ACOUSTIC APPROACH TO THERMAL MANAGEMENT: MINIATURE THERMOACOUSTIC ENGINES

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Abstract:

An acoustic approach to thermal management in electronics can be efficient and it can be directly interfaced with electronic devices. It is based on two types of thermoacoustic heat engines, which are being developed for microcircuit applications. One type of device, the prime mover, converts heat to sound; energy is radiated away acoustically. This is achieved with essentially no moving parts. The other type of device, a heat pump or refrigerator, moves heat from one reservoir to another reservoir using sound waves. Both devices are resonant and hence their size scales inversely with operating frequencies. Devices presented here operate in the frequency range of 4 kHz to 21 kHz, depending on their size. The components are simple and they can be fabricated using microcircuit techniques. They consist of an acoustic resonator, heat exchangers, a stack of high surface area material for heat storage, and a working gas such as air or helium or gas mixture (He – Ar). The cooler has a loudspeaker to generate the sound for pumping heat, while the prime mover has a coupler to the source of heat. Working devices range in size from 2 cm to a few millimeters. Their efficiency, which depends on geometrical factors, is an appreciable fraction of Carnot. An important feature is a high power density. Working models and modeling show that power densities of several watts per cubic centimeter can be achieved by optimizing the parameters and working conditions. Performance characteristics of miniature prime movers and refrigerators will be presented.

1. Introduction:

In order to manage the ever-increasing levels of waste heat in electronic circuits, a variety of thermal management techniques have been proposed and implemented. An acoustic approach, as presented here, shows much promise for such applications. It is simple, it can be quite efficient, and it is capable of coping with high power densities. Moreover the working fluid is environmentally safe. Thermoacoustic devices have been developed for a variety of applications [1] mainly large scale, but only recently they were proposed for thermal management tasks [2]. This is possible because, being resonant systems, they can be miniaturized by raising the operating frequency, and thus be interfaced with electronic circuits for removing waste heat.

There are two types of thermoacoustic devices, and they can both be used in thermal management. One type of device uses heat to create a temperature gradient along a stack of plates which leads to the production of sound in a resonator coupled to it, i.e. heat generates sound. This is known as a prime mover. The second type of device works in the opposite direction, in that sound can pump heat up a temperature gradient along a stack of plates in a resonator. This is known as an acoustic refrigerator or acoustic heat pump. The basic elements in both devices are a resonator, a stack of large surface area plates, a heat exchanger at each end of the stack, a working fluid, and a source of heat or a source of sound. Device size scales inversely with operating frequency. An acoustic cooler is typically about 4 cm long for an operating frequency of 4.2 kHz; at 24 kHz it is 7.2 mm long.

The thermal interaction between the sound field in the working gas and each element of the stack is the driving force of this type of engine; it provides the timing mechanism and it also provides amplification for the engine. In both devices heat is shuttled up or down the stack elements in small steps of displacement x_1. Here $x_1 = u_1/\omega$ where u_1 is the speed of the gas particles in the sound field of the standing wave at angular frequency ω. The direction of the heat flow between the stack plates and surrounding gas of sound field determines whether the engine is a prime mover or a refrigerator. This is represented by the ratio Γ of the temperature gradient ∇T along the stack normalized to a critical temperature gradient ∇T_{crit}, where $\Gamma = \nabla T / \nabla T_{crit}$. At the ∇T_{crit} the temperature rise of the gas due to an acoustic pressure change p_1 is equal to the temperature of the stack when the air parcels are displaced by x_1; hence there is no temperature difference between the two and hence no heat flow. When $\Gamma < 1$, the device pumps heat up a temperature gradient and when $\Gamma > 1$ heat flows down the temperature gradient generating sound. Because of the complementary nature of the two devices, the refrigerator is an active device while the prime mover is a passive device.

2. Experimental Details

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A. Thermoacoustic Cooler/ Heat Pump

The basic components of this unit consist of an acoustic driver for pumping heat, a resonator, a stack of plates for storing heat, a heat exchanger at each end of the stack for injecting heat and removing heat, and a working gas such as air, or helium, or gas mixtures like He – Ar. The stack consists of fibrous material such as cotton wool or glass wool. Since the acoustic devices presented here were designed for the frequency range from the high-audio frequencies to ultrasonic frequencies, the drivers consist of piezoelectric films arranged in a bimorph or monomorph configuration; the driver is coupled to the resonator by means of a light rigid cone attached at the bimorph apex (it is an impedance match to the working fluid). The resonator is tuned to the driver; typically it is a half-wave resonator. A half-wave standing wave is set up in the resonator and this sustains the phasing of this engine. The stack is located at a position in the resonator where the acoustic intensity p_1 u_1 is large. Here p_1 is the pressure amplitude of the sound field and u_1 the particle speed amplitude of the gas in the sound field. Fig.1 shows the basic unit.

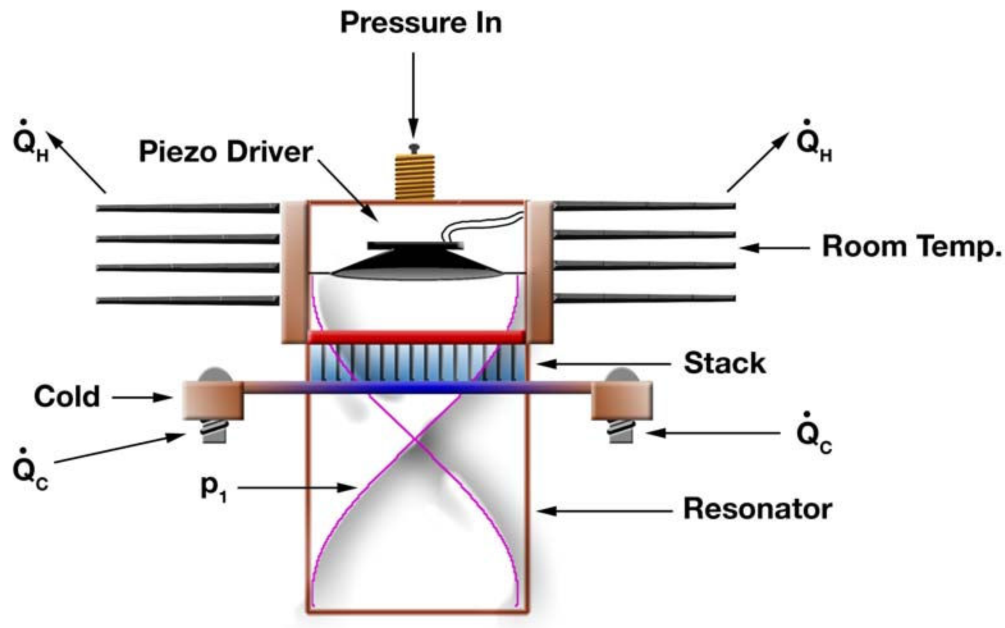

Fig. 1 Basic thermoacoustic refrigerator

Heat pumping along the stack is caused by the sound field which forces air molecules to move heat from the cold heat exchanger to the hot exchanger by means of bucket-brigade type of small steps of magnitude x_1. Critical to this is the thermal interaction between the sound field and each element of the stack. There is a characteristic distance δ_k next to each stack [3] element and it determines the distance over which there is substantial lateral heat flow between the stack elements and the gas next to them. This thermal penetration depth is given by

$$\delta_k = \left(\frac{2K}{\omega}\right)^{1/2}$$

where K is the thermal diffusivity of the gas; δ_k is approximately 44 μm for air at one atmosphere at 5kHz. This distance determines the spacing that needs to be maintained between the stack elements. It is typically 2-4 δ_k.

In the devices described here the pump acoustic frequencies range from 4 kHz to 24 kHz, and hence their size scales inversely with the frequency. The cold heat exchanger extends out of the resonator and it is coupled thermally to the device needing thermal management. Heat is pumped from the cold heat exchanger to the hot exchanger along the stack elements. This is shown in Fig. 2.

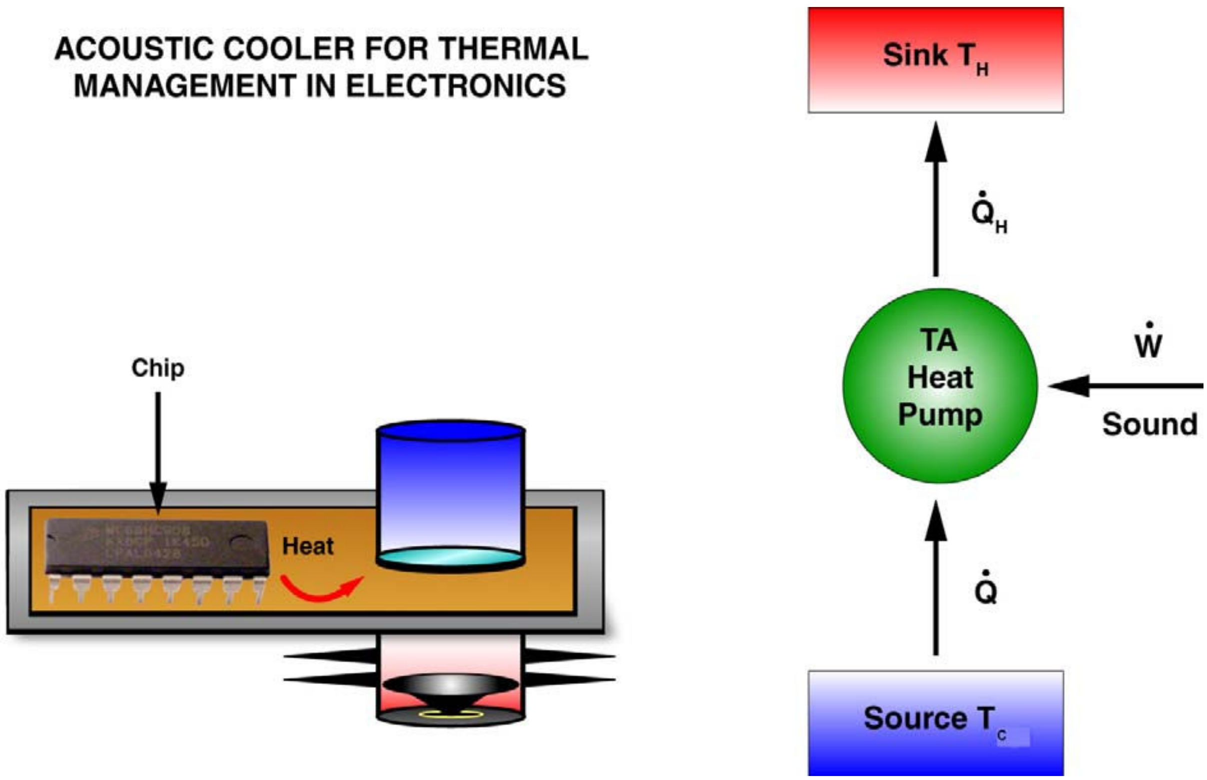

Figure 2. Acoustic cooler used as heat pump in a circuit.

It represents a heat pump which extracts heat from a reservoir and transfers it to a hot reservoir as shown schematically on the right side of the figure. The size of the acoustic device, and hence the working frequency, is determined by the heat dissipation requirements of the circuit needing heat management.

An estimate of the rate of heat $\dot{Q}_2$ pumped along the stack leads to a value which depends on engine parameters. Neglecting losses, the heat flow is [3]:

$$\dot{Q}_2 = -\frac{1}{4}\Pi\delta_k\left(T_m\beta\right)p_1u_1\left(\Gamma-1\right) \qquad (1)$$

where Π is the perimeter around the stack fibers, β is the gas thermal expansion, and T_m is the mean temperature. Here $\Pi\delta_k$ is $\approx 0.7\pi R^2$ where R is the radius of stack. Eq. 1 shows that to pump a large quantity of heat, high sound intensity p_1 u_1 is needed; also the stack radius R should be as large as possible. For a sound intensity of 160dB inside the resonator with air at 1 atmosphere, the power density which this device can pump can be larger than 0.5 watt/cm^2. This number represents a lower limit for an ideal case assuming no losses; device parameters like mean gas pressure and geometric factors can be optimized to provide larger power densities. Tests with air at pressures up to 15 atmospheres lead to an increase in power density by a factor of up to 15. Since the acoustic devices are relatively small, such pressures are substantially below the strength of materials limit. Moreover changing the working gas from air to helium also increases the power density due to the higher speed of sound with helium. Such improvements lead to heat pumping power densities of 15 to 20 watts/cm^2 at frequencies of 4 to 5 kHz.

In order to calculate the coefficient of performance of this device, an estimate of the work flow $\dot{W}_2$ is needed. Neglecting losses, the work flow is [3]:

$$\dot{W}_2 = \frac{1}{4}\Pi\delta_k\Delta x\frac{\left(\gamma-1\right)\omega\, p_1^2\left(\Gamma-1\right)}{\rho_m a^2} \qquad (2)$$

where Δx is the length of the stack, γ is the ratio of specific heats, ρ_m is the density of the fluid, and a is the speed of sound in the fluid.

The coefficient of performance (COP) is the ratio of rate of heat pumped divided by the rate of doing work acoustically. It can be simplified to [3]

$$COP \approx \frac{\Gamma T_m}{\Delta T} \qquad (3)$$

where ΔT is the temperature span of the refrigerator equal to $T_{hot} - T_{cold}$ and T_m is the mean temperature in the stack. This shows that although the device is irreversible by nature (due to heat flow between sound field and stack elements) its performance can be a substantial fraction of Carnot rendition.

Raising the operating frequency from 4 kHz to 24 kHz leads to a smaller and more compact device which is capable of high power density heat pumping. Here as well the performance depends on geometric factors and sound intensity. Assuming that an ultrasonic driver delivers a sound intensity of 160 dB, the power density will be 0.5 watt/cm^2 with air at 1 atmosphere. Pressurizing the unit to 15 atmospheres and using helium gas, the power density will be raised here as well to the 15-20 watts/cm^2 level. In fact much higher pressures can be applied since the unit is so small (length of 7 mm).

The performance of the above units has been limited by the level of the sound intensity delivered by the driver. Drivers capable of delivering more than 160 dB inside the resonator would raise the cooling power density of the cooler.

B. Prime Mover

This is a passive device which produces sound in a resonator when driven by heat. Many of the components of this device are the same as in the acoustic cooler. There is a resonator ¼ wavelength, a stack with a heat exchanger at each end, a working fluid, and a source of heat to drive the acoustic oscillation. The source of heat is used to establish a temperature gradient along the stack. The operation condition is different from the cooler in that $\Gamma > 1$. Fig. 3 Shows the basic unit.

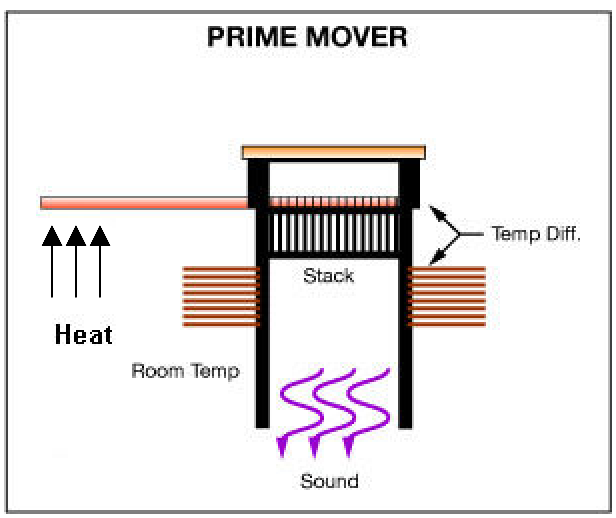

Figure 3. Basic Thermoacoustic Prime Mover

Above a threshold temperature difference across the stack, the parameter $\Gamma > 1$ and oscillations are initiated and sustained by heat input to the hot heat exchanger. It is a heat engine which takes heat from a hot reservoir and it does work by producing sound, the rest of the heat being rejected to a heat reservoir at low temperature. There is energy conversion, from heat to sound. This provides a simple opportunity for thermal management. The approach is shown in Fig. 4 where excess heat from a circuit is coupled to the prime mover which radiates this energy in the form of sound and the rest is absorbed by the cold heat exchanger. The schematic to the right of the device in Fig. 4 shows the basic heat engine approach.

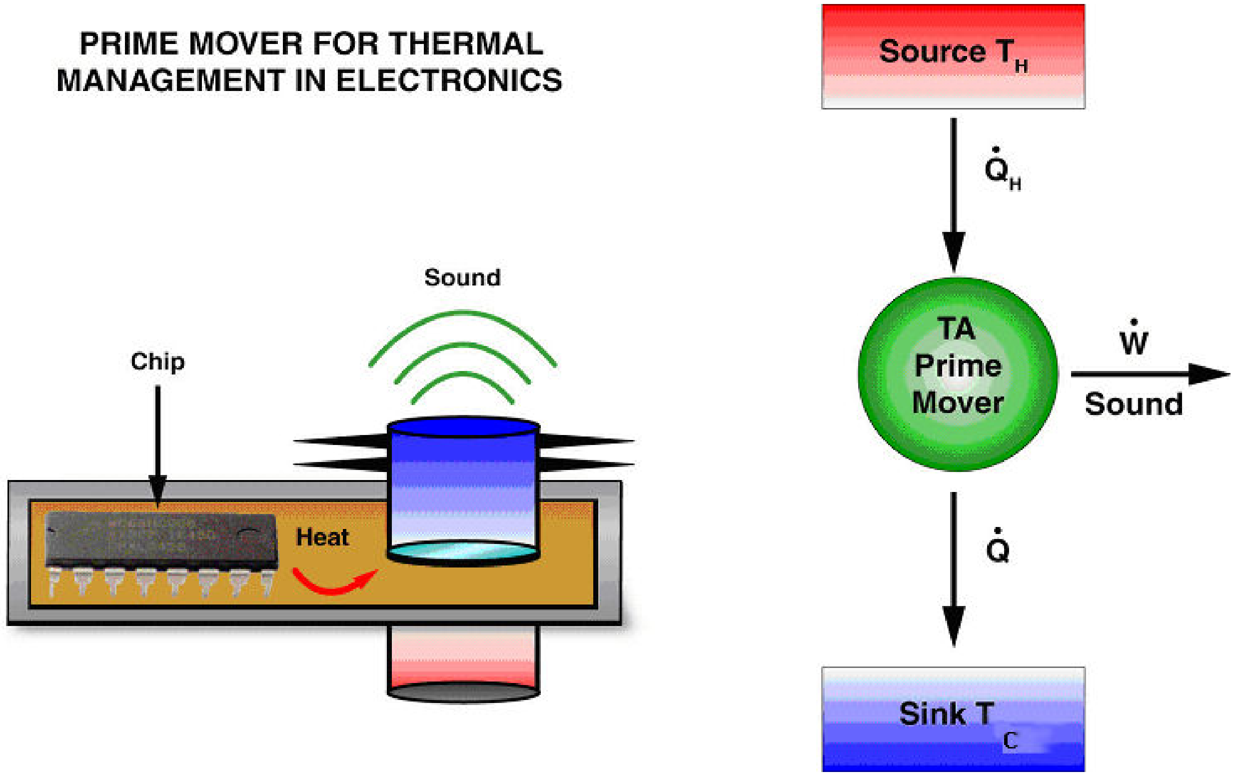

Fig. 4 Prime mover converting heat from a circuit to sound

Equation 1 and 2 are applicable here. The efficiency of this engine, which is the generated acoustic work divided by the heat input, can be written as [3]

$$\eta \approx \frac{\Delta T}{\Gamma T_m} \tag{4}$$

Here as well the efficiency is less than Carnot because of the irreversible nature of the device (heat flow between gas in sound field and stack elements). A low threshold ΔT across the stack for oscillation is useful for thermal management in circuits which cannot tolerate a high ΔT. At onset for oscillation heat is removed form the circuit by generation of sound, as shown in Fig.2. Depending on the application, a suitable ΔT for onset can be selected; this ranges from a low onset ΔT =20°C to much higher values, in the range of hundreds of degrees. This is determined by geometric factors such as size, shape of resonator and stack configuration, and standing wave ratio in the resonator. Depending on the value of the temperature gradient ∇T along the stack, sound levels of 160 dB and higher can be generated. This corresponds to a power density of 1 watt/cm^2, using air at 1 atmosphere. Here as well pressurizing the working fluid raises the devices power density in proportion to the mean fluid pressure. A more efficient way of converting heat to sound can be achieved by cascading a few units in series.

The process of converting heat to sound can be considered as a heat conduction effect [4,5,6] with very large heat transport due to spontaneous acoustic oscillations. Heat flow in the device can be simply written as

$$\dot{Q}_2 = \pi R^2 K_{eff} \nabla T \tag{5}$$

where K_{eff} is an effective heat conductivity induced by the gas oscillation, and ∇T is the temperature gradient along the stack providing the drive. The effective conductivity depends on frequency, mean gas pressure, and acoustic pressure p_1. It can be several orders of magnitude larger than the normal heat conductivity of the gas.

3. Conclusions

Two relatively new approaches to thermal management in electronic circuits using thermoacoustics are presented. One deals with an active device where high intensity in a resonator sound pumps heat up a temperature gradient. Cooling power densities of around 20 watts/cm^2 can be achieved by optimizing the device. The second approach deals with a passive device where waste heat from an electronic circuit can radiate sound energy when coupled to a stack and a resonator. An important feature of this approach is that there are no moving parts other than the oscillating gas which is driven by the heat. Both approaches have efficiencies which are a large fraction of Carnot performance and which compare well with other technologies [7,8]. Moreover they are environmentally safe, they are simple and they are quite efficient. As the thermoacoustic devices are miniaturized they can be arranged in array configurations for handling high power levels. Further improvements can be attained by reducing the inherent irreversibilities of the engines when a traveling wave component is introduced [9,10,11].

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