What is thermoacoustics?

A brief description, with technical details and citations

Greg Swift

Condensed Matter and Thermal Physics Group,

Los Alamos National Laboratory,

Los Alamos, New Mexico 87545

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A sound wave in a gas is usually regarded as consisting of coupled pressure and motion oscillations, but temperature oscillations are always present, too. When the sound travels in small channels, oscillating heat also flows to and from the channel walls. The combination of all such oscillations produces a rich variety of "thermoacoustic" effects.

Research in thermoacoustics began with simple curiosity about the oscillating heat transfer between gas sound waves and solid boundaries. These interactions are too small to be obvious in the sound in air with which we communicate every day. However, in intense sound waves in pressurized gases, thermoacoustics can be harnessed to produce powerful engines, pulsating combustion, heat pumps, refrigerators, and mixture separators. Hence, much current thermoacoustics research is motivated by the desire to create new technology for the energy industry that is as simple and reliable as sound waves themselves.

The rich history of thermoacoustics has many roots, branches, and trunks intricately interwoven, supporting and cross-fertilizing each other. It is a complicated history because in some cases invention and technology development, outside of the discipline of acoustics, have preceded fundamental understanding; at other times fundamental science has come first.

Rott[1–3] took the meaning of the word "thermoacoustics" to be self-evident—a combination of thermal (heat) effects and sound. He developed the mathematics describing acoustic oscillations in a gas in a channel with an axial temperature gradient, with lateral channel dimensions of the order of the gas thermal penetration depth δ_κ (typically of the order of 1 mm), this being much shorter than the wavelength (typically of the order of 1 m). The problem had been investigated by Rayleigh and by Kirchhoff, but without quantitative success. In Rott's time, motivation to understand the problem arose largely from the cryogenic phenomenon known as Taconis oscillations—when a gas-filled tube reaches from ambient temperature to a cryogenic temperature, the gas sometimes oscillates spontaneously, with large heat transport from ambient to the cryogenic environment. Yazaki[4] demonstrated most convincingly that Rott's analysis of the Taconis oscillation was quantitatively accurate.

A century earlier, Rayleigh[5] understood the qualitative features of such heat-driven oscillations: "If heat be given to the air at the moment of greatest condensation [i.e., greatest density] or be taken from it at the moment of greatest rarefaction, the vibration is encouraged." He had investigated Sondhauss oscillations,[6] the glassblowers' precursor to Taconis oscillations. Rayleigh's criterion was also understood to apply to Rijke oscillations.[7] Similar oscillations can also occur when combustion takes place in a cavity.[8] The oscillations occur spontaneously if the combustion progresses more rapidly or efficiently during the compression phase of the pressure oscillation than during the rarefaction phase. Such oscillations must be suppressed in rockets to prevent catastrophic damage, but they are deliberately encouraged in some gas-fired residential furnaces and hot-water heaters to improve their efficiency.

Applying Rott's mathematics to a situation where the temperature gradient along the channel was too weak to satisfy Rayleigh's criterion, Hofler[9] invented a standing-wave thermoacoustic refrigerator, and demonstrated[10] again that Rott's approach to acoustics in small channels was quantitatively accurate. In this type of refrigerator, the coupled oscillations of gas motion, temperature, and heat transfer in the sound wave are phased in time so that heat is absorbed from a load at low temperature and waste heat is rejected to a sink at higher temperature. The offspring of Hofler's refrigerator are still under study today.

Meanwhile, completely independently, pulse-tube refrigeration was becoming the most actively investigated area of cryogenic refrigeration. This development began with Gifford's[11] accidental discovery and subsequent investigation of the cooling associated with square-wave pulses of pressure applied to one end of a pipe that was closed at the other end. Although the relationship was not recognized at the time, this phenomenon shared much physics with Hofler's refrigerator (but in boundary-layer approximation). Mikulin's[12] attempt at modest improvement in heat transfer in one part of this "basic" pulse-tube refrigerator led unexpectedly to a dramatic improvement of performance, and Radebaugh[13] realized that the resulting "orifice" pulse-tube refrigerator was in fact a variant of the Stirling cryocooler.

Orifice pulse-tube refrigerators and Stirling refrigerators are available today from several companies, and are used for cooling infrared sensors on satellites as well as on Earth.

Development of Stirling engines and refrigerators started in the 19th century, the engines at first as an alternative to steam engines.[14,15] Crankshafts, multiple pistons, and other moving parts seemed at first to be essential. An important modern chapter in their development began in the 1970s with the invention of "free-piston" Stirling engines and refrigerators, in which each piston's motion is determined by interactions between the piston's dynamics and the gas's dynamics rather than by a crankshaft and connecting rod. Analysis of such complex, coupled phenomena is complicated, because the oscillating motion causes oscillating pressure differences while simultaneously the oscillating pressure differences cause oscillating motion. Urieli[16] analyzed these by assuming sinusoidal time oscillations of all important variables and using complex numbers to account for amplitudes and time phases. Ceperley[17,18] added an additional acoustic perspective to Stirling engines and refrigerators when he realized that the time phasing between pressure and motion oscillations in the heart of their regenerators is that of a traveling acoustic wave. Many years later, acoustic versions of such engines were demonstrated by Yazaki,[19] deBlok,[20] and Backhaus,[21] the latter achieving a heat-to-acoustic energy efficiency comparable to that of other mature energy-conversion technologies. Stirling and thermoacoustic-Stirling engines are under development today for applications including spacecraft power and combined-heat-and-power systems on Earth.

To me, the word "thermoacoustics" represents one unifying analytical and conceptual approach to all of these devices and phenomena.[22] The thermoacoustic approach begins with the assumptions that the oscillations of pressure p, temperature T, density ρ, velocity u, and entropy s can be thought of as "small" and that they are adequately represented as sinusoidal functions of time. Results of engineering interest are obtained as time-averaged products of the oscillating variables: heat fluxes are proportional to the product of T and u, work to the product of p and u, mass fluxes to the product of ρ and u, etc. Surprisingly, despite the assumption that the oscillations must be small and monofrequency, the results of the thermoacoustic approach are usefully accurate even for large oscillations with substantial harmonic content.

The spatial dependences of the amplitudes and time phases of the oscillating variables can be very complex, varying smoothly within components and abruptly at the interfaces between components. Typically, the interface between one component and another is accompanied by a dramatic change in geometry or boundary conditions, which enables a desired macroscopic phenomenon such as refrigeration. For example, the regenerators of Stirling engines and refrigerators have pore sizes much smaller than the thermal penetration depth δ_κ, and stacks of standing-wave engines and refrigerators have pore sizes comparable to δ_κ. The so-called "pulse tubes" in pulse-tube refrigerators and other open spaces in other systems are much wider than δ_κ, and these components are insulated from their surroundings while the heat exchangers abutting them are tied to external thermal reservoirs. Wheatley[23] highlighted the importance of the abrupt changes in the gas's environment at such interfaces between components by using the phrase "broken thermodynamic symmetry."

In one important new development based on the thermoacoustic approach, Olson[24] extended Rott's analysis[25] of Rayleigh streaming in a tube with an axial temperature gradient to include arbitrary p–u time phasing, and showed how slightly tapering the tube can suppress Rayleigh streaming in it. This work effectively eliminates a harmful source of heat leak in some thermoacoustic devices, especially pulse-tube refrigerators.

Another new development is based on the discovery of thermoacoustic mixture separation by Spoor,[26] in which radial oscillating thermal diffusion and axial oscillating viscous motion in a gas mixture in a tube create time-averaged separation of the components of the gas mixture along the length of the tube. Geller[27] has used this method in a 2.5-m long tube to separate a 50–50 helium–argon mixture into 30% helium and 70% argon at one end and 70% helium and 30% argon at the other end. Neon, a mixture of 9% ^{22}Ne and 91% ^{20}Ne, was separated to create 1% isotope-fraction differences from end to end. The separation occurs because the sound wave's oscillating pressure causes radial oscillating temperature gradients in the tube, which in turn cause opposite oscillating radial thermal diffusion of the light and heavy components of the mixture. Thus, the two components of the gas take turns being partially immobilized in the viscous boundary layer, so that the wave's axial oscillating motion carries light-enriched gas toward one end of the tube and heavy-enriched gas toward the other end.

This summary highlights only some of the interesting inventions, discoveries, insights, and fundamental demonstrations of thermoacoustics in the past half century. Hoping that this review won't already look silly next year (and mindful of previous "experts" predicting, e.g., that no market for personal computers would "ever" develop, or that household robots would "soon" be commonplace), I won't try to anticipate which of the thermoacoustic technology-development efforts currently underway in businesses, national laboratories, and universities worldwide might eventually succeed!

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