Thermoacoustic Engines and Refrigerators

Thermoacoustic effects, which convert heat energy to sound, have been known for over a hundred years. They have generally been considered mere curiosities, but in the early 1980s our engine-research group at Los Alamos, led by John Wheatley, began to consider thermoacoustic effects as a practical way to make efficient engines. One serious impediment to rapid progress on our experimental Malone engines was the large number of precision moving parts required. While looking for simpler engine designs, we came across the work of Peter Ceperley at George Mason University, who had realized that the timing between pressure changes and motion in Stirling engines and heat pumps is the same as in a traveling sound wave. Inspired by his work, we eventually invented thermoacoustic heat pumps (and new types of thermoacoustic engines) that had at most one moving part.

As Figure 1 shows, our thermoacoustic heat pumps use standing (rather than traveling) sound waves to take the working fluid (a gas) through a thermodynamic cycle. They rely on the heating and cooling that accompany the compression and expansion of a gas in a sound wave. Although ordinary, conversational-level sound produces only tiny heating and cooling effects, extremely loud sound waves produce heating and cooling effects large enough to be useful. Whereas typical heat pumps have crankshaft-coupled pistons or rotary compressors, thermoacoustic heat pumps have no moving parts or a single flexing moving part, such as a loudspeaker, and have no sliding seals. The lack of moving parts gives thermoacoustic refrigerators the advantages of simplicity, reliability, and low cost. Because the sound waves are confined in sealed cavities, the machines are fairly quiet.

For us thermoacoustic heat pumps had the additional advantages of conceptual elegance and easy, low-cost prototype development. We hoped that those features would lead to near-term successes (which would help keep our research well funded and lend credibility to our longer-term Malone program). The development of thermoacoustic refrigerators has indeed had successes, such as the 1992 flight in a space shuttle of a thermoacoustic refrigerator built at the Naval Postgraduate School and a 1993 test of a thermoacoustic sonar projector (an engine rather than a heat pump) by Bill Ward in the Laboratory’s Advanced Engineering Technology Group.

After Tim Lucas, an inventor, noticed an article about our thermoacoustic work in a popular science and technology magazine, he added yet another chapter to the story of novel refrigeration at the Laboratory. Lucas had invented the Sonic Compressor (Figure 2), a device for compressing conventional refrigerant vapors that con-

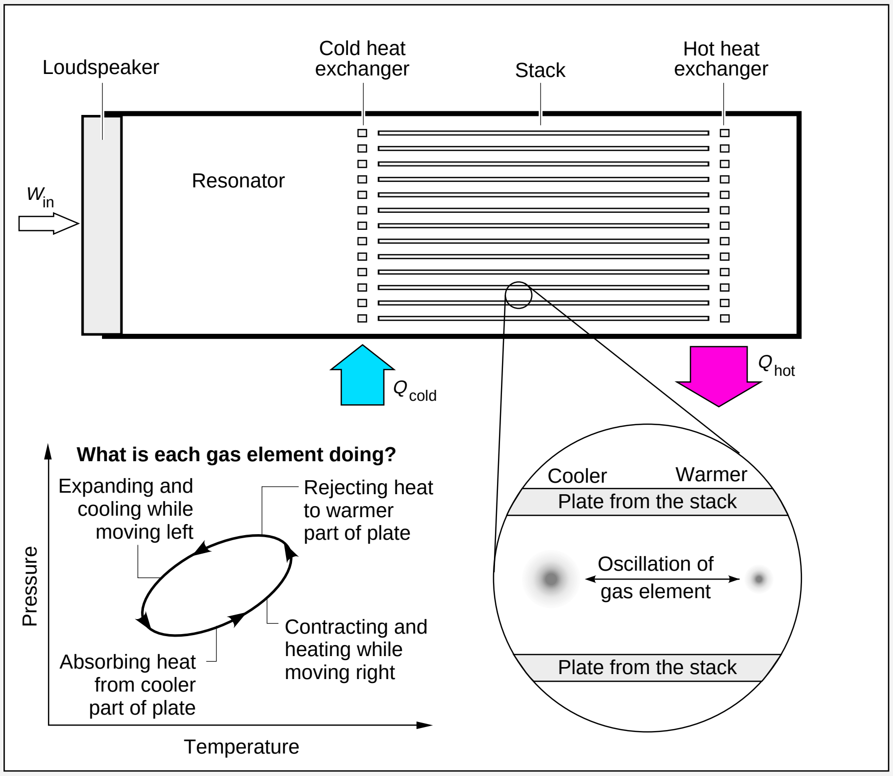

Figure 1. The Thermoacoustic Refrigerator
An electrically driven, radically modified loudspeaker maintains a standing sound wave in an inert gas in a resonator. The sound wave interacts with an array of parallel solid plates called the stack. The resulting refrigeration can be understood by examining a typical small element of gas between the plates of the stack. As the gas oscillates back and forth because of the standing sound wave, it changes in temperature. Much of the temperature change comes from compression and expansion of the gas by the sound pressure (as always in a sound wave), and the rest is a consequence of heat transfer between the gas and the stack. In the example shown the length of the resonator is one-fourth the wavelength of the sound produced by the speaker, so all the elements of gas are compressed and heated as they move to the right and expanded and cooled as they move to the left. Thus each element of gas goes through a thermodynamic cycle in which the element is compressed and heated, rejects heat at the right end of its range of oscillation, is depressurized and cooled, and absorbs heat at the left end. Consequently each element of gas moves a little heat from left to right, from cold to hot, during each cycle of the sound wave. The combination of the cycles of all the elements of gas transports heat from the cold heat exchanger to the hot heat exchanger much as a bucket brigade transports water. The spacing between the plates in the stack is crucial to proper function: If the spacing is too narrow, the good thermal contact between the gas and the stack keeps the gas at nearly the same temperature as the stack, whereas if the spacing is too wide, much of the gas is in poor thermal contact with the stack and does not transfer heat effectively to and from it.

tains no sliding parts. Instead a resonant sound wave in a cavity compresses the vapor and two one-way valves ensure that only low-pressure vapor enters and only high-pressure vapor leaves the compressor. Since the Sonic Compressor needs no lubricating oil, it is attractive for compressing HFC refrigerants, which do not destroy the ozone layer but have the draw-back of being less compatible with lubricants than CFCs are (see "CFCs and Cooling Equipment: The Size of the Problem"). The lack of sliding parts should also lead to higher efficiency in small systems. Furthermore, the Sonic Compressor can replace the piston-driven compressor in present refrigerators without requiring any changes in other parts.

Lucas needed to suppress the production of shock waves in his compressor by the high-amplitude sound because the shock waves wasted energy by turning it into heat. He sought help from us because of our experience with high-amplitude sound in thermoacoustics. Working together we found that the shock waves resulted from nonlinear self-interactions in the desired fundamental resonance in the cavity and from unwanted resonances at frequencies that were exact integral multiples of the fundamental frequency. When we changed the shape of the cavity to that shown in Figure 2, the frequencies of the extra resonances changed so that they were no longer significantly excited by nonlinear self-interaction in the fundamental.

Lucas's collaboration with us was an example of totally successful "tech transfer." During

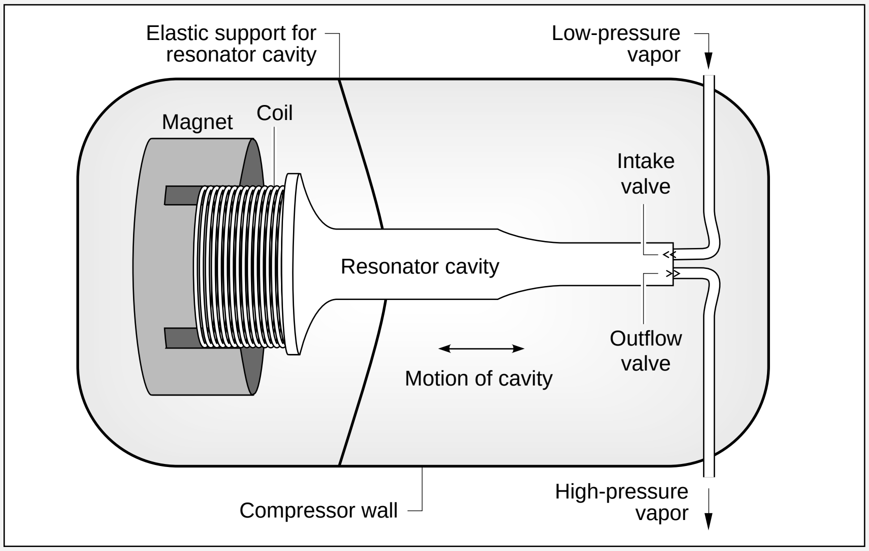

Figure 2. The Sonic Compressor
The Sonic Compressor uses electric power to compress a conventional refrigerant vapor by means of a high-amplitude sound wave; the model depicted can replace the piston compressor in a conventional cooling system such as the household refrigerator shown in Figure 1 of "Malone Refrigeration." The electricity drives a radically modified loudspeaker that shakes a cavity back and forth at a resonance frequency of the working-fluid vapor inside (300 hertz). In the figure the cavity is shown at the rightmost point of the vibration. The motion of the cavity causes the vapor to slosh back and forth—in other words, the motion generates a standing sound wave. The shape of the cavity is designed to prevent the formation of shock waves. The standing sound wave compresses and expands the gas; at the end of the tube farther from the loudspeaker, the range of pressure is 8 atmospheres. A pair of one-way valves at that end, which are opened and closed at the operating frequency by the pressure itself, admits low-pressure vapor from the intake pipe and ejects high-pressure vapor into the outflow pipe.

the year he spent here, we solved his shock problem. Of equal importance to him, we did not jointly invent anything patentable, so the business aspects of his project were not complicated by the involvement of intellectual-property rights belonging to the Laboratory. As Lucas's visit was successful, the Sonic Compressor could come into production in a few years. Thermoacoustic refrigeration will not be ready for the market until a few years later. Malone refrigeration will take still more time to develop but appears to be the most efficient option of the three to which we at Los Alamos are contributing. ◻

ventional CFC refrigerator! A totally different design was clearly required if Malone technology was ever to enjoy widespread use. So in our present CO_2 machine we are using a linear free-piston configuration, which was invented only recently and is being employed in gas-based Stirling engines intended for solar power or for use in space. The pistons in a linear free-piston machine are driven, not by a rotating motor connected to a crankshaft, but by a "linear" electric motor that provides reciprocating force and motion directly in the same way as a loudspeaker. This configuration minimizes the number of moving parts and eliminates the need for high-force bearing surfaces. Careful design can even eliminate the need for any mechanical connection to the displacer piston—the piston moves with the correct amplitude and phase simply in response to the fluid pressures acting on it.

The present crisis in the cooling industry is a unique opportunity for a new, potentially more efficient technology to break the monopoly of a technology that has enjoyed decades of incremental improvement. The primary challenge of the next year or two is to keep this difficult experimental project moving ahead, though the funding only pays for a third of the time of one researcher, while trying to attract the interest of an industrial collaborator. At best, years of further work costing millions of dollars will be required to bring Malone refrigeration to the threshold of possible widespread application. Meanwhile, as described in "CFCs and Cooling Equipment: The Size of the Problem," industry is proceeding promptly with more straightforward interim measures. In the intermediate time scale, mature new technologies such as the Sonic Compressor and perhaps thermoacoustic re-