Design and construction of a solar-powered, thermoacoustically driven, thermoacoustic refrigerator

Jay A. Adeff, Thomas J. Hofler

Department of Physics, Naval Postgraduate School, Monterey, CA 93943, USA
adeff@nps.navy.mil tjhofler@nps.navy.mil

Abstract: A thermoacoustically driven thermoacoustic refrigerator powered by solar thermal energy has been successfully built and tested. A 0.457 m diameter Fresnel lens focuses sunlight onto the hot end of a 0.0254 m diameter reticulated vitreous carbon prime mover stack, heating it to 475°C, thereby eliminating the need for the most troublesome component in a heat driven prime mover, the hot heat exchanger. The high intensity sound waves produced by the prime mover drive a thermoacoustic refrigerator to produce 2.5 watts of cooling power at a cold temperature of 5°C and a temperature span of 18°C.

PACS numbers: 43.10.Ln, 43.35.Ud [HEB]

Introduction

Recent research efforts in thermoacoustic refrigeration have moved away from the use of electrodynamic loudspeakers as a source of the high intensity sound waves required to power these devices. In particular, the authors have been successful in building a thermoacoustically driven thermoacoustic refrigerator (TADTAR), which is powered by electric heater cartridges delivering 600 watts of heat at 450°C directly to the hot heat exchanger of the prime mover section, while producing 90 watts of useful cooling power at a cold temperature of 0°C. With this device, the reliability of thermoacoustic refrigerators has been substantially increased because of a lack of moving parts associated with an electrodynamic loudspeaker. However, a new problem has been created as a result of the elevated temperatures at which the prime mover must operate.

A heat driven TADTAR requires that the prime mover's hot heat exchanger be capable of functioning at very high temperatures. In fact, the hotter this heat exchanger is capable of operating, the more efficiently the prime mover will function. The reader is referred to Swift's review and tutorial on thermoacoustic engines[1] for a complete description of the physics behind thermoacoustic engines. There is, however, a fundamental temperature limit to any material used for the heat exchanger. Copper, the most commonly used material because of its low thermal resistance, is capable only of withstanding temperatures up to 450°C before becoming too soft to maintain its structural integrity. High temperature alloys such as stainless steel require specialized fabrication techniques, which can be costly and time consuming and are not always readily available to researchers on a tight budget. Worse yet, these materials typically have very high thermal resistances relative to copper. Another possibility would be to apply electric heater wires directly to the hot end of the stack. However, the authors felt that the simplest solution to this problem was to replace the prime mover hot heat exchanger and any associated heater elements with direct solar heating.

Direct solar heating of the prime mover

The idea to use sunlight concentrated and focused by an optical lens as a source of thermal energy, is not new. People have made use of just such a device for cooking food or heating water for many years. It is no great surprise, therefore, that a thin plastic Fresnel lens can be used to focus sunlight directly onto the hot end of a thermoacoustic prime mover or, better yet, directly onto the hot end of the prime mover stack. In the latter case, no heat exchanger is required to transfer the heat to the stack.

Reticulated vitreous carbon (RVC) was introduced by the authors as a stack material for thermoacoustic engines,[2] replacing previous materials such as plastic roll stacks in refrigerators[3] and wire mesh stacks in prime movers.[4] An RVC stack is not only easier and less labor intensive to produce, it also has the ability to withstand extremely high temperatures in non-oxidizing environments making it an ideal material for high temperature prime movers. In addition, RVC has a random fibrous structure that eliminates any optical path for light to penetrate directly through it, which is particularly attractive for direct solar heating.

Experimental Apparatus

A low-powered prototype of a small temperature span, solar thermal powered TADTAR was designed, built, and tested at the Naval Postgraduate School in a period of only six months with the aid of a graphical numerical thermoacoustic engine simulation program developed by Purdy and Hofler.[5] The goal for this project was to build a compact device capable of producing five to ten watts of cooling power at 0°C and prove that a solar powered thermoacoustic refrigerator is not only possible but potentially very practical, simple, and reliable.

The project's objective was not necessarily to optimize the design of the refrigerator. Rather it was to arrive at a simple design that would have a high probability of working the first time out and produce a measurable amount of refrigeration. The resonator vessel measures just 0.318 m in length and has a stack diameter of 0.0254 m. A 0.457 m diameter Fresnel lens with a focal length of 0.61 m was used as the solar collector, delivering an estimated 100 watts of solar thermal power of heat energy to the prime mover. A 60-pore per linear inch (ppi) RVC stack was used for the prime mover, whereas a conventional plastic roll stack with a plate spacing of 0.38 mm was chosen for the refrigerator. To keep the device entirely solar powered, solar voltaic cells were used to power electric cooling fans impinging on external heat sinks to reject heat from the prime mover and refrigerator ambient heat exchangers. The final design, shown in Figure 1, is of a half-wave resonant tube with pressure anti-nodes at the closed ends.

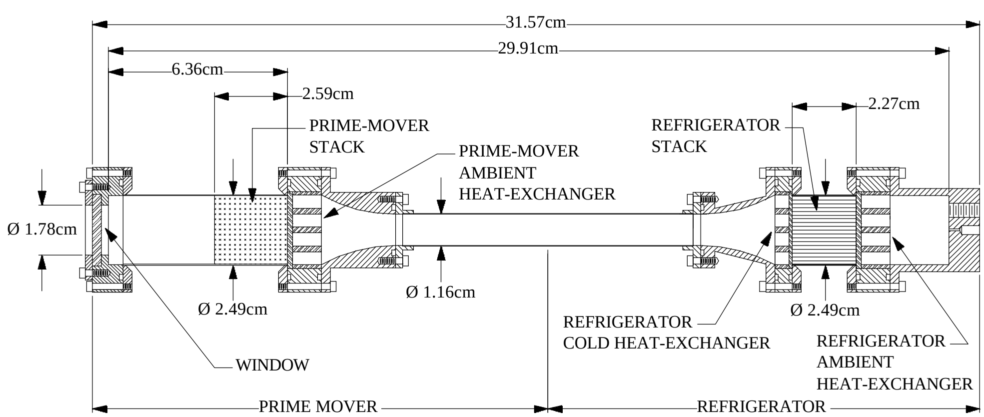

Fig. 1. An assembly section of the solar powered TADTAR

The solar TADTAR is designed to operate with an inert gas mixture of 18% argon and a balance of helium at a pressure of six bar absolute. The two ambient heat exchangers, the refrigerator cold heat exchanger, and their respective flanges were all made of copper, whereas the remainder of the resonator was made of stainless steel. Thin walled stainless steel tubes were used for the stack sections to limit heat conduction along the resonator wall, while still providing enough strength to withstand temperatures of up to 600°C without the danger of rupturing. A fused quartz window was located in the prime mover end plate to allow the focused sunlight to be projected directly onto the hot end of the prime mover stack. The diameter of this window was kept to a minimum by locating the focal point of the Fresnel lens close to the window. Three thermocouples were inserted directly into the heat exchangers, and a fourth was attached to the outside of the prime mover resonator wall at a location corresponding to the hot end of the prime mover stack. Finally, high temperature ceramic fiber insulation was used to cover the entire prime mover tube. Figure 2 shows the TADTAR ready to operate.

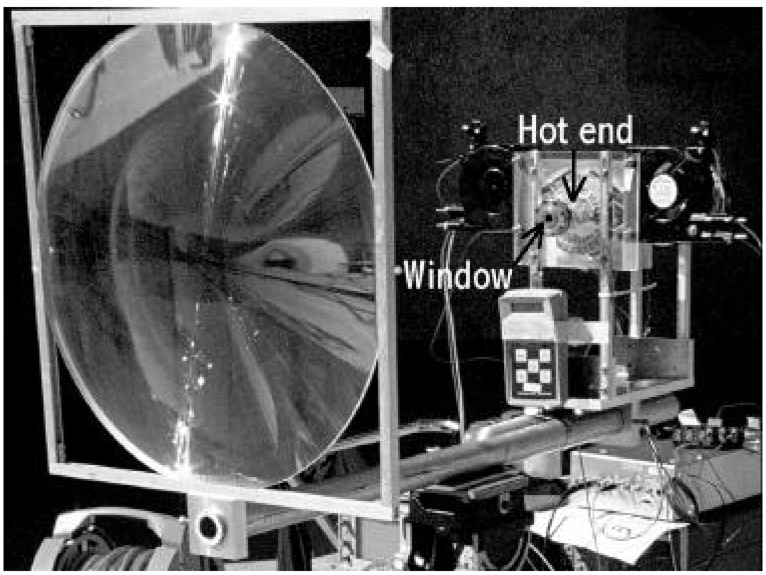

Fig. 2. The solar powered TADTAR ready to run.

Measurements

The solar-powered TADTAR was run during the first two weeks of October when there was approximately 650 W/m^2 of solar heat flux available or 100 watts from the solar collector itself. A microphone placed at the refrigerator end of the resonator indicated that a peak acoustic pressure amplitude of 4.3% of the resonator mean pressure or 26.5 kPa was being generated by the prime mover. This was obtained with the hot and ambient ends of the prime mover at an equilibrium temperature of 480°C and 35°C, respectively. The procedure for quantifying the refrigerator's performance was to measure the cold heat exchanger's temperature as a function of time while the device was cooling down and again while it warmed back up to room temperature after being shut off. These measurements could then be used to estimate the cooling power and heat leak.[6]

The rate at which heat is pumped away from the cold end of the refrigerator, Q_{TOTAL}, can be determined from the following relation:

$$Q_{TOTAL} = \frac{dT_C}{dt} C_p \, , \tag{1}$$

where dT_c/dt is the time rate of change of the refrigerator's cold end temperature, and C_p is the total heat capacity of the cold end. The heat capacity is determined by multiplying the measured mass of the cold end by the heat capacity of the material from which it has been fabricated.

The time rate of change of the refrigerator's cold end temperature can be obtained by assuming that sections of the cool-down or warm-up data can be fitted with an exponential curve having the form

$$T_C(t) = T_0 + A_0 e^{-(t - t_0)/t} , \tag{2}$$

where $T_C(t)$ is the cold temperature as a function of time, t_0 is the time at which the experiment begins, and t is the cool-down time constant. T_0 is a limiting temperature value that would be achieved in steady state equilibrium for very long time values. This limiting value is at or near room temperature for the warm-up data and is defined as $T_{0,wu}$, but it is the limiting coldest temperature observed for the cool-down data and is defined as $T_{0,cd}$.

The fact that the cool-down data can be fitted with an exponential curve is purely an empirical result and not derived from a theory for the thermoacoustic refrigeration mechanism. Taking the time derivative of Eq. (2) gives

$$\frac{dT_C}{dt} = \frac{-A_0}{t} e^{-(t - t_0)/t} = \frac{-1}{t}(\Delta T(t)), \tag{3}$$

where $DT(t) = T_c(t) - T_0$. Substituting Eq. (3) into Eq. (1) gives

$$Q_{TOTAL} = \frac{-C_p}{t} \Delta T(t) = K \Delta T(t) , \tag{4}$$

or

$$K = \frac{-C_p}{t} , \tag{5}$$

where K is defined as a total thermal conductance. The physical value of C_p for the refrigerator cold end is 70 Joules per degree centigrade.

For the warm-up data, K_{HL} is a conductance representing the total heat leak from the ambient end of the refrigerator stack to the cold end. For the cool-down data, we define K_{EC} as a thermal conductance, which corresponds to an "excess cooling" power given by the difference between the total cooling power of the refrigerator and the heat leak power from room temperature. The conductances are

$$K_{HL} = \frac{-C_p}{t_{wu}} , \tag{6}$$

and

$$K_{EC} = \frac{-C_p}{t_{cd}} , \tag{7}$$

where t_{wu} and t_{cd} are the warm-up and cool-down time constants, which are obtained by fitting an exponential curve of the form of Eq. (2) to the warm-up and cool-down data.

Figure 3 shows a plot of the refrigerator cold end temperature as a function of time, along with a curve fit to the data having the form of Eq. (2). Figure 4 shows a plot of the warm-up data taken immediately after this cool-down run, as well as a curve fit to the data.

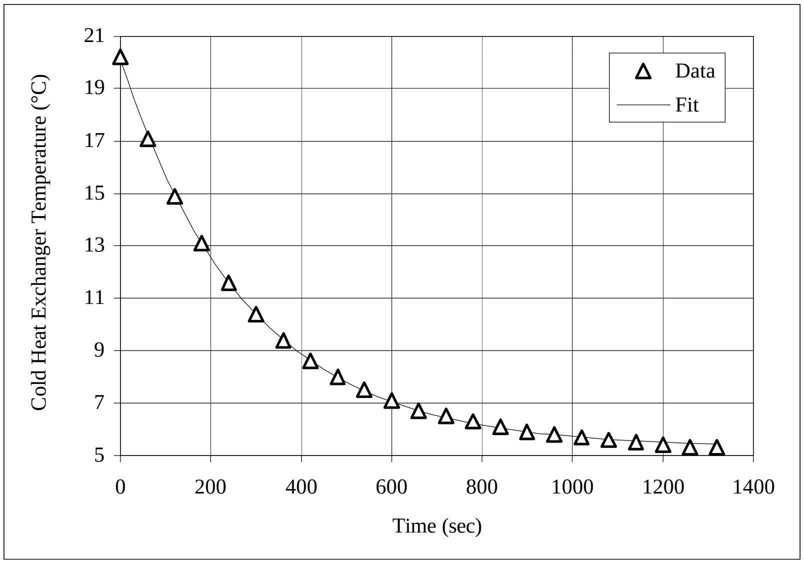

Fig. 3. A plot of the refrigerator cold heat exchanger temperature as a function of time showing the data and an exponential fit to the data.

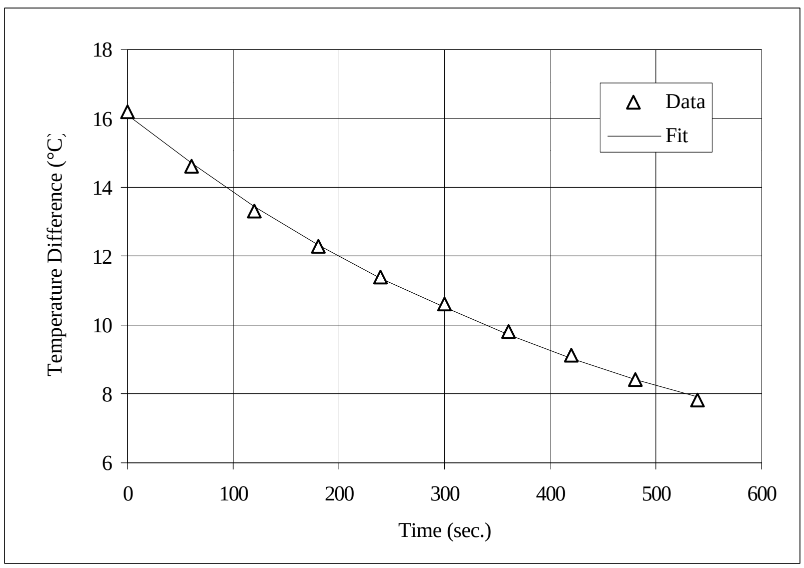

Fig. 4. A plot of the temperature difference between the refrigerator's ambient and cold heat exchangers as a function of time after the refrigerator had been shut down.

From the curve fits in Figures 3 and 4, the numbers obtained for the cool-down and warm-up time constants are:

$$t_{cd} = 281 \text{ s} \tag{8}$$

and

$$t_{wu} = 509 \text{ s}, \tag{9}$$

from which the total conductances are obtained:

$$K_{EC} = 0.249 \text{ W/°C}, \tag{10}$$

$$K_{HL} = 0.138 \text{ W/°C}. \tag{11}$$

The total cooling power is then

$$Q_{TC} = Q_{EC} + Q_{HL} = K_{EC}\Delta T_{EC} + K_{HL}\Delta T_{HL} \,. \tag{12}$$

At the largest span observed by the refrigerator of ΔT_{HL} = 17.7°C and ΔT_{EC} = 0, the total cooling power was therefore 2.5 watts. Figure 5 shows a plot of the cooling power as a function of the cold heat exchanger temperature.

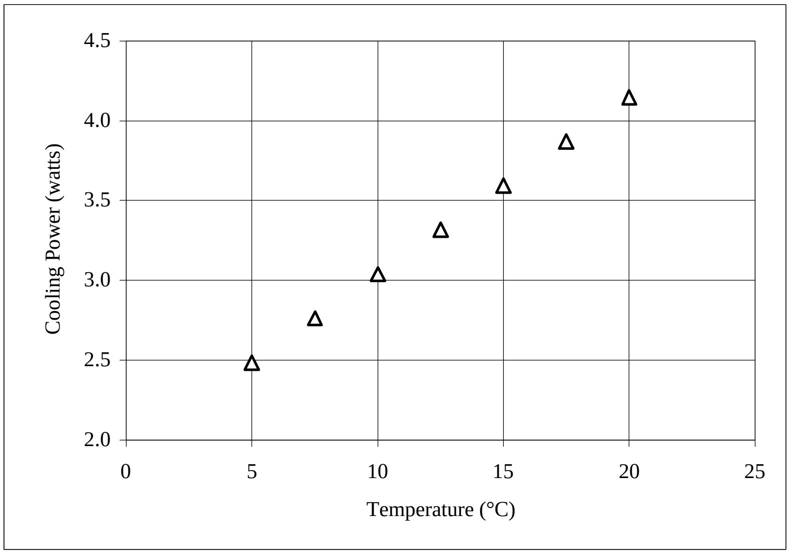

Fig. 5. A plot of the refrigerator total cooling power as a function of the cold heat exchanger temperature.

Conclusions

Based on these measurements, we believe that solar-powered thermoacoustic refrigeration is a viable technology worthy of further investigation and significant improvements can be made in the cooling power available. This could be accomplished by using a larger solar collector to increase the amount of solar power available and improving the design of the heat exchangers and insulation. Such a device could be valuable in geographical areas where sunlight is abundant year round but electrical power is not. Ice could be manufactured during daylight hours and used to store perishables within an insulated icebox.

References

[1] G.W. Swift, "Thermoacoustic engines," J. Acoust. Soc. Am. **84**, 1145 (1988).

[2] J.A. Adeff, T.J. Hofler, A.A. Atchley, W.C. Moss, "Measurements with reticulated vitreous carbon stacks in thermoacoustic prime movers and refrigerators," J. Acoust. Soc. Am. **104**(1), July 1998.

[3] J.A. Adeff, "Measurement of the space thermoacoustic refrigerator performance," Master's thesis, Naval Postgraduate School, Monterey, California, 1990.

[4] M.S. Reed and T.J. Hofler, "Measurements with wire mesh stacks in thermoacoustic prime movers," J. Acoust, Soc. Am. **99**, 2559 (1996).

[5] Purdy, E.W., "Development of a graphical numerical simulation for thermoacoustic research," Master's thesis, Naval Postgraduate School, Monterey, California, 1998.

[6] T.J. Berhow, "Construction and performance measurement of a portable thermoacoustic refrigerator demonstration apparatus," Master's thesis, Naval Postgraduate School, Monterey, California, 1994.