the cold side of the stack shows a temperature rise, i.e., due to the rejected heat from engine performance. To visualize the sound on sound off cycle, the sound output was measured by the piezoelectric device at the bottom of the acoustic cavity. This is shown in Fig. 4, the shutter was quite effective at switching the sound off or on.

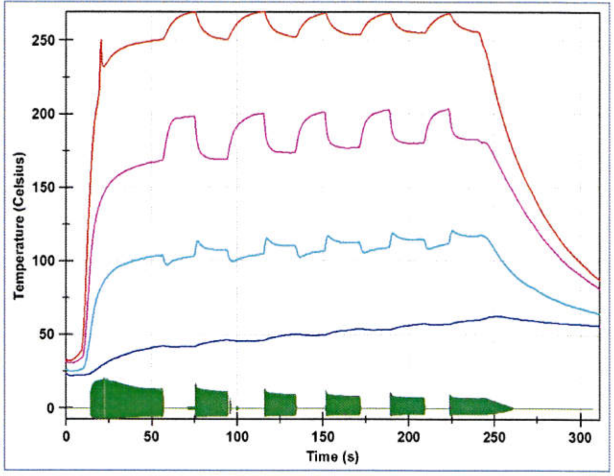

Figure 4 Temperature profile during sound on, sound off, cycles with continuous heat input.

The bottom trace shows the sound on, sound off behaviour; the top trace shows the temperature T_H of the hot side of resonator. The second trace shows the hot side temperature of the stack, the third trace corresponds to the temperature of the cold side of the stack. Trace four shows the temperature of the cold heat exchanger. Such behaviour is due to the constant heat input mode of operation. It is interesting to note that sound is generated for a $\Delta T = 60^{0}$C across the stack. Such small ΔT is desirable for many applications. The temperature changes observed in the stack–heat exchanger section are due to the constant heat flow mode of operation. Clearly not all the temperature drop is across the stack, although this would be ideal. To improve the performance of the device, the mode of operation was changed to constant temperature difference across the engine. This was achieved by reducing the thermal resistance between some of the components of the engine. Contact to the hot plate was made via a heat transfer compound (Thermalcote Thermal joint compound). The hot heat exchanger was thermally anchored to the hot side of the resonator via a thick copper heat exchanger [11]. Also, the cold heat exchanger was thermally attached to the cold heat sink, the cold side of the resonator. Following this, the temperature at specific spots on the engine was followed again while the engine was on. Because of the reduced stray thermal resistances, the device was operated in the constant temperature mode. Fig. 5 shows the new results.

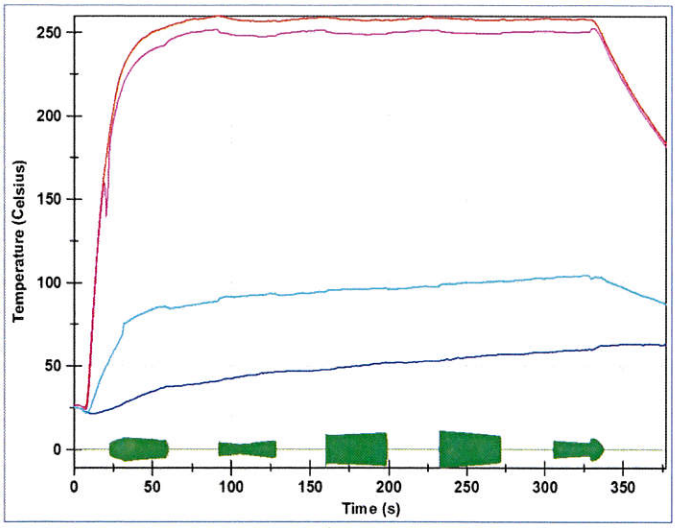

Figure 5 Temperature at hot exchanger, cold exchanger, and each side of the stack; bottom trace is the sound intensity.

The top trace shows the temperature of the hot heat exchanger, and the second trace that of the the hot side of the stack. Both are almost at the same temperature. Across the stack, the temperature difference is now $\Delta T=150^0C$ and the step structure has disappeared even though the sound is on, or off, as shown by the bottom trace. For the same temperature difference across the whole engine as before the ΔT across the stack has been raised from 60^0C to $\Delta T=150^0C$, i.e. raising the device efficiency substantially. The heat flux has been raised by a factor of 2.5. Trace four shows the temperature of the cold heat sink of the engine. This type of engine can be applied to thermal management of the heat stack in a power plant or to the exhaust of an automobile or for conversion of solar energy.

RESULTS: 24 KHZ ENGINE

In optimizing the thermoacoustic heat engine for applications, development was also needed for very small acoustic devices. By using small engines at higher frequency, the power density can be increased, because:

$$\text{Power/Volume} = \left(\frac{\omega}{4\pi}\right)(\mathrm{T_m}\beta)(\gamma-1)\left(\frac{{p_1}^2}{\rho_m a}\right)(\Gamma-1)$$

Consequently, devices were developed for operation in the ultrasonic frequency range. They were 3.8 mm long with a 1 mm inner diameter (volume of 3 mm^3). In developing such engines, they were essentially scaled down from the above 2 kHz devices; heat was injected by means of a heater attached to the hot side of the resonator. The cold side was thermally anchored to room temperature. Fig. 6 shows a 8.9 kHz device which was a precursor of the present 24 kHz engine presented here.

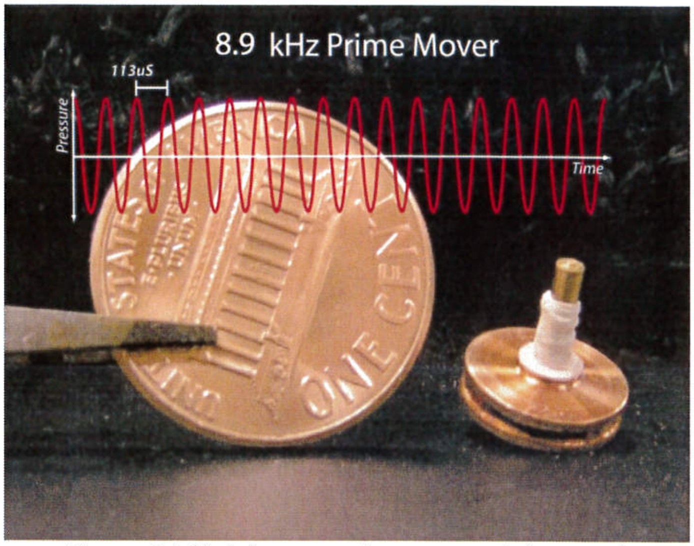

Figure 6 A high frequency thermoacoustic heat engine.

Since the reduction in device length by a factor of 10 was too sudden, an intermediate size engine was developed at 8.9 kHz before going on to 24 kHz.

Although the development of an ultrasonic 24 kHz device is an important achievement in the field of heat engines, such engines do not produce much power (power density is about 10 times those of the 2 kHz device). This can be overcome by assembling arrays of ultrasonic devices. Because a thermoacoustic engine is a self-sustained oscillator its phase of oscillations cannot be predicted [12]; such devices are triggered randomly by a fluctuation. Here, for array application it would be beneficial to synchronize the devices. In preparation for this, two ultrasonic thermoacoustic devices were coupled for synchronization. They were coupled by a common acoustic cavity, as shown in Fig. 7.

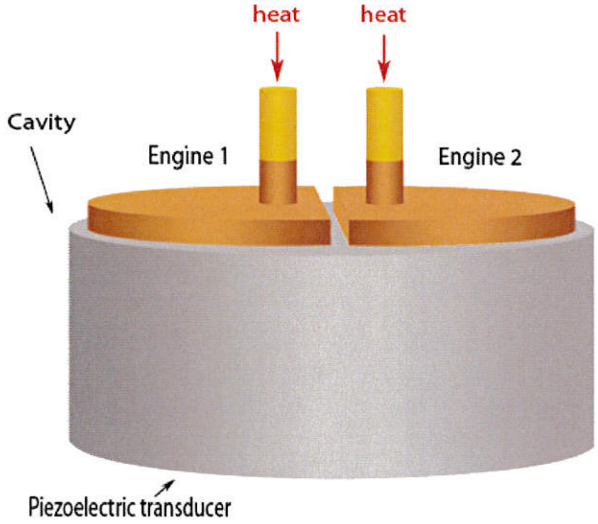

Figure 7 Two coupled ultrasonic engines.

The field of synchronization is an important area, for example in devices such as lasers and in other fields; in-phase synchronization can lead to a maximum signal, which is relevant to the acoustic energy converter presented here. For N signals, combined together with in-phase coherence the resultant signal is N times larger. For N signals combined incoherently, the resultant signal is $\sqrt{N}$ times larger.

The results of the coupling of two engines, one at 20.4 kHz and the other at 20.2 kHz, are shown in Fig. 8. Both were heated individually using electric heaters; they started at the same time, then engine 1 had its heater off at the time of ~18 sec, but engine 2 still had its heater on. At 21 sec, the heater for engine 2 was switched off.

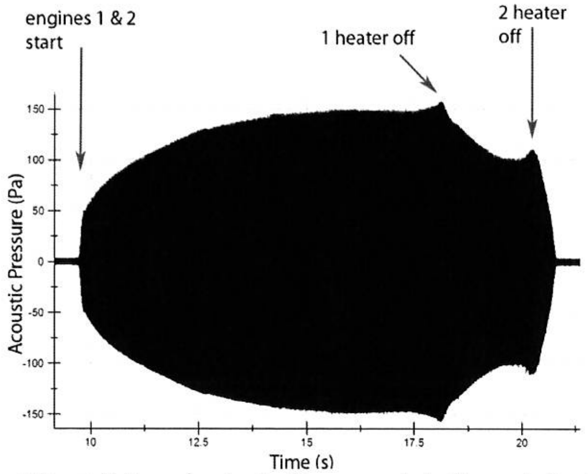

Figure 8 Sound output of two coupled ultrasonic heat engines.

A FFT measurement was taken at t=15 sec. It shows a simple sharp line at the frequency of 2.13 kHz, the line width being very narrow with a width of 5 Hz FWHM. This is shown in Fig. 9. Although both engines had different resonant frequencies, coupling then resulted in one single frequency, which was quite narrow. At this stage it is not clear if the engines were synchronized in-phase, especially since the change in sound level when one engine was switched off corresponds to $\sqrt{2}$. The resultant single frequency suggests that they were. Further studies of this are needed.

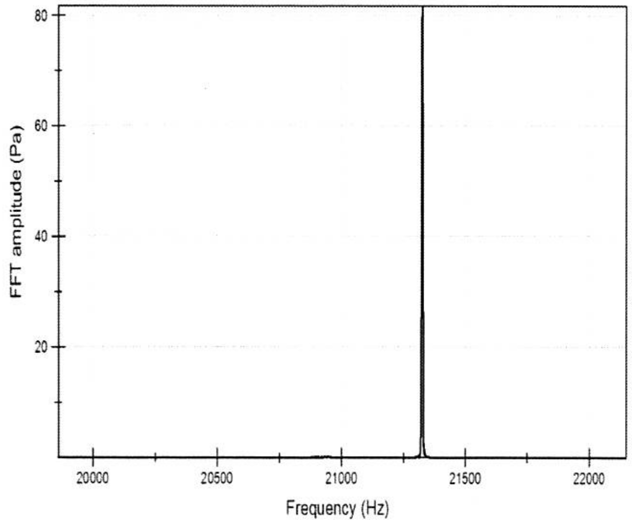

Figure 9 FFT of signal from 2 coupled thermoacoustic engines operating in the ultrasonic range.

The performance of such small thermoacoustic devices opens the field for large system arrays which could be integrated with a variety of applications. These could be for thermal management of computers and laptops, and other electronics, heat removal in server farms, and even waste heat recovery in power plants. The advantage of an array is the increase in power output and the convenience of interfacing to specific applications.

CONCLUSION

This work has presented thermoacoustic engine development features which led to some optimization of their performances as energy converts for applications. By operating the heat engines in the constant heat flow and constant temperature difference modes, the performance led to reducing stray temperature drops in various device parts and concentrating it mainly across the stack, which is where most of the engine action takes place [13]. In fact the temperature difference ΔT along the stack was raised by a factor of 2.5 for the same temperature difference across the whole engine. This raised the heat flux to the hot side of the stack by a factor of 2.5. The development of miniaturizing the devices produced engines working in the ultrasonic range with increased power density. Coupling of two such engines together caused increased power output with possible synchronization [14,15]. This opens the way for array assemblies and further miniaturization using MEMS. By careful design of the resonators the temperature difference for onset of oscillation can be reduced to ΔT less than 50^0C. The optimization presented here opens the field to numerous applications based on heat and/or waste heat; both are plentiful. It is interesting to point out that the operation of the engines described here is based on heat exchange between the sound field and the stack, and irreversible effect [16].

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