Thermo-Acoustic Refrigeration

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Thermoacoustics

Fig. 1: Petrus Rijke, inventor of the "Rijke tube," ancestor of our thermo-acoustic tube

At first glance, it might not be thought that thermodynamics (the flow of heat) and sound have anything to do with each other. But they do; and the study of the relationship between them is known as thermoacoustics [1].

Some of the first pioneers in the field were the Irish chemist Byron Higgins, who investigated "singing flames" in an open tube in 1777, and German physicist Karl Friedrich Julius Sondhauss, who noticed in 1850 that a half-closed tube produces sound when its closed end is heated. A breakthrough was made in 1859 by Dutch physicist Petrus Leonardus Rijke (Fig. 1), who greatly amplified the effect by inserting what we now know as a "stack" inside the tube. All these phenomena were explained in 1877 by English scientist Lord Rayleigh (John William Strutt), who wrote "If heat be given to the air at the moment of greatest condensation or taken from it at the moment of greatest rarefaction, the vibration is encouraged." In modern times, pressure waves are more often used to manipulate heat, rather than the other way around. This is known as thermo-acoustic refrigeration.

How it works

The common element in thermodynamics and acoustics is *pressure*. When a standing wave is produced in a tube, the gas molecules are subject to greater forces midway between the nodes where amplitude is greatest, and are hence pushed toward the nodes. This creates higher pressures, and hence higher temperatures at those nodes. If this difference in temperature can be sustained, for example by introducing a "stack" that allows sound waves to travel freely but restricts the flow of heat, then the sound wave will produce a thermal gradient (as Rijke discovered). This phenomenon has many applications, including as a "pre-cooler" for the refrigerators that cool the infrared detectors on the recently launched James Webb telescope. We set out to see if we could build a simple version for ourselves.

Stack

In professional thermo-acoustic refrigerators, the stack consists of parallel plates cut to fit the shape of the tube (Fig. 2). Sound waves pass easily through the gaps between the plates, which are made of material with low thermal conductivity.

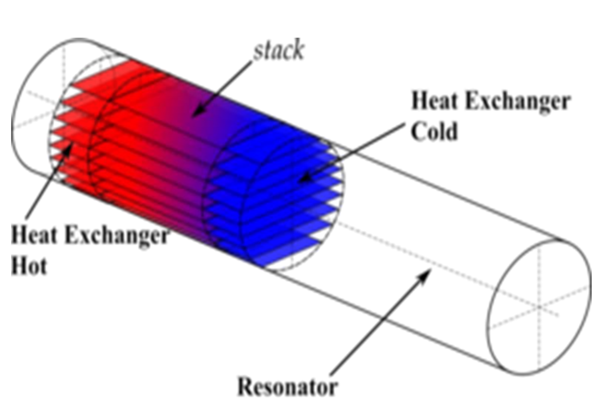


Fig. 2: schematic of the stack in a professional thermo-acoustic refrigerator

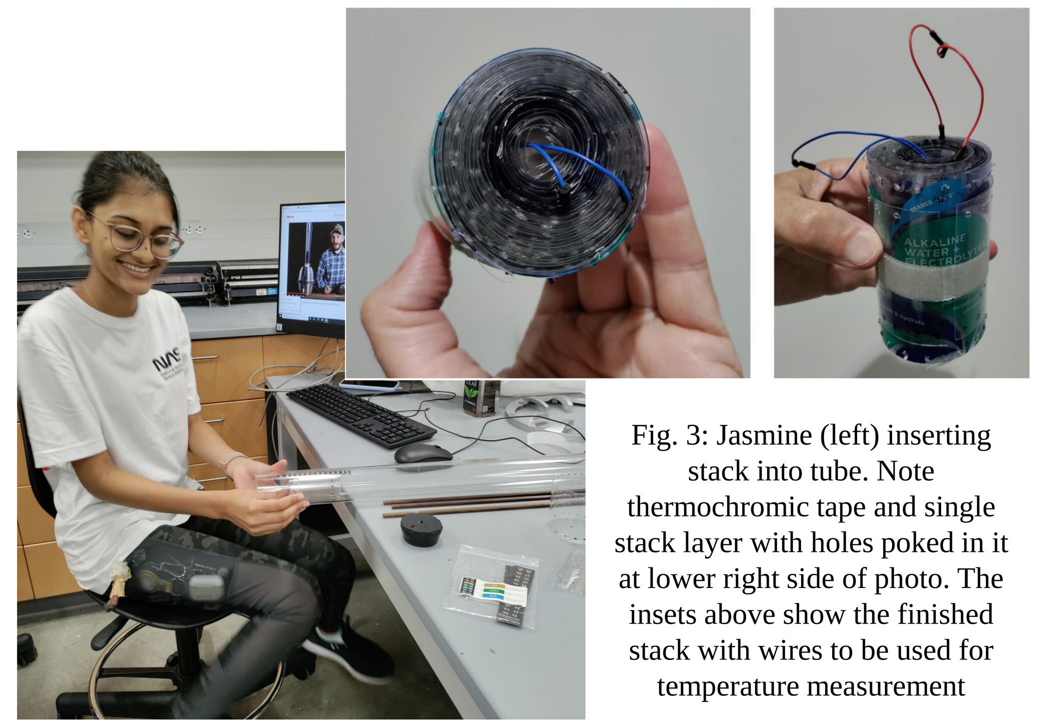


Fig. 3: Jasmine (left) inserting stack into tube. Note thermochromic tape and single stack layer with holes poked in it at lower right side of photo. The insets above show the finished stack with wires to be used for temperature measurement

For our stack, we followed the lead of youtuber Ben Cusick, whose video "Acoustic Cooling & How To Manipulate Heat With Sound" proved invaluable [2]. We cut a number of smooth-sided water bottles into rectangular sheets and poked rows of holes along two edges to create "craters" (Fig. 3). When rolled up in layers, these craters would hold the layers apart, creating the air gaps (a few tenths of a mm thick) through which sounds waves could pass. The plastic used in water bottles has low thermal conductivity, so they will maintain a temperature gradient. When completed, our stack was 11 cm long and 5 cm in diameter, consisting of 18 concentric layers of plastic.

Tube and subwoofer

To create the standing waves, we obtained an old car subwoofer, connected it to a signal generator and amplifier, and mounted the tube above one of the speaker ports (Fig. 4).

Fig. 4a (top left): Sean exploring different possibilities for connecting the tube to the subwoofer

Fig. 4b (bottom right): Sean holding the thermometer while Jasmine lowers the stack into the tube (mounted above the open port on the subwoofer and held in place with modeling clay)

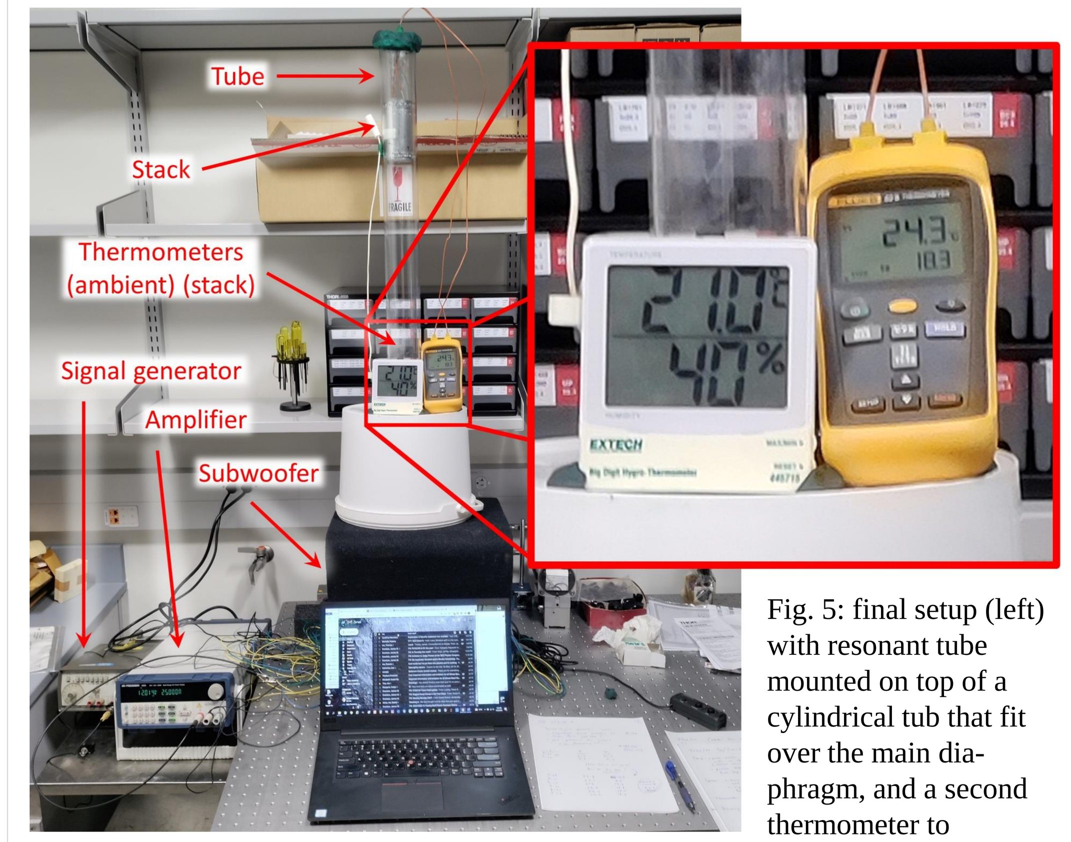


Fig. 5: final setup (left) with resonant tube mounted on top of a cylindrical tub that fit over the main dia-phragm, and a second thermometer to monitor ambient temperature (inset)

Final setup

We experimented with different stack lengths, layer densities and locations inside the tube. We obtained best results with a stack length about 1/6th the length of the tube, positioned about 1/6th of the way down from the top (Fig. 5).

Performance was improved by enclosing the subwoofer diaphragm in a plastic tub and then positioning the tube on top of the tub. The total length of tub+tube was then 94 cm. The tube was closed by a stopper at the top, so the fundamental frequency had a wavelength double this, $\lambda = 1.88$ m. Our resonant frequency was thus

$$f = \frac{v_s}{\lambda} = \frac{343\ \mathrm{m/s}}{1.88\ \mathrm{m}} = 182\ \mathrm{Hz}$$

where v_s is the speed of sound at standard pressure and temperature. It was critical to make sure no air escaped from the top of the tube, as this carried away heat and cooled both the top and bottom of the stack.

Results

Data for a typical run are plotted in Fig. 6, showing a temperature gradient of 6 degrees developing over 23 minutes.

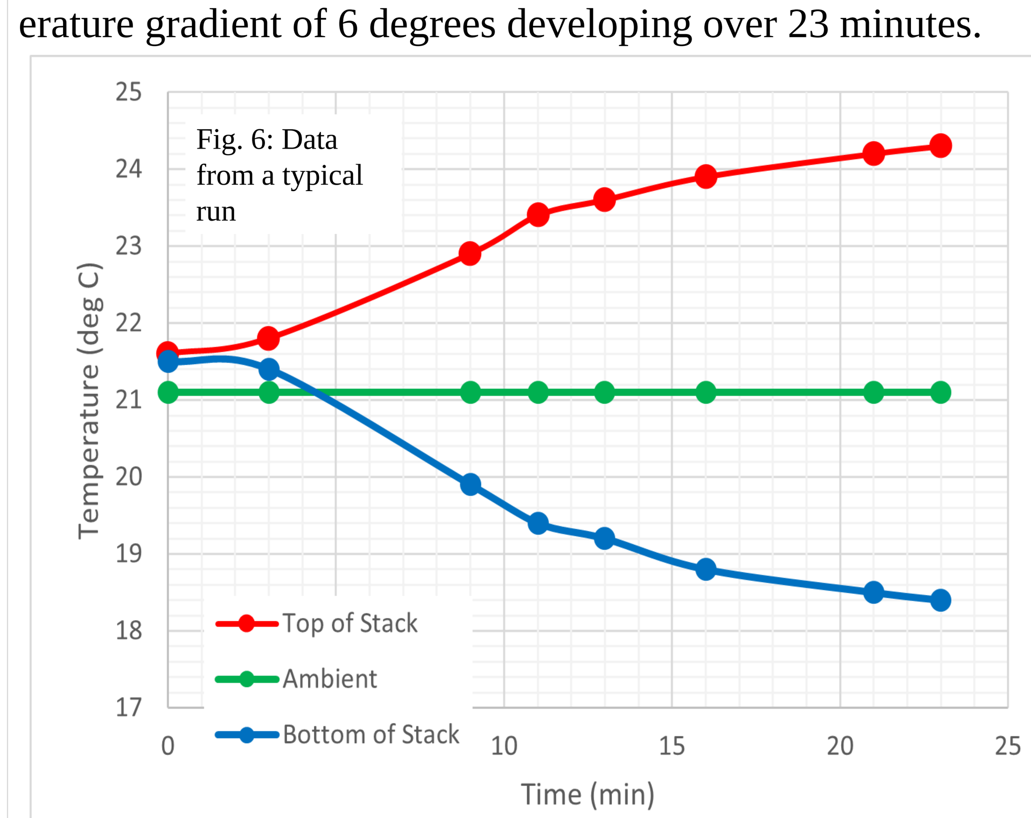
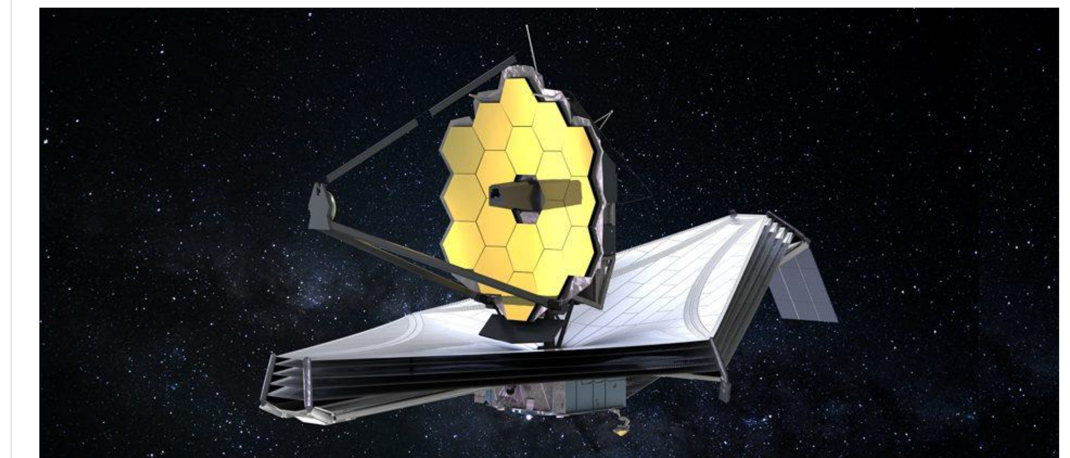


Fig. 6: Data from a typical run



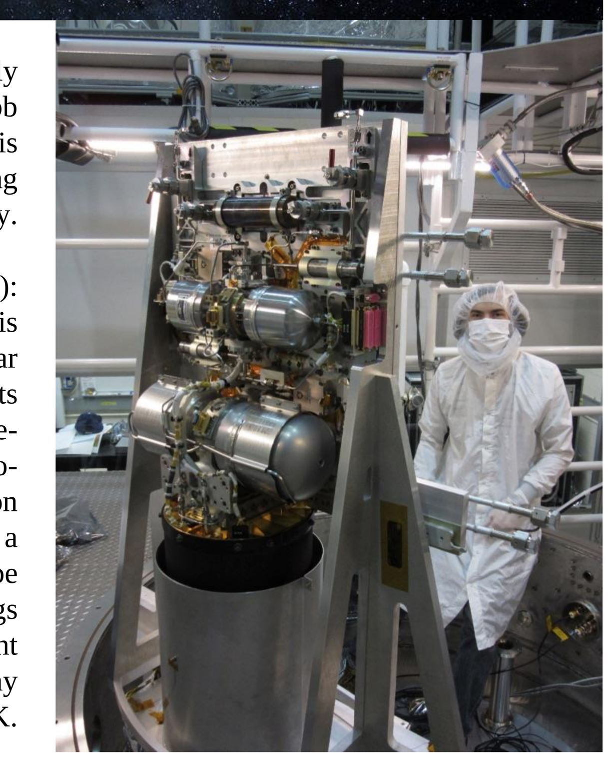


Fig. 7a (top): the recently launched James Webb Telescope, which is revolutionizing astronomy.

Fig. 7b (bottom): Webb's MIRI detector is designed to see so far into the infrared that its cooler must itself be pre-cooled by a thermo-acoustic refrigeration system known as a helium pulse-tube compressor. This brings the MIRI instrument from 42K all the way down to the required 7K.

Application to astronomy

Thermo-acoustic refrigeration systems like this have many uses. In what is perhaps currently the most exciting application, a version of our demonstration serves as a "pre-cooler" for the main cooling system for the MIRI instrument aboard the recently launched James Webb Telescope (Fig. 7a). This detector is designed to peer through intervening gas and dust so that it can discover the oldest and farthest phenomena in the Universe. To do this, it must see using infrared light, not optical. But infrared radiation is heat! Thus any heat must be blocked from the detector, because it would masquerade as a signal. Whereas most of the instruments aboard Webb can operate at a very low 42K, MIRI must be driven all the way down to an ultralow 7K. The refrigeration system that accomplishes this is a thermo-acoustic refrigerator known as a pulse-tube compressor (Fig. 7b). Thus our project has a direct connection to some of the most exciting cutting-edge science being carried out today.

Acknowledgments

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References

[1] Swift, G.W. (2014). Thermoacoustics. In: Rossing, T.D. (eds) Springer Handbook of Acoustics. Springer Handbooks. Springer, New York, NY.

[2] Cusick, Ben (aka "NightHawkInLight"), "Acoustic Cooling & How To Manipulate Heat With Sound (Thermoacoustics Part 2)" (instructional video), https://www.youtube.com/watch?v=kkBBkQ8jFRY&t=204s (accessed July 27, 2022)