Tabletop thermoacoustic refrigerator for demonstrations

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An inexpensive (less than $25) tabletop thermoacoustic refrigerator for demonstration purposes was built from a boxed loudspeaker, acrylic tubing and sheet, a roll of 35 mm film, fishing line, an aluminum plug, and two homemade thermocouples. Temperature differences of more than 15 °C were achieved after running the cooler for several minutes. While nowhere near the efficiency of devices described in the literature, this demonstration model effectively illustrates the behavior of a thermoacoustic refrigerator. © *2002 American Association of Physics Teachers.*
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I. INTRODUCTION

The basic workings of heat engines and refrigerators are commonly described in the undergraduate physics curriculum. Thermoacoustic heat engines and refrigerators, however, are topics usually reserved for graduate level courses and research. Recent articles in popular scientific journals have made the concepts behind such devices understandable to a much wider audience.[1,2] A demonstration apparatus, as described in this note, can effectively introduce students to the physics behind thermoacoustic refrigerators. The basic operating principles are simple enough to be understood by beginning students, and this apparatus may be used to attract students to physics, or to upper level courses. The first author of this paper uses this apparatus regularly as a demonstration for prospective students and their parents during campus tours. This apparatus is not designed to be efficient; it is intended more as a proof of concept demonstration. However, it could readily serve as a starting point for a senior level research project complementing a thermodynamics or acoustics course.

II. CONSTRUCTION OF THE APPARATUS

The thermoacoustic refrigerator demonstration described in this note is of the standing wave variety,[3] and consists of a quarter-wavelength resonator (an open-closed tube) driven by a loudspeaker. While this is the easiest resonator shape to build, it is the least efficient of the standing-wave type refrigerators.[4] Since the primary purpose of this apparatus is to demonstrate the action of an acoustic refrigerator, efficiency was not a primary concern. A schematic drawing of the refrigerator is shown in Fig. 1(a).

The resonator for this refrigerator was a 23 cm length of acrylic tubing with an inner diameter of 2.2 cm. The length defines the resonance frequency of the system, which was 385 Hz for our apparatus. A hole was cut in the center of an acrylic cover sheet and the tube was glued to the cover sheet, which was then placed over the speaker. The speaker was a 4-inch boxed speaker[5] capable of handling 40 W, and a 4-inch diameter o-ring was used to provide a seal around the edge of the speaker. An aluminum plug was milled to fit snugly into the end of the tube, forming the closed end.

The most important part of an acoustic refrigerator is the stack, which consists of a large number of closely spaced surfaces aligned parallel to the length of the resonator tube. The stack for this apparatus was constructed, as suggested Hofler,[6] by winding a roll of 35-mm photographic film around a central spindle so that adjacent layers of the spirally wound film provide the stack surfaces. Lengths of 15-lb nylon fishing line separated adjacent layers of the spirally wound film stack so that air could move between the layers along the length of the stack parallel to the length of the resonator tube. Figure 1(b) shows a cross section of the rolled-film stack, with layers separated by fishing line.

The primary constraint in designing the stack is the fact that stack layers need to be a few thermal penetration depths apart, with four thermal penetration depths being the optimum layer separation.[1] The thermal penetration depth, δ_k, is defined as the distance that heat can diffuse through a gas during the time $t=1/\pi f$, where f is the frequency of the standing wave.[7] It depends on the thermal conductivity, κ, and density, ρ, of the gas and the isobaric specific heat per unit mass, c_p, according to

$$\delta_k = \sqrt{\frac{\kappa}{\pi f \rho c_p}}. \tag{1}$$

If stack layers are too far apart the gas cannot effectively transfer heat to and from the stack walls. If the layers are too close together viscous effects hamper the motion of the gas particles. For a frequency of 385 Hz in air one thermal pen-

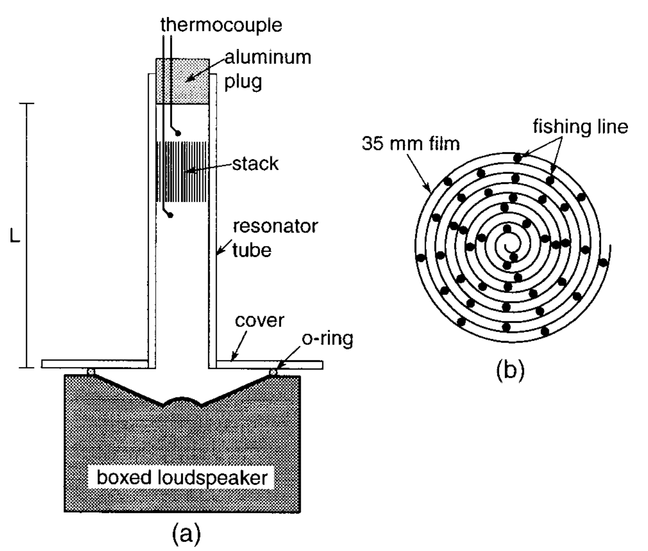

Fig. 1. (a) Schematic diagram of the demonstration thermoacoustic refrigerator; (b) cross section of the stack showing how the film layers were separated by fishing line.

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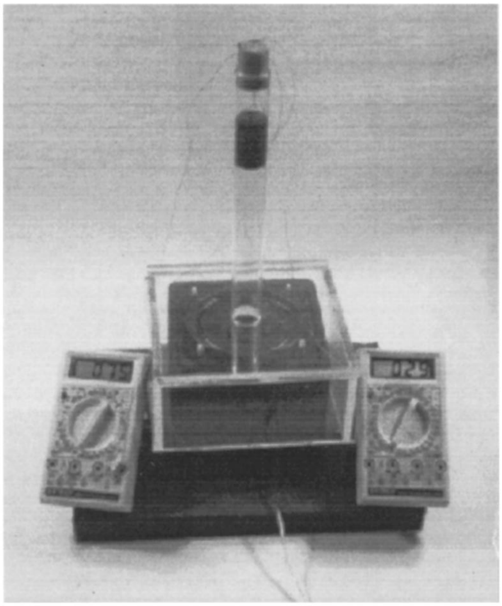

Fig. 2. Photograph of the thermoacoustic refrigerator demonstration showing the temperatures in °F, above (left) and below (right) the stack after several minutes of operation.

etration depth is 1.33×10^{-4} m. The 15-lb nylon fishing line has a diameter of 3.40×10^{-4} m; the stack layers in this apparatus were therefore separated by about 2.5 thermal penetration depths.

To construct the stack, a roll of 35-mm film was unrolled. Lengths of fishing line were glued across the width of the film at equal intervals using a spray adhesive. To keep lines straight the line was first wound onto a ''loom,'' a cardboard frame with slits cut every 5 mm. After spraying the glue onto the lines, the frame was placed over the film and a teflon weight was placed on top, to press the lines against the film. Once the glue was set, the fishing line was cut flush with the edges of the film. This process was repeated for approximately 1 meter of film. The film was then rolled around a small diameter acrylic rod and layers were gradually peeled off until the film roll fit snugly into the tube. The stack was positioned in the tube approximately 4 cm from the closed end so as to be close to the pressure maximum, but away from the particle displacement minimum.

Two thermocouples were made by soldering copper and constantan wires together. One thermocouple was inserted through the outermost winding of the stack to detect the temperature below the stack, while the other was allowed to dangle just above the stack. Leads for both thermocouples passed through a small hole drilled in the aluminum plug at the end of the tube. Digital multimeters were used to display the temperature above and below the stack. The loudspeaker was driven by a sine wave generator through a 100 W audio amplifier. The pressure amplitude inside the resonator tube was not measured, but the power to the speaker was increased until a second harmonic became barely audible, indicating that the system was becoming nonlinear.

III. TYPICAL RESULTS

Figure 2 shows a photograph of the apparatus after it had been running for about 10 minutes at a high sound level. The multimeter to the right of the apparatus shows the temperature below the stack; it started at 66 °F and dropped to 29 °F. The multimeter to the left of the apparatus shows the temperature above the stack; it started at 66 °F and increased to 75 °F. A temperature difference of 46 °F (25.6 °C) was obtained across the stack after just 10 minutes with air as the ''coolant,'' and with the loudspeaker cone being the only moving mechanical part.

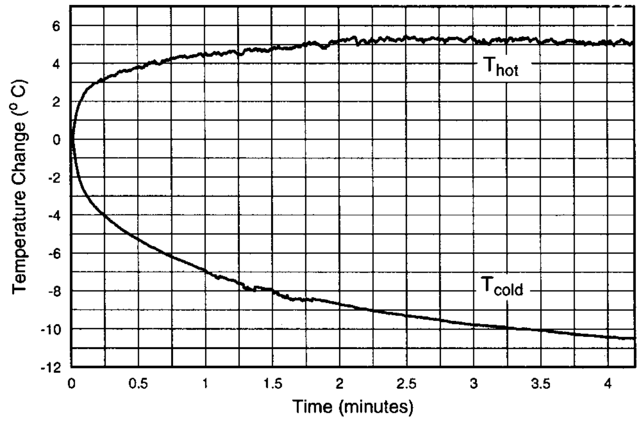

Fig. 3. Temperature variation above (T_{hot}) and below (T_{cold}) the stack as a function of time.

Figure 3 shows typical results for the temperatures above the stack (T_{hot}) and below the stack (T_{cold}) as a function of time. The starting temperatures were normalized to zero, so the plot shows the changes in temperature as measured by each thermocouple. To produce this plot the thermocouple leads were connected to a two-channel digital oscilloscope with an 8 minute capture time. The plot shows that the temperature below the stack (T_{cold}) begins decreasing immediately after the sound is turned on, dropping 4 °C in the first 15 seconds, with the rate of temperature change decreasing with time. After 4 minutes of operation the temperature below the stack has dropped by 10.5 °C and is still decreasing. The temperature above the stack (T_{hot}) increases, also more rapidly at first, as the heat is being pumped through the stack. After approximately 2 minutes the temperature above the stack has increased by 5 °C. After that it stops increasing as the rate at which heat is moved through the stack equals the rate at which heat is conducted through the aluminum cap into the surrounding room. After 4 minutes of operation, the temperature difference between the top and bottom of the stack is about 15.5 °C, a difference large enough to be detected by touching a finger along the outside of the acrylic tube. The trends in Fig. 3 are similar to those found in the literature.[8]

IV. HOW IT WORKS

Figure 4 shows the basic operation of a heat engine and heat pump, or refrigerator. In a heat engine, heat is transferred from a high temperature reservoir to a lower temperature reservoir doing work in the process. In a heat pump, or refrigerator, externally applied work transfers heat from the lower temperature reservoir to the higher temperature reservoir. In the case of a thermoacoustic refrigerator the external work is supplied by the standing sound wave in the resonator.

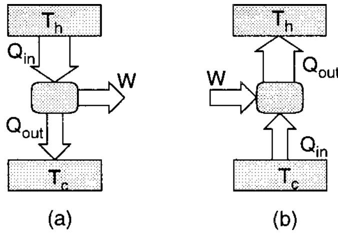

Fig. 4. Schematic diagram showing the basic action of (a) a heat engine, or prime mover and (b) a heat pump, or refrigerator.

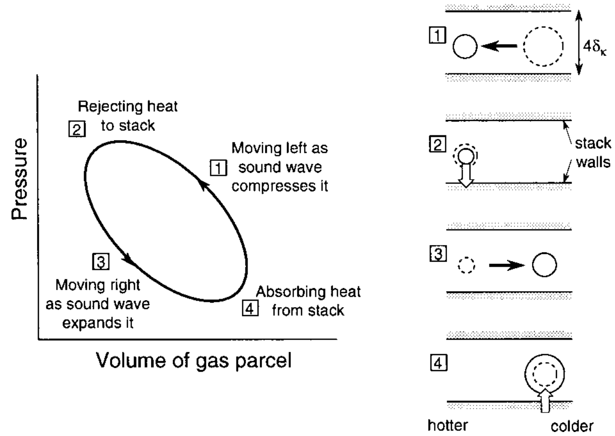

Fig. 5. $P-V$ diagram showing the four stages in the thermoacoustic refrigerator cycle. The left end of the stack wall is towards the closed end of the resonator tube. (After Ref. 1.)

The longitudinal standing sound wave causes the gas particles to oscillate back and forth parallel to the walls of the stack. The alternating compression and rarefaction of the gas causes the local temperature of the gas to oscillate due to the adiabatic nature of sound waves. If the local temperature of the gas becomes higher than that of the nearby stack wall, heat is transferred from the gas to the stack wall. If the local temperature of the gas drops below that of the stack wall, heat is transferred from the wall to the gas.

The second most important factor in the performance of a thermoacoustic refrigerator is the critical longitudinal temperature gradient[7]

$$\nabla T_{\mathrm{crit}} = \frac{p}{\xi \rho c_p}, \tag{2}$$

where p and ξ are the acoustic pressure and displacement amplitudes, respectively. No heat is transferred when the peak-to-peak temperature variation caused by adiabatic compression of the gas, $2p/\rho c_p$, exactly matches the variation in the local wall temperature, $2\xi\nabla T_{\mathrm{crit}}$, between the extremes of the gas particle motion. Only when the sound wave induced temperature variation in the gas is greater than the temperature gradient between the cold and hot ends of the stack will heat be moved from lower temperature to higher temperature causing refrigeration. This requires a rather intense sound wave inside the resonator. A boxed loudspeaker with as tight a seal as possible between the speaker and resonator helps to reduce the sound level in the room to tolerable levels.

The thermoacoustic refrigeration cycle is illustrated in Fig. 5. As the motion of the sound wave causes a gas parcel in the stack to move left (towards the closed end of the tube) the pressure increases and the gas is compressed. The compressed gas parcel is now hotter than the nearby stack wall so it dumps heat to the cooler stack, thus shrinking in volume. As the standing wave continues through its cycle the parcel is pulled back to the right where the pressure is lower. The rarefied parcel is now cooler than the nearby stack wall so it absorbs heat from the warmer stack wall and expands. The cycle repeats with the net effect of a small amount of heat being moved a short distance along the stack from the colder towards the hotter end. A ‘‘bucket brigade’’ of particles can move a significant amount of heat from one end of the stack to the other.

V. INCREASING THE EFFICIENCY

This simple and inexpensive thermoacoustic refrigerator effectively demonstrates the basic physical principles behind its operation. As shown, however, it is rather inefficient as a heat transfer device. If both ends of the stack were connected to heat exchangers, thus coupling the stack to a heat source or heat sink, the transfer of heat would be more efficient. Other improvements could be made by modifying the shape of the resonator[4] or increasing the stack layer separation to an optimal four thermal penetration depths.[1] One could also study the performance as a function of sound level inside the resonator. Such studies might make for an interesting senior research project.

ACKNOWLEDGMENTS

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[2]S. L. Garrett and S. Backhaus, ‘‘The power of sound,’’ Am. Sci. **88**, 516–525 (2000).

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[4]G. W. Swift, ‘‘Thermoacoustic engines,’’ J. Acoust. Soc. Am. **84**, 1145–1180 (1988).

[5]Optimus XTS 40 loudspeakers (4-inch, 150–18 000 Hz) are available from Radio Shack (Catalog No. #40-1991). They are quite often on sale for under $10.00.

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