Eco-Friendly Alternative Refrigeration Systems

2. Thermoacoustic Refrigeration

S S Verma

We saw in Part 1[1] of this article the need, suitability and the technological developments of two eco-friendly alternative, i.e. magnetic and thermoelectric, refrigeration systems. In the present article, we briefly introduce the principle of thermoacoustic refrigeration technique along with the latest developments in this technology.

S S Verma is a senior lecturer in the Department of Physics, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab.

Introduction

The relevance of acoustic principles is by no means limited to sound and hearing. Presently [1-4], applications of acoustic waves is becoming a powerful tool in a wide variety of fields, e.g., sonar and ultrasonics. An electrical signal may be converted to acoustical (i.e. sound) signals with a transducer using a principle similar to that used in loudspeakers. Sound waves in a gas causes changes in both pressure and displacement. Change in pressure leads to change in temperature. Thus, the combination of sound waves and the temperature variations due to them and their interaction with solid boundaries provides a variety of *thermoacoustic effects*. Although these effects, as they occur in everyday life, are too small to be noticed, one can harness high intensity sound waves in acoustically sealed chambers to produce refrigerators known as *thermoacoustic refrigerators*.

[1] Part 1, Magnetic and thermoelectric refrigeration, *Resonance*, Vol.6, No.10, p.52, 2001.

Thermoacoustic Refrigeration System

In a simple thermoacoustic refrigerator (as shown in *Figure* 1), an electrostatic transducer at the left delivers acoustic power W to the resonator, producing refrigeration Q_c at low temperature T_c and rejecting waste heat power Q_h to a heat sink at T_h. In *Figure* 1a, with both ends of the resonator closed, the lowest resonant mode is that which fits a half-wavelength standing wave in the resonator, with displacement nodes and pressure

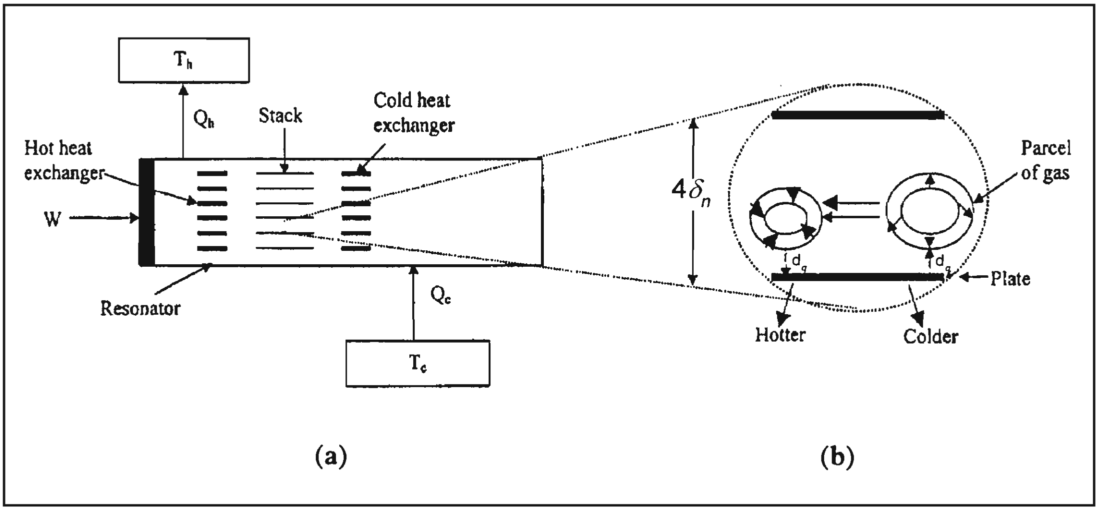

Figure 1. Schematic diagram of a thermoacoustic refrigerator module.

antinodes at the ends, as shown in the lower portion of the *Figure* 1b). The heat exchange elements: hot and cold heat exchangers and a stack between them are located where oscillating gas displacements are nonzero. Each of the two heat exchangers is typically a set of copper fins open to gas flow (like a car radiator) and is thermally anchored to its reservoir by circulating fluids or by metallic heat conduction. The stack is simply a well-spaced stack of solid plates with a high heat capacity, also open to gas flow, supporting the smooth temperature profiles between two heat exchangers. Analytical studies have predicted that a spacing between plates of about four thermal penetration depth $\delta_\kappa = \sqrt{\kappa/\pi f \rho C_p}$ is best, where κ is the thermal conductivity of the gas, ρ is its density, C_p its isobaric specific heat and f the frequency of the acoustic oscillation; δ_κ (as shown in *Figure* 1) is roughly the distance heat can diffuse through the gas during a time $1/\pi f$.

One of the most important parameters in a thermoacoustic device is the length (generally falls in the range of 10 cm to 10 m) of its resonator, which (together with the gas sound speed) determines the operating frequency. The second important parameter is the distance between plates in the stack, which determines the nature of the thermal contact between the plate and the typical parcel of gas.

Thermodynamics

To understand the conversion of acoustic power to heat by this structure, consider the magnified view of part of the stack in *Figure 1b*, which shows typically a parcel of gas at four instants of time during one cycle of the acoustic wave. The standing wave carries the parcel left and right, compressing and expanding it. As the gas oscillates along the stack, it experiences changes in temperature. Much of the gas temperature change comes from adiabatic compression and expansion of the gas by the acoustic pressure, and the rest is a consequence of heat transfer with the stack. The leftmost position of the parcel of gas as shown in the *Figure* 1b, rejects heat to the stack, because its temperature was raised above the local stack temperature by adiabatic compression caused by the standing wave. Similarly, at its rightmost position, the parcel absorbs heat from the stack, because adiabatic expansion has brought its temperature below the local stack temperature. Thus, the parcel of gas moves a small quantity of heat from right to the left along the stack, against the temperature gradient, during each cycle of the acoustic wave.

All the other parcels in the stack behave similarly, so the overall effect, is a progressive net transport of heat from the cold heat exchanger to the hot heat exchanger, with Q_c absorbed at T_c and Q_h rejected at T_h. The parcel absorbs acoustic work from the standing wave, because thermal expansion of the parcel of gas occurs during the low-pressure phase of the acoustic wave and thermal contraction during the high-pressure phase. A loudspeaker, a thermoacoustic engine or other means, can supply the necessary acoustic power W absorbed by all the parcels in the stack. In typical thermoacoustic refrigerators the amplitude of the pressure oscillation is 3-10% of the mean pressure, and the displacement amplitude is also around 3-10% the length of a plate in the stack. The externally imposed temperature gradient in the stack makes a simple acoustic oscillation to transfer heat between the parcel of the gas and the stack. The network the parcel does on its surroundings is delivered in each cycle of the acoustic oscillation.

Finally, each parcel absorbs a little heat from one location in the stack and deposits it a little farther. The steepness of the temperature gradient in the stack determines whether the thermoacoustic device is a refrigerator or an engine. Below a certain critical value of the temperature gradient, the device functions as a refrigerator.

Commercial Developments

Attempts to develop practical thermoacoustic refrigerating devices began just a few years ago. The first efficient thermoacoustic refrigerator was developed by Tom Hoffer in 1986. High-pressure helium gas was used. High pressure increases the power per unit volume of apparatus; helium has the highest sound speed and thermal conductivity among the inert gases. This further increases the power density and allows spacing within the stack and heat exchangers to be as large as possible which simplifies fabrication. Acoustic power was delivered with the help of a loudspeaker/transducer with high force and small displacement. This system reached a T_c of –70°C and had a cooling power of several watts with acoustic pressure amplitudes of 3% of the mean pressure.

A prototype of thermoacoustic food refrigerator has been built by a government laboratory in South Africa. It is a symmetrical, essentially half-wavelength device driven by modified loudspeaker on both sides, with two stacks, each with two heat exchangers. Use of two stacks maximizes cooling power for a given resonator size. Cooling power of the order of 100 W and temperatures suitable for residential food refrigeration are reported. Scientists at Ford Motor Company (USA) built a thermoacoustic refrigerator putting the driver at the displacement maximum of the quarter-wave length standing wave instead of at the pressure maximum. One more corporation in USA (Tektronix) is developing a system for cooling electronics to cryogenic temperatures. For this they are trying to make use of a thermoacoustic device along with an orifice-pulse tube (Stirling) refrigerator.

Power and Efficiency of a Thermoacoustic Refrigerator

Power of such a device is roughly proportional to $p_{avg}Aa$ $(p_{osc}/p_{avg})^2$, where p_{avg} is average pressure, 'A' the cross-sectional area of the stack, 'a' the sound speed of gas and p_{osc} amplitude of the oscillatory pressure. The efficiency of thermoacoustic devices falls below Carnot's efficiency because of five major sources of irreversibility i.e., (i) inherent (means the poor energy transfer rate of sound waves) (ii) viscous (iii) conduction (iv) auxiliary and (v) transduction losses. For many high power density designs, first four sources of irreversibility contribute roughly equally to the inefficiency of the device. However, higher efficiencies are possible for low power density. The most efficient refrigerator is reported to provide gross cooling power at 20% of Carnot efficiency, which is comparable to efficiencies of small commercial (mechanical) refrigerators. Moreover, if future inventions and improvements to the basic understanding can improve the efficiency or raise the power density of thermoacoustic refrigerators without sacrificing their simplicity, they will have the potential for widespread use.

Conclusion

Although thermoacoustic effects as they occur in everyday life are too small to be noticed, one can harness extremely loud sound waves in acoustically sealed chambers to produce a large refrigeration effect. Thermoacoustic devices may be of practical use where eco-friendliness, simplicity, reliability or low cost is more important than efficiency. The fundamentals of thermodynamic at low amplitude are reasonably well understood and a few practical uses of thermoacoustics have been tentatively identified. Considerable study remains to be done before these simple, elegant devices reach their full potential.

Suggested Reading

[1] G W Swift, Thermoacoustic engines and refrigerators, *Physics Today*, pp. 22-28, July 1995.

[2] Sound waves at work, *Mechanical Engineering* (*ASME*, USA), Vol. 120, No.3, pp. 80-84, March 1998.

[3] J R Olson, G W Swift, *J. Acoustic Soc. Am.*, Vol. 95, 1405, 1994.

[4] B C Sales, D Mandms, R K Williams, *Science*, Vol.272, 1325, 1996.

Address for Correspondence
S S Verma
Department of Physics, Sant Longowal Institute of Engineering and Technology
Longowal, District Sangrur
Punjab 148 106, India.