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A small thermoacoustic refrigerator was developed for operation at 5 kHz. Its main components are a piezoelectric driver of the bimorph type, a cotton wool stack, a ½-wave resonator (operated at its 3rd harmonic), and photolithographically processed copper heat exchangers. Tests with air at 1 atmosphere as the working gas produced a temperature difference ΔT across the stack of 32°C in 4 seconds for an acoustic power input level of 160dB. The refrigerator did not have thermal insulation. Improved performance is expected with pressurized helium gas and helium-xenon mixtures. The performance of this refrigerator and its small size make it attractive for applications in high speed electronics and possibly IR detectors.

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Annual Report

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"High-Frequency Thermoacoustic Refrigerator"

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Abstract

A small thermoacoustic refrigerator was developed for operation at 5 kHz. Its main components are a piezoelectric driver of the bimorph type, a cotton wool stack, a ½ wave resonator (operated at its 3rd harmonic), and photolithographically processed copper heat exchangers. Tests with air at 1 atmosphere as the working gas produced a temperature difference ΔT across the stack of 32°C in 4 seconds for an acoustic power input level of 160dB. The refrigerator did not have thermal insulation. Improved performance is expected with pressurized helium gas and helium-xenon mixtures. The performance of thi refrigerator and its small size make it attractive for applications in high speed electronics and possibly IR detectors.

1. Description of the Project

This project deals with the development of a high frequency thermoacoustic refrigerator and the study of its performance. The reasons for going to high frequencies are:

- It leads to a small compact refrigerator operated in a resonant mode at short wavelengths.
- It leads to a small mini-refrigerator which can interface well with high speed electronics and devices needing refrigeration.
- It is in a frequency range where piezoelectric drivers can be used. Such drivers are very efficient; they are small and light.
- Higher power densities can be achieved.
- To explore new physics as presented by the small scale of the refrigerator.

The operating frequency was chosen arbitratily around 5 kHz with the intention of working at a frequency which is about 10 times higher than the ones used in conventional thermoacoustic refrigerators.

It is interesting to note how the operating frequency of thermoacoustic engines has evolved, from the early experiments of Merkli and Thomann at around 100 Hz, to those of Wheatley and collaborators at 500 Hz. We wish to extend this trend to 5,000 Hz in view of the advantages that this offers, some of them mentioned above. Gifford and Longworth in their paper on Surface Heat Pumping did forsee this and they stated that for a Pulse Tube refrigerator there should be scaling in the parameters of the refrigerator for optimum pulse rate, i.e. operating frequency. Recently Olson and Swift presented results on similitude in thermoacoustics, an important paper for scaling up the operating frequency as in our refrigerator.

The refrigerator parameters that are directly affected by the operating frequency are:

- the thermal penetration depth
- the viscous penetration depth
- the resonator dimensions
- the critical temperature gradient, which is the boundary between the behavior of the thermoacoustic engine as heat pump and prime mover
- acoustic impedance of working gas

These parameters have determined the design of our refrigerator and its expected performance.

We are developing a mini-refrigerator which works on thermoacoustic principles. The driver is a light piezoelectric bimorph loaded with a cone which sets up standing waves in a ½-wave resonator. The working fluid is air, with plans for using helium and helium-xenon mixtures at high pressures. Because the wavelength in air is about 7 cm, the refrigerator is short; fine adjustments are necessary for positioning the stack and heat exchangers. The stack is presently made out of cotton wool, but other types have also been investigated. The heat exchangers are copper plates made by photolithographic techniques. We have studied the performance of this refrigerator and the results will be presented in the next sections of this report.

Such mini-refrigerator has applications for cooling high speed electronic devices, infra-red detectors, and hopefully even high T_c superconductors. Moreover the study of this refrigerator is important for the understanding and further developments of thermoacoustic devices.

2. Approaches Taken

A. Working Gas

The results presented in this report have been with air as the working gas. We are planning in the near future to use helium gas, and a helium-xenon mixture, both pressurized. We started with air at atmospheric pressure because it is simple and it does not require a closed system. Such advantages helped in making quick experiments which led to the development of the refrigerator. Optimal performance is expected with helium-xenon, as demonstrated by the Thermoacoustic Group at the Naval Postgraduate Academy, Monterey. No precautions were taken to have a leak-tight system at this stage in the project.

B. Driver

The driver consisted of a Motorola piezoelectric tweeter stripped down to the bimorph element and the cone load. The circular PZT bimorph consists of two wafers, 0.89" in diameter, and 0.0055" thick and the push-pull bending action creates the sound. Its sensitivity is 93dB at 1 meter away for 1 watt of electrical power. It is broadband with small variations of about 3dB over the whole spectrum. The electro-acoustic efficiency of this driver is from 75% to 90%. Fig. 1 shows the bimorph driver with its cone.

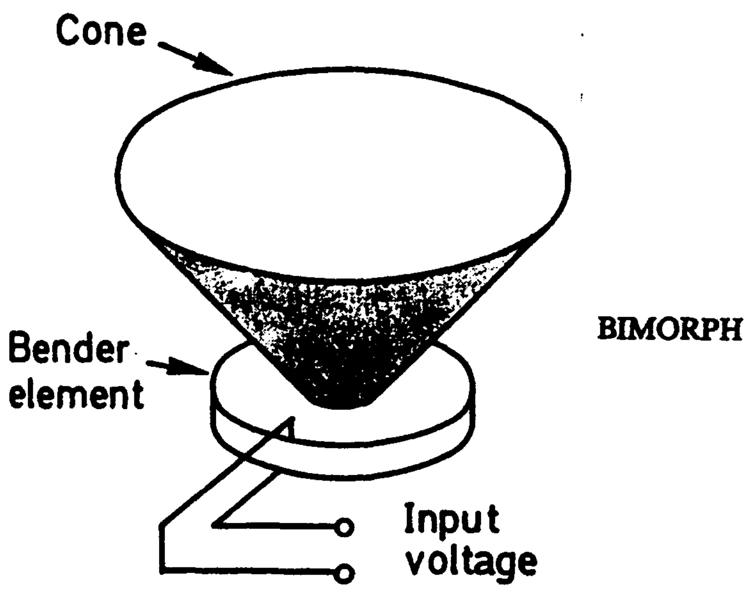

Fig. 1 Bimorph Piezoelectric Driver

C. <u>Resonator</u>

Its function is to amplify the sound level by its Q and to set up a standing wave so that the refrigerator phasing could be maintained at the correct point. It consists of a plastic tube, 4.0 cm in diameter and its quality factor Q is 70 when it is empty. When loaded with the stack and heat exchangers, its Q drops to 47. In order to achieve such high Q we chose the dimensions of the resonator such that it is used as a 3rd harmonics 1/2-wave resonator, i.e. the standing wave is 3/2 of a wavelength long, and it is driven at ~5 kHz.

D. <u>Stack</u>

We tried 4 types of stacks:

- thin mylar sheet with fishing line nylon spacers rolled up (reference: Hofler)
- spongy material used in swamp coolers
- glass wool
- cotton wool

The well-defined geometry of the mylar sheet-fishing line spacers was not practical at this stage of the project as it took too long to adjust for the changes, which always occured. We had the best results with cotton wool. Because the wavelength is ~7 cm, the stack was made out of 2 to 3 mm thick cotton wool, tightly placed between the two heat-exchangers. Such random combination of loose fibers can maintain the diffusive flow of heat by the thermoacoustic effect.

E. <u>Heat Exchangers</u>

These were made out of copper sheet, 0.010" thick. The pattern was generated by a computer and then they were fabricated by photolithographic techniques. Fig. 2 shows the heat exchangers; they were pressed mechanically against the stack. Heat transfer relied upon that contact.

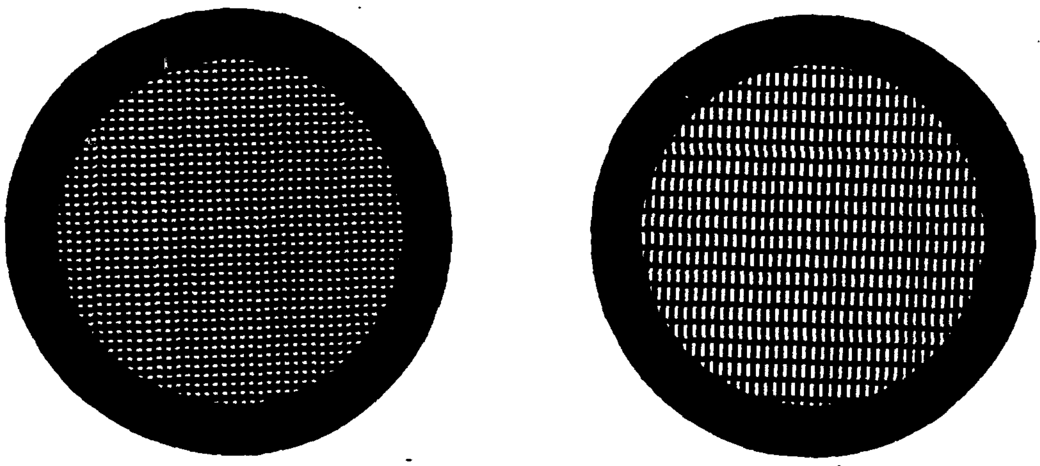

Fig. 2 Copper Heat Exchangers

F. Auxilliary Equipment

Temperatures were monitored by constantan-chromium thermocouples.

The piezoelectric driver was driven by a Radio Shack power amplifier, model M95-95.

Alignment and tuning of the inner components of the refrigerator were achieved by very small microphones, of the electret type, which were located inside the resonator.

G. Refrigerator

Fig. 3 shows the assembled mini-refrigerator. Adjustment the stack and heat exchangers for the optimal position was achieved by means of a screw on top of the refrigerator; this moved the stack for the maximum ΔT position. It total length is about 10 cm. It could have been abou 4 cm if we were to operate it on its first harmonic.

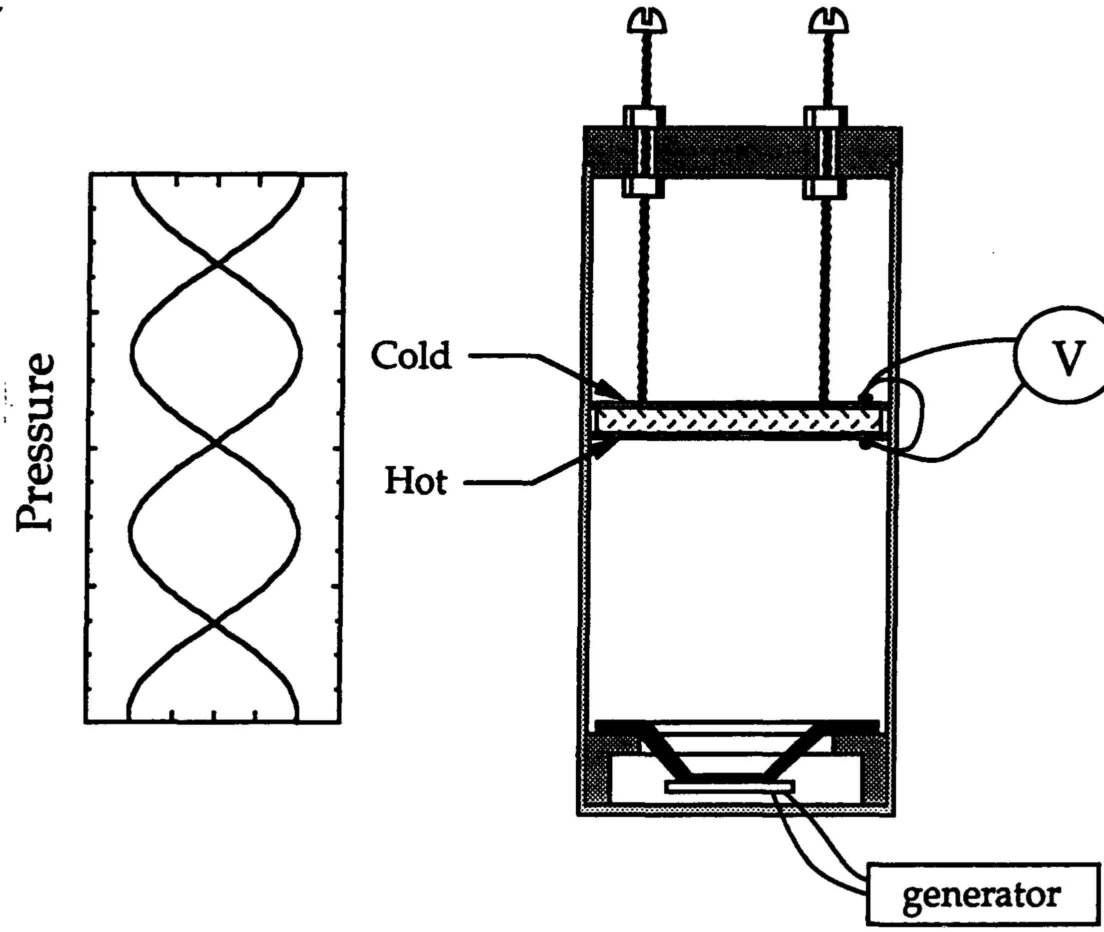

Fig. 3 Four to Five KiloHertz Refrigerator

3. Accomplishments

A. Tests

Because we are operating at a very short wavelength, approximately 7 cm, the positioning of the stack and heat exchangers relative to the standing wave is critical. Fine screws were used for the adjustment. Fig. 4 shows how critical the positioning is. Once the

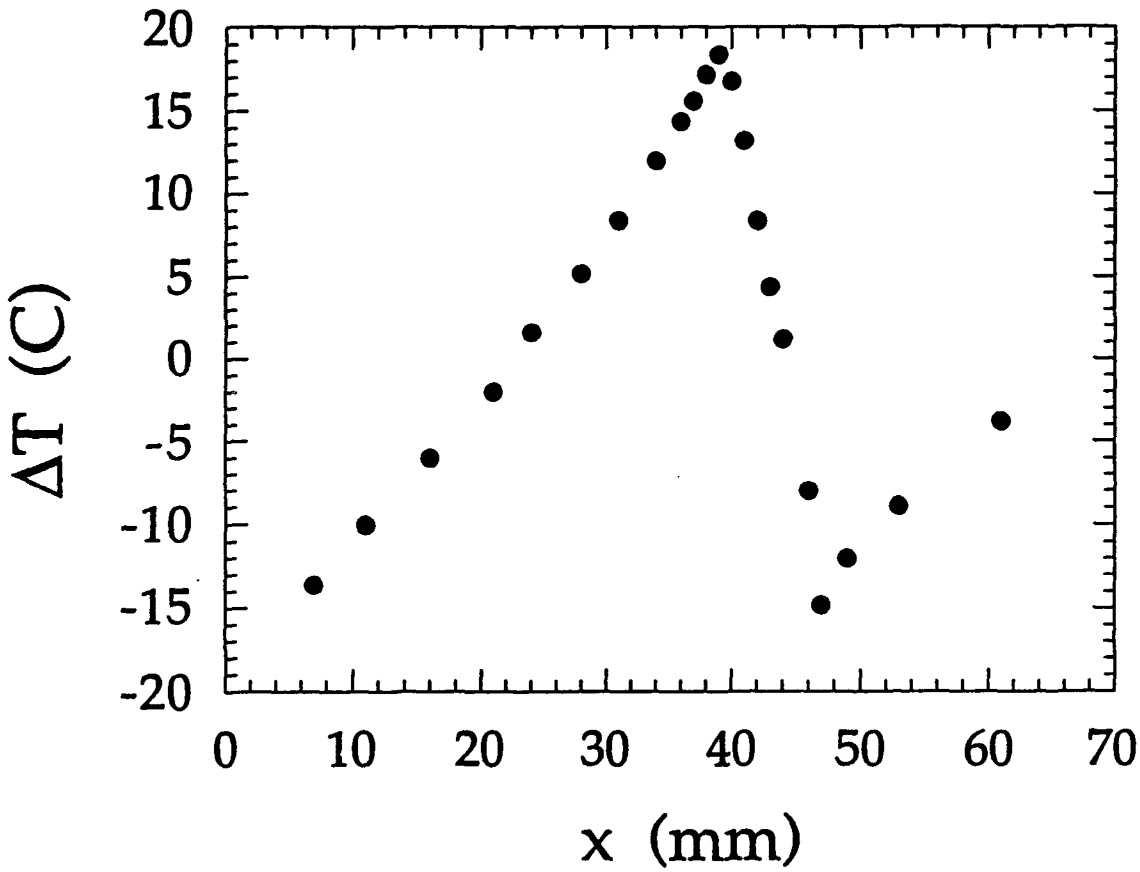

Fig. 4 Positon of stack on standing wave and its effect on ΔT.

optional position is found, a large ΔT is produced in a very short time. Fig. 5 shows the ΔT across the stack produced by a sound level of 160dB at the position of the stack for a frequency of 4.2 kHz.

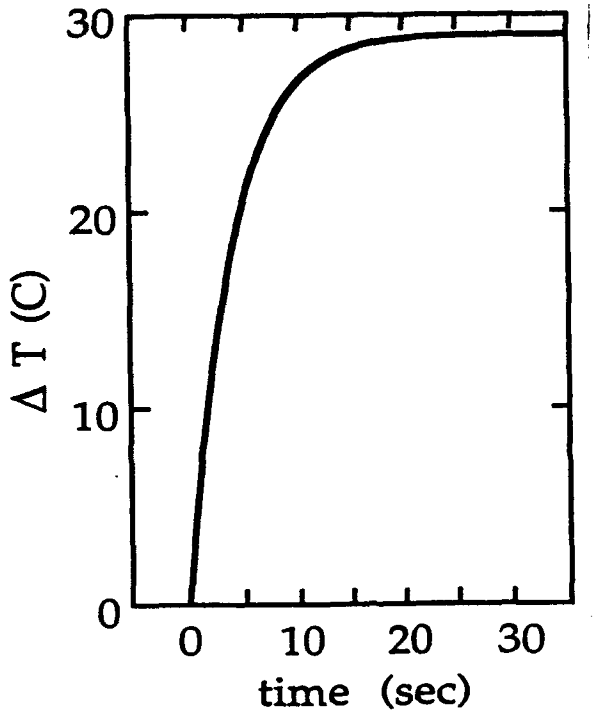

Fig. 5 Time dependence of ΔT when driver puts out 160dB of sound at 4.2 kHz.

Our operating frequencies were in the range of 4 kHz to 5 kHz, as there was quite a bit of variation in the performance of drivers. The variations were in the frequency response and sensitivity (by as much as 10dB).

In order to avoid convection problems, the stack was located in the resonator such that the hot heat exchanger was near the top of the refrigerator. This is shown in Fig. 6. It is important to note that there was no thermal isolation of the refrigerator, and hence, the stray heat leaks were large.

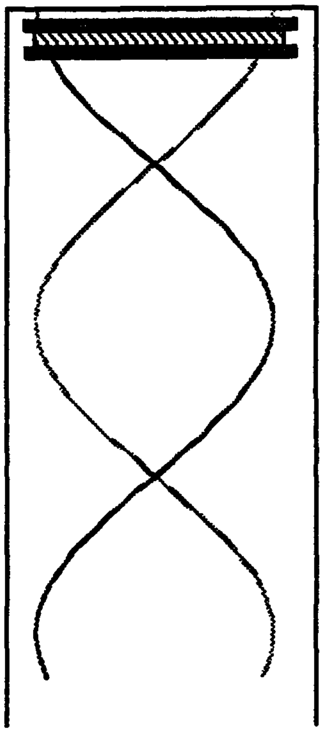

Fig. 6 Position of stack and heat exchangers on standing wave inside resonator.

In Fig. 7, the electrical power input to the driver determines the achieved ΔT in the presence of stray heat leaks.

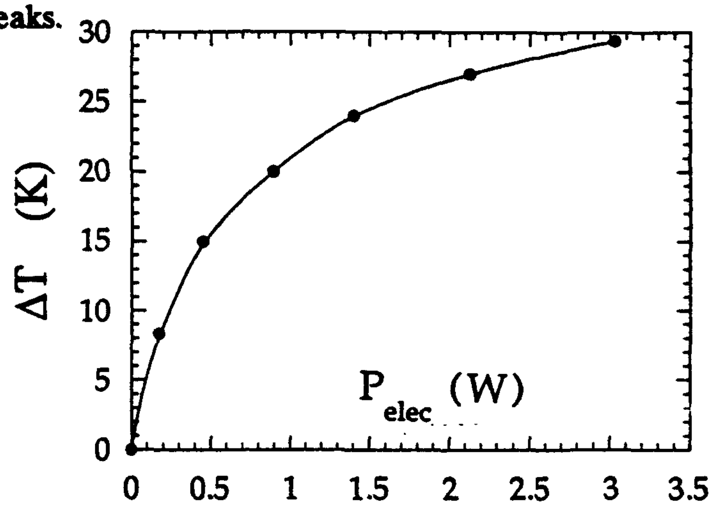

Fig. 7 Performance of refrigerator as function of input electrical power to drivers.

Since the stack is very short, having a Δx of 2 to 3 mm in length, we are limited in the cooling power. A test was made with a double stack, each located at the appropriate part of the standing wave. This is shown in Fig. 8.

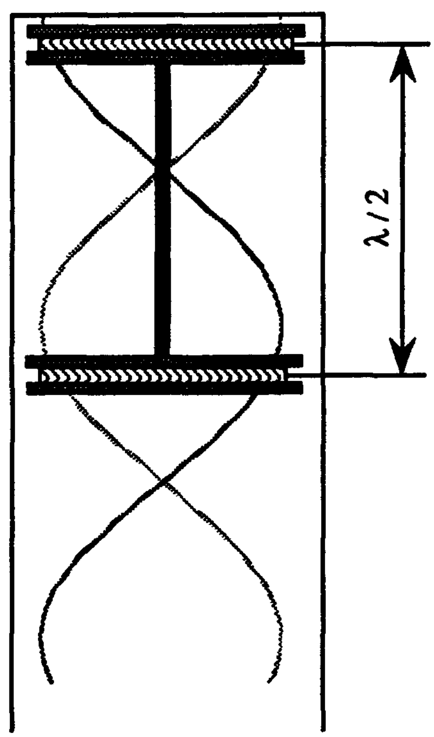

Fig. 8 Double Stack Refrigerator.

Although the adjustment of such arrangement was tricky, the results were very encouraging; the first stack produced a ΔT of 10°C and the second one produced a ΔT of 20°C. Hence, the total ΔT was 30°C, as with a single stack. However the double stack has potentials which will be discussed later on in this report. Fig. 9 shows the ΔTs produced across each stack.

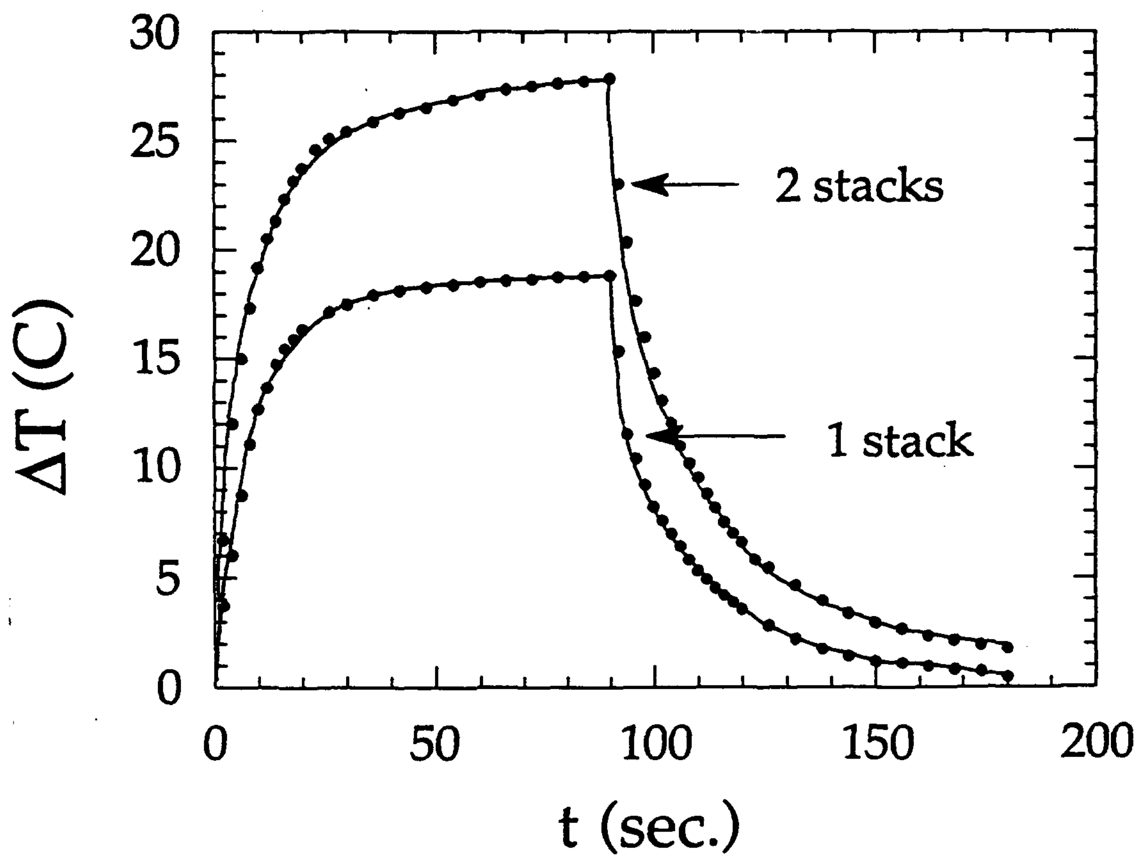

Fig. 9 Temperature difference across each stack in the resonator for a double stack arrangement.

The tests were extended for the case where the hot heat exchanger was thermally anchored at room temperature. In that case, the cold heat exchanger showed a temperature drop of 7°C for 150dB sound input. This case shows the effects of stray heat leaks and limited cooling power of the refrigerator.

The present experiments are aimed toward higher sound levels, and reduced thermal losses. Also, we will try air at pressures above 1 atmosphere. Experiments are planned for different working gases, such as pressurized helium and helium mixtures. The present air results are a lower bound on the performance of this simple and compact refrigerator.

B. Analysis

From the critical gradient of 120 K/cm for our refrigerator and the stack length Δx, we get a critical temperature difference of 30K. Hence, the ratio Γ of temperature difference to critical temperature diffemce is 0.67 for a temperature difference of 32°C. The temperature difference of 32°C was achieved with a stack 4 mm long.

The cooling and warm-up curves as a function of time provide us with information on the cooling power and stray heat leaks. The stray heat leak is 10 m watts/°C and this is mainly due to heat conduction across the stack (which is only 2-3 mm long) by the cotton wool and gas inside it. Analysis of our data on the thermoacoustic engine used as refrigerator gives a Coefficient of Performance which is ~12% of a Carnot engine. A typical cooling power is 0.6 watt for a sound input of ~0.15 watt. Its performance as a heat pump gives a Coefficient of Performance which is ~50% that of a Carnot engine.

The results with air at 1 atmosphere are very encouraging, especially since the thermoacoustic properties of air are relatively poor. Nevertheless we are expecting a ΔT of ~50°C with atmospheric air, and improved performance with helium and helium mixtures. We are currently working on the problem of heat transfer between the stack and heat exchangers. Since we are at high frequencies, the gas displacement (u/ω) is very small, being a tiny fraction of a millimeter. Heat transfer occurs mainly by contact between the stack and the heat exchangers. It is for that reason that the cotton wool gives the best performance; it makes good contact to the heat exchangers.

The results with the double stack are very important in that they open the possibility of working at higher frequencies, the ultrasonic range. In that case, precisely fabricated stacks and heat exchangers could be located on a harmonic standing wave inside the resonator. It can be produced by thin film technology and satisfy the condition $\Delta x < \lambda\!\!\!^{-}$.

In conclusion, we have developed a small refrigerator, about 10 cm long, which is light and compact, and its performance especially <u>without</u> thermal isolation is very encouraging.

4. Publications

"High Frequency Thermoacoustic Refrigerator Operated with Air", by T. Klein, O.G. Symko, and D.J. Zheng, in preparation.

We intend to publish this when we reach a ΔT of 50°C.

5. Personnel

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– Thierry Klein, Postdoctoral Fellow

– De Juan Zheng, Research Associate Professor

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b. Number of Papers Published in Referred Journals: 0
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