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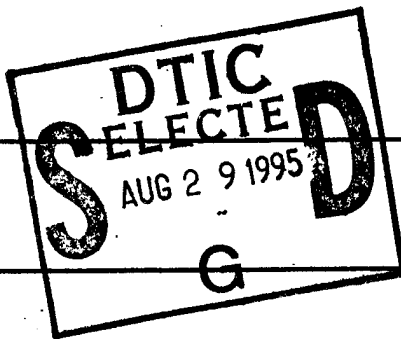
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13. ABSTRACT (Maximum 200 words)

Results are presented on the development of a high frequency thermoacoustic refrigerator and its performance. The device consists of a piezoelectric driver, operated around 5kHz, which is coupled to a cylindrical resonator containing air at 1 atmosphere as the compressible fluid. For sound levels of 155dB at the stack, a maximum T of 41 C was reached across a cotton wool stack 4mm long. A cooling power of 1.2 watt was achieved with a coefficient of performance of 3. This simple and lightweight refrigerator shows promise for cooling of small samples and electronic components. The performance of this type of refrigerator at high frequencies leads to high efficiency and power density. Research is aimed at improving its performance by optimizing some of the critical parameters such as the sound level and the thermal interface between stack and heat exchangers.

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<u>Annual Summary Report</u>
(for year ending May 30, 1995)

"High-Frequency Thermoacoustic Refrigerator"

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Abstract

Results are presented on the development of a high frequency thermoacoustic refrigerator. The device consists of a piezoelectric driver, operated at around 5kHz, which is coupled to a cylindrical resonator containing air as the compressible fluid. For sound levels of 155 dB at the stack, a maximum ΔT of 41°C was reached across a stack 4mm long. A cooling power of 1.2 watt was achieved with a coefficient of performance of 3. This refrigerator shows promise for the cooling of small samples and electronic components. Its performance can be improved by optimizing some of the parameters such as the sound levels and the thermal interface between stack and heat exchangers. High frequency operation of this type of refrigerator leads to higher efficiency and improved power density.

1.   DESCRIPTION OF PROJECT

This project has 3 main goals:

(i)   to develop a simple, compact thermoacoustic refrigerator operating at an audio frequency of ~5kHz.

(ii)   to investigate the performance of a thermoacoustic refrigerator driven at high frequency.

(iii)   to explore new design concepts and materials for thermoacoustic refrigerators.

The study presented here deals with the development and characterization of a high frequency thermoacoustic refrigerator, especially from the point of view of efficiency, power density, and applications. The operation of this type of refrigerator at high frequencies leads to its miniaturization, as it scales directly with the wavelength of the audio driver because of its resonant nature. For special conditions and geometries, thermal phenomena can be quite rapid and this is applied to the cooling device presented here. The high frequency approach brings in new techniques of miniaturization useful for interfacing this type of refrigerator to cooling electronic components and small samples.

2.   APPROACHES

The thermoacoustic [1] refrigerator has evolved from the class of refrigerators which operate on the surface heat pumping effect [2]; driven on resonance this type of refrigerator achieves an enhancement of thermodynamic effects over dissipative ones. Indeed, its operation at audio frequencies (about 500 Hz) has led to improved power density and to the development of a refrigerator which recently has attracted a great deal of attention [3]. The present project takes such approach even further by developing a refrigerator which is driven at frequencies 10 times higher than the original thermoacoustic refrigerator (which was at 500 Hz). The expected benefits of such an approach are: improved efficiency, higher power density, and miniaturization.

The approach taken here uses components specifically developed for this refrigerator, keeping in mind that the dimensions have to be scaled down by a factor of ten from the conventional thermoacoustic refrigerator. The components are:

(i)   driver: piezoelectric bimorph, operating at 4-5 kHz, coupled to acoustic resonator of refrigerator by a horn, very compact, high power density, very efficient; this unit is shown in Fig. 1.
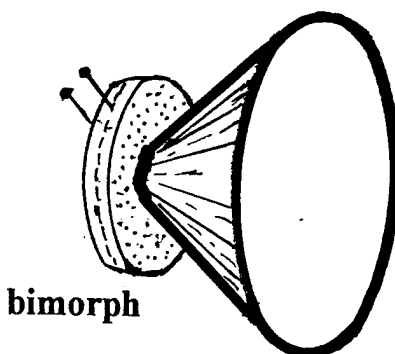

bimorph

Fig. 1 Piezoelectric driver

(ii)   acoustic resonator: 1 wave cylindrical tube, operated with second harmonic standing wave.

(iii)   primary thermodynamic medium: air at one atmosphere, simple, useful to study basic principles of refrigeration.

(iv)   stack: cotton wool, random configuration.

(v)   heat exchangers: copper plates with perforations, fabricated photolithographically.
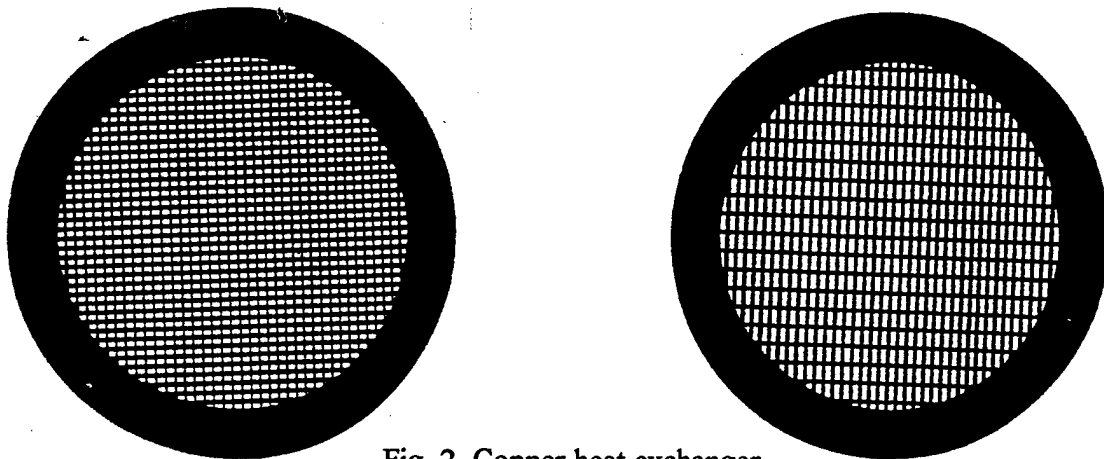

Fig. 2 Copper heat exchanger

The logic for the approach taken here is:

-     the efficiency of a piezoelectric driver can be very high, 75-92%, depending [4] on the loading conditions. An important parameter of this device is the electromechanical coupling coefficient (k) which is the ratio of (mechanical energy stored/electrical energy applied)$^{1/2}$. For lead zirconate titanate, EC-66, k is 0.72.

-     power losses in a piezoelectric driver are very small, as its impedance is high (typically 25 to 500 ohms); it is a voltage device rather than a current device [5]. The small amount of heat generation is caused by hysteresis due to domain reversals in the dielectric.

-     operation at 5 kHz provides a better acoustic impedance match of the thermodynamic medium to driver, i.e. the impedance of air matches the driver better at 5 kHz than at 500 Hz since this depends on ωm, ω being the operating frequency and m the mass of driven air [4].

-     power density is large in the driver and refrigerator (it varies as ω).

-     critical gradient increases with frequency ω since $\nabla T_{crit} = \dfrac{2\pi(\gamma-1)}{\lambda} \tan\left(\dfrac{2\pi x}{\lambda}\right)$.

-     since the volume of the refrigerator goes as $1/\omega$, a small volume will favor quick cool down and hence short time constants.

3.   ACCOMPLISHMENTS

A.   Apparatus

One version of the refrigerator is shown in simplified form in Fig. 3. It is 10 cm long and this includes the cylindrical acoustic resonator driven at its second harmonic (5 kHz). It is driven at one end by a piezoelectric bimorph driver (Motorola) whose diameter is 23 mm; it is loaded by a paper exponential horn whose mouth has a diameter of 41 mm. The total mass of this driver is 1.34 g. Its sensitivity is ~94 dB/1W/1m.

The stack consists of a random uniform packing of cotton wool, pressed between the cold and the hot heat copper exchangers. Its optimum length Δx was determined experimentally to be 4 mm. The hot heat exchanger is anchored thermally to another heat exchanger which is more massive and which has a larger thermal conductance.

For our case the critical temperature gradient is 120° C/cm and this determines the maximum ΔT which can be achieved across the stack. (i.e. 50-60° C).

For simplicity we chose the working fluid to be air at one atmosphere. In that case the wavelength at 5kHz is ~6.9 cm, and this dictates the dimensions of the refrigerator.

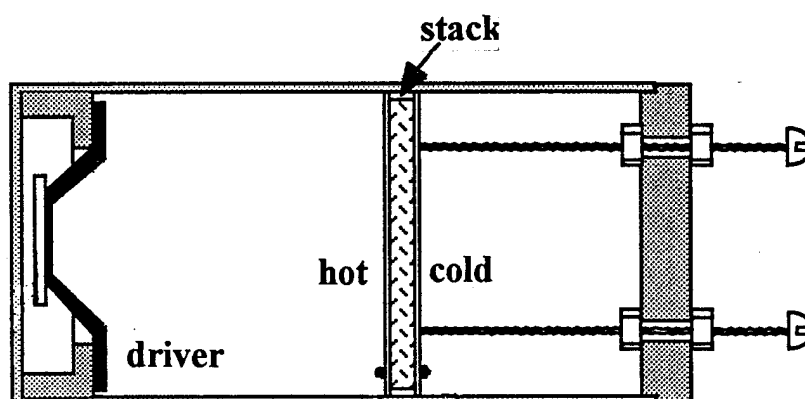Fig. 3 Basic high frequency refrigerator

B. Results

(i) Fig. 4 shows a typical performance for our refrigerator producing a $\Delta T=38°C$ for a sound level of 155dB at the stack; this corresponds to a normalized sound pressure level (to working gas pressure) of $P_1/P_m = 1.1\%$. The response is rapid being in the range of seconds.
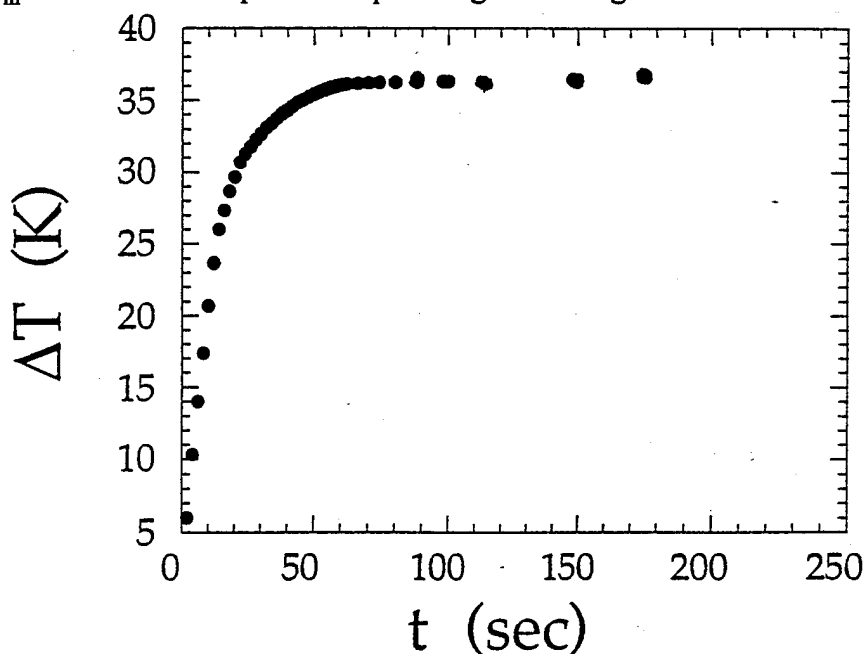

Fig. 4 ΔT as a function of time

The cooling power is calculated to be 1.2 watt and this gives a coefficient of performance C.O.P. of 3. The C.O.P. is defined as: (cooling power/sound power in) at stack; this is not the conventional definition of C.O.P. as in a home refrigerator! The normalized temperature gradient $\Gamma(=\nabla T/\nabla T_{crit})$ for this case is 0.58.

With similar conditions the largest ΔT that was achieved was 41°C. This is a reasonable ΔT as the ΔT_{crit} across the 4mm long stack is 62K. Higher ΔTs were not achieved because we worked

at the power limit of the Motorola driver; prolonged operation caused failure of the driver. This limitation can be overcome by using a more powerful driver (for example, a unimorph).

(ii)   The incorporation of this device into a useful refrigerator requires thermal isolation and adequate thermal anchoring of the hot heat exchanger to room temperature and cooling of the resonator by the cold heat exchanger. Thermal isolation was provided by a vacuum jacket around the cold part. Fig. 5 shows the basic arrangement of this apparatus. The resonator is reduced to a smaller diameter in order to amplify the sound level [6]. In this case, cooling was also observed and
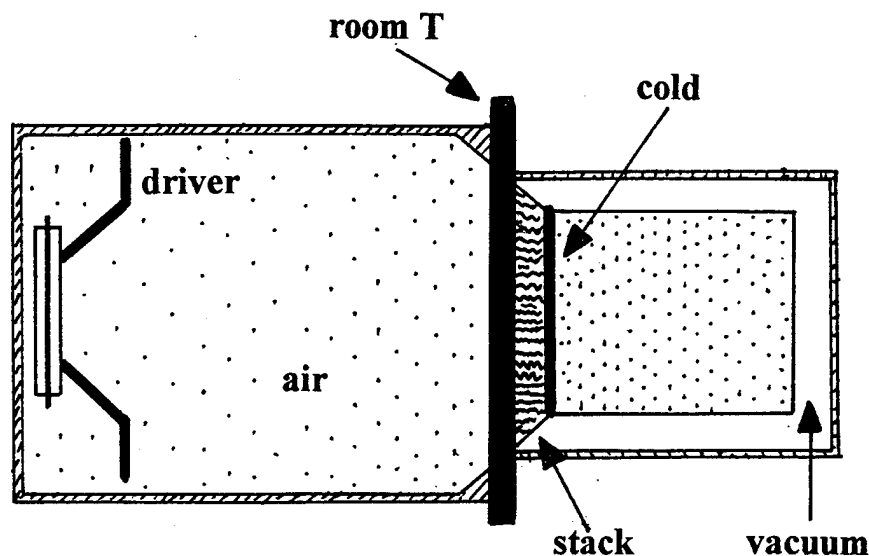
Fig. 5 Thermoacoustic Refrigerator with thermal isolation

the cold heat exchanger cooled the acoustic resonator (20 c.c. volume) with a time constant of a few minutes. Both the hot end and cold end of stack showed a saturation with time of their respective temperatures, maintaining a fairly constant ΔT between them. However the temperature of the hot end of the stack was 30 to 40% above that of the hot heat exchanger anchored to room T. This indicates that there is a problem in heat transfer between stack and heat exchanger. Indeed such a problem was anticipated as the thermal resistance between 2 solids touching each other lightly is approximately 1-10°C cm^2/W. Fig. 6 shows how the hot end of stack rides above room temperature even though the hot heat exchanger was well anchored thermally to room temperature.
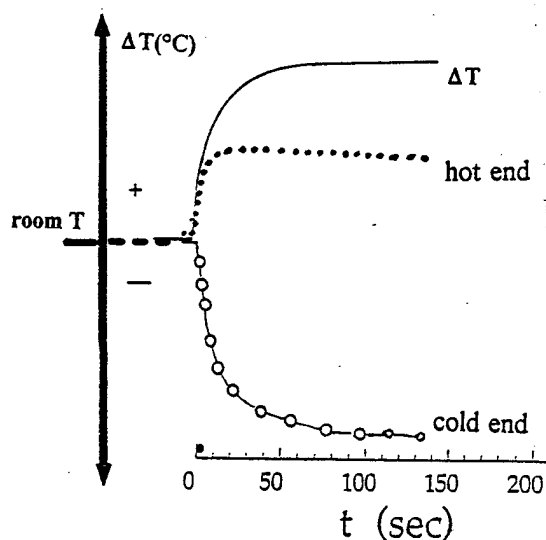
Fig. 6 Temperature of cold side of stack and of hot side

C.   Discussion

The performance of the high frequency thermoacoustic refrigerator shows that a simple miniature refrigerator can be developed for cooling all sorts of small objects, ranging from biological samples to electronic components. The maximum ΔT of 41°C achieved here at sound levels of 155dB compares favorably to the performance of regular thermoacoustic refrigerators. Better performance is anticipated since the present high frequency refrigerator is not optimized. The problems that have to be solved are:

(i)   Heat transfer at stack-exchanger interface. The gas displacement in the sound field is too small (less than 0.1mm) to be useful in transferring heat from stack to heat exchanger. We are relying on the mechanical contact between stack and heat exchanger for heat transfer across the large boundary resistance which exists at the interface. Usually it is difficult to transfer heat across a surface above 1 watt/cm^2. Our geometry has to be changed in order to improve the heat transfer.

(ii)   Gas mixtures for thermodynamic compressible medium. The Prandtl number for air is 0.71; some gas mixtures have much smaller Prandtl numbers and hence we will try them. This approach has been successful in the regular thermoacoustic refrigerator [7].

(iii)   Achieving higher sound power levels. We have reached the limit with the Motorola driver at a sound level of 155dB (there is a variation of ~±5dB from one driver to the next in a batch!). Higher levels are expected from a unimorph (which can handle higher power levels) or from an array of piezoelectric elements. Recently, polymer piezoelectric materials have shown much promise as high power drivers.

(iv)   Larger ΔT. Although we are limited by the length Δx of the stack, larger ΔTs can be achieved by using dual stack-heat exchanger units (this was demonstrated in the previous report, of last year) at appropriate locations in a second or higher harmonic or by using gases with higher speed of sound.

In conclusion, by operating the thermoacoustic refrigerator at high frequencies, we have scaled down [8,9] its size and weight and increased its efficiency. The small volume of this refrigerator leads to a large power density which can be used for all sorts of refrigeration applications.

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4. PUBLICATIONS

"High Frequency Thermoacoustic Refrigerator Operated with Air", by O.G. Symko, T. Klein, and D.J. Zheng, in preparation.
We intend to publish this when we reach a ΔT of 50°C.

5. PERSONNEL

- Thierry Klein, Postdoctoral Fellow

- De Juan Zheng, Research Associate Professor

- Orest G. Symko, Professor and Principle Investigator

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a. Number of Papers Submitted to Referred Journal but not yet published: __0__

b. Number of Papers Published in Referred Journals: __0__
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How many of each are females or minorities?	][Grad Student Minority	_____
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Amindians, etc and those of Hispanic or	][	
Asian extraction/nationality. This Asians	][Post-Doc Female	__1__
are singled out to facilitate meeting the	][	
varying report semantics re "under-	][Post-Doc Minority	_____
represented")	][	
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