Advancements in Thermophones: Sound Generation from Nanoscopic Heaters

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Researchers adapt solid-state sound-generation techniques discovered shortly after the invention of the telephone.

Introduction

It is often stated that "nothing is new" to portray the idea that everything that we do and learn is, in one way or another, a recycled version of something that someone else has done before. I find this statement to be true everywhere I look, and in the instances in which it didn't appear to be true, it was only because I hadn't looked hard enough. Of course, there is nothing wrong with this. It seems only natural that we learn through imitation before we can then adapt what we've learned to something else by "standing on the shoulders of giants," to borrow a metaphor. Even, at times, when our insights seem serendipitous or of our own accord, another has already come across the same concept before. Such was the case when, in 2008, a group from Tsinghua University in Beijing, China, passed an alternating electric current through a thin, transparent sheet of carbon nanotubes (CNTs) and discovered that it produced sound (Barras, 2008). With a bit of investigation, they found that such a device, called a thermophone, had existed for over a century but that the modern nanomaterial had simply made it much more efficient than those of previous generations. In fact, there is currently an entire field of physics called thermoacoustics that is undergoing a revitalization and progressing because of advancements in modern technologies such as lasers, computing, and very large scale integration (VLSI) that enables the manufacture and patterning of nanoscale materials. Thermoacoustic research shows promise for new devices as well as alternative takes on existing devices. Such devices range from biomedical imaging tools and sonar transmitters to engines to refrigerators.

Thermoacoustics

Thermoacoustics, or study of the interaction between heat and sound, has been a curiosity of individuals long before the "self-explanatory" term was made popular by Rott (1980). Recorded observations of sound generation by heat date as far back as 1568 when a Buddhist monk described tones generated by a ceremonial Japanese rice cooker (Noda and Ueda, 2013). A video demonstration using a handmade variant of these rice cookers is can be seen at bit.ly/2NNGCHv.

The discovery of "singing flames," which is flame heat inducing air motion along tubes or jars to produce sound, is attributed to Higgins (1802). This article reported the effect, along with a letter from Higgins claiming the initial discovery in 1777, which had become somewhat of a novelty demonstration by his students (Higgins, 1802). The article describes placing the neck of various sized jars at some distance over a hydrogen gas flame that produced "several sweet tones." Various publications surfaced attempting to explain the mechanism of sound production in terms of water vapor evaporation and condensation or a series of small combustion explosions, none of which held up successfully to scrutiny. It was not until after experiments were performed by Sondhauss (1850) and Rijke (1859) that an adequate theory was developed by Lord Rayleigh (1878).

Experiments were performed by Sondhauss and Rijke between 1850 and 1860 resulting in the setups that bear their names. A Sondhauss tube is a thermoacoustic device with a long cylindrical neck that is closed off at one end, sometimes in a bulbous structure (**Figure 1A**). When the bulb or closed end is heated, sound may emit from the opening in the neck, with a frequency dependent on the resonant structure created by the bulb and neck. This effect had long been known by glassblowers who, at times, noticed a sound produced as blown glass bulbs began to cool. In the Sondhauss tube, a parcel of cool air enters the heated bulb and heats up as it is compressed further into the bulb. The heated parcel subsequently expands and further cools as it comes in contact with the colder tube. The rarefied region then collapses again toward the bulb as it heats, completing a cycle. Rayleigh posed that the condition that enables the amplification of sound (which occasionally needs a small "kick" to jump start) is that the parcel is heated during compression and cooled during rarefaction by displacing to the hot and cold regions of the tube, respectively.

A Rijke tube is a simple vertical cylinder open on both ends, with a heat source, often a heated wire mesh or gauze, inserted in the bottom half of the tube (**Figure 1B**). Here, convective flow rises through the bottom of the tube and is heated as it passes through the mesh. The gas first expands and then contracts as it interacts with the sidewalls of the tube. Eventually, a standing wave is created (which can be mathematically represented as a combination of traveling waves moving up and down the tube, being partially reflected at the openings) superimposed on the convective flow. Early embodiments of both devices by Herschel (1874) can be seen in **Figure 1C**.

The source of heat for "singing flames" was originally through the combustion of hydrogen gas, although, the ability to produce an acoustic response is largely independent of how the heat is generated. Instead, what matters most is how heat is distributed and how it propagates throughout the system. Some Rijke tubes, even early on, used battery-powered resistive heating (Joule heating) of coiled wires. Furthermore, if the heating element is fine enough, sound can be produced without the resonating tube by oscillating the temperature of the element at acoustic frequencies. Such a device is called a thermophone, a term coined by Weisendanger (1878a,b).

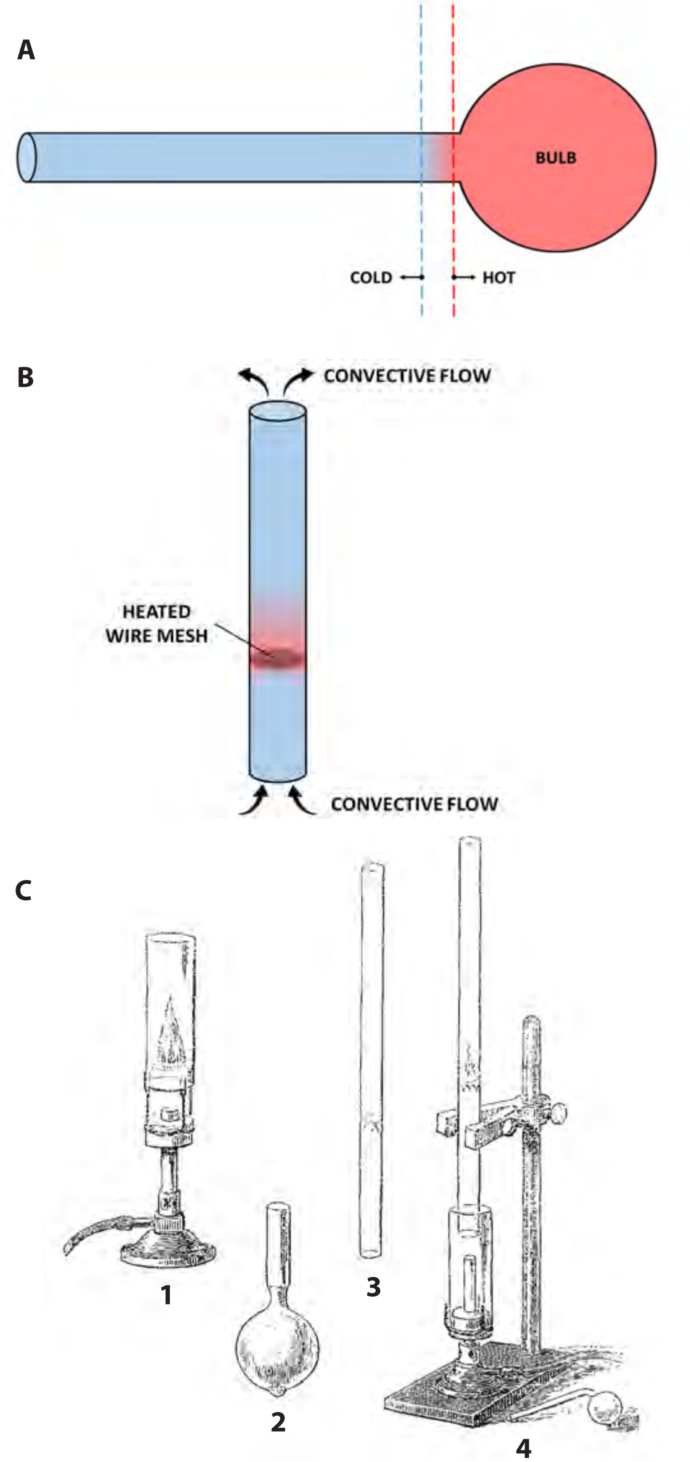

Figure 1: ***A****: a simple bulb-end Sondhauss tube. Typically, a flame is used to heat the bulb externally.* ***B****: a Rijke tube with open ends and a heated wire mesh inserted in the bottom half of the tube.* ***A*** *and* ***B****: heuristic representations of the hot (****red****) and cold (****blue****) regions and are not accurate representations of the temperature profiles. See text for details.* ***C****: various embodiments of Rijke and Sondhauss tubes, although not referred to as such, by Herschel (1874).* ***1*** *and* ***4****: Bunsen burners, emit a flammable gas that rises into a short (****1****) or long (****3*** *and* ***4****) vertical Rijke tube. The gas combusts at the hot wire gauze located partway up from the bottom of the tube. Even after the gas is shut off, a loud sound can be heard that fades as the gauze cools.* ***2*** *and* ***4****: Two short bulbous Sondhauss tubes.*

Thermophones operate by rapidly changing the temperature of an electrically conducting heater element, be it a wire or thin sheet, which interacts with gas in its immediate vicinity. This heated gas rarefies or expands and then cools and contracts again in accordance with the ideal gas law as the current through the heater is decreased. A video by Michigan Tech Acoustics demonstrates a simple thermophone playing music at a conference exhibition (see acousticstoday.org/mDEcx). A driving requirement for thermophones is that the heater element have a low heat capacity and a large surface area by which it can exchange energy with the surrounding gas. It is perhaps ironic that Weisendanger's (1878a,b) original thermophone, which was incited by the excitement surrounding acoustics following Alexander Graham Bell's communication on the telephone two years before, was claimed to operate due to a thermally induced dimensional change in the wire itself, modernly characterized by a materials coefficient of thermal expansion.

Although it is possible that Weisendanger's (1878a,b) thermophone was enhanced at certain frequencies due to a dimensional change in the wire, modern thermophones don't rely on mechanical actuation of the element itself. There was, in fact, much confusion and doubt as to what the particular transduction mechanism was at the time. Preece (1880) reported that it was noted by De la Rive, in 1843, that sounds were produced by passing current through iron wires, but the effect was attributed to magnetism. Preece (1880) also reported that Bell suggested straight pieces of iron, steel, and graphite could also produce sound when driven by a battery.

Bell and Tainter (1880) also presented the photophone in 1880, a device in which intermittent light, that is, light modulated by a chopper or fan, impinging on a thin disk of nearly any hard substance would produce a sound of frequency corresponding to the modulation rate. Bell considered this one of his greatest inventions. Even by 1898, Braun (1898), to whom many have presumptively attributed the invention of the thermophone, described the acoustic sound as being partly produced by a change in length of wire. It becomes understandable then, especially considering the limitations of observing thermal changes at acoustic frequencies, that it was uncertain as to which mechanism produced sound, temperature fluctuations causing mechanical strain in the material or temperature fluctuations causing mechanical strain in the air.

In actuality, both mechanisms mentioned above occur to one degree or another. Which of these a user wishes to interrogate is the subject of various photoacoustic techniques. For example, in thermal wave imaging, a sample containing optical absorbers is placed in a water-filled cavity with ultrasound detectors placed along its edge. Short laser pulses excite the sample-producing acoustic waves due to thermoelastic expansion of the material that is recorded by the detectors. In photothermal beam deflection spectroscopy, the refractive index gradients in a coupling liquid produced by the "mirage effect" will deflect a laser beam that is near the sample surface. In a gas-microphone approach originating from Bell, periodic or intermittent monochromatic light impinges on a sample, is absorbed, and thus produces periodic heating. Heat diffusion to an adjacent inert gas then produces thermal rarefactions and compressions in the gas as a thermally driven acoustic wave. The acoustic signature is recorded using microphones mounted flush within a resonant absorption cell that houses the sample and inert gas.

These various photoacoustic techniques can be utilized for imaging, spectroscopy, or material characterization. Initial photoacoustic theory established in a series of articles by Preece (1881) and Mercadier (1881a-c) was more comprehensively formulated many years later by Rosencwaig and Gersho (1976). This has led to various applications for photoacoustics, particularly in regard to biomedical imaging applications. Manohar and Razansky (2016) provide a much more extensive historical review of photoacoustics for the interested reader.

The Thermophone

The first quantitative theory for thermophone sound production was developed by Arnold and Crandall (1917), which paved the way for the thermophone to be used as a functional device. Since then, the thermophone has historically found most use as a precision source of sound for microphone calibration. Such thermophones consist of an active element, such as gold leaf or thin platinum wires, suspended above a metal backplate that is then coupled with a front plate housing the microphone element to be calibrated. Two narrow capillaries in the backplate serve as an inlet and outlet to supply hydrogen gas to the cavity formed when the two sides of the device are brought together. Hydrogen gas has a much higher sound speed than air and shifts the internal cavity resonances higher in frequency, thereby extending the usable bandwidth of the calibration instrument. One of these thermophones on its backplate is shown in **Figure 2A** along with a diagram in **Figure 2B**.

The usefulness of a thermophone is due to its predictable and relatively smooth frequency response over a wide bandwidth. This is primarily the result of a lack of mechanical moving parts that always have accompanying passive structural resonances. Normally, these resonances are "pushed out" of the band of interest through a combination of material choice and appropriate sizing of structural parts. For thermophones used as a precision source of sound, the only dimensions of concern that would limit bandwidth are those of the cavity encasing the thermophone and microphone element being calibrated. It remains today that one of the most attractive features of thermophones is that their acoustic response is largely decoupled from any mechanical parts.

Thermophones saw utility as a precision source of sound but were never widely used for any other purpose due to their poor efficiency compared with the electrodynamic loudspeaker and other more conventional transduction sound sources. As with some other transducers, thermophones are also hindered when it comes to reproducing arbitrary waveforms due to their intrinsically nonlinear transduction. The acoustic response is quadratic with respect to the driving voltage or current and requires a DC bias to linearize the response. Similar to what occurs in a variable reluctance transducer, this bias current continuously generates excess heat and reduces efficiency. Other modern conventional signal-processing techniques such as amplitude modulation, pulse width modulation, and pulse amplitude modulation can be used as well to rectify arbitrary signals. Bouman et al. (2016) provide a comparison of their thermophone's efficiency with a biased input signal versus an amplitude-modulated one. Even with rectified signals, however, the various frequency components of an arbitrary input signal will still generate corresponding heterodynes as well as second harmonics. Although typically undesired, such nonlinearities can be exploited to probe material properties (Heath and Horsell, 2017).

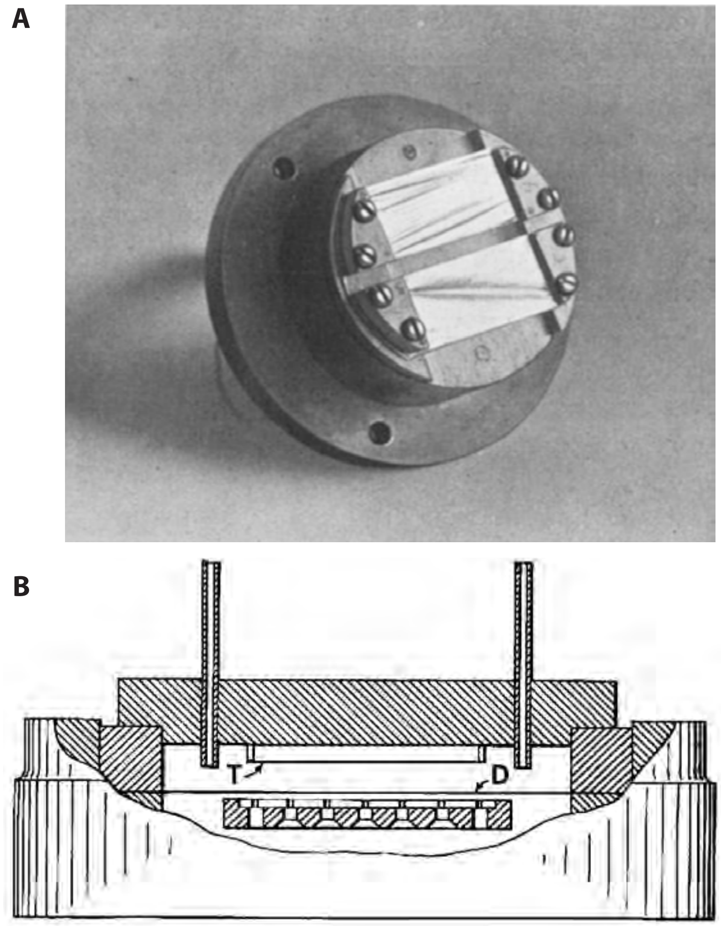

*Figure 2. **A**: thermophone on its backplate used as a precision source of sound for microphone calibration (Ballantine, 1932). **B**: a schematic of an assembled thermophone and microphone from Sivian (1931). T, thermophone active element; D, electrostatic microphone diaphragm. Images reprinted from Nokia Bell Laboratories, with permission.*

Modern Thermophones

Relatively few articles concerning thermophones were published after the 1940s until Shinoda et al. (1999), inspired by photoacoustic studies on porous silicon, presented a porous doped silicon thermophone for ultrasonic emission. Interest grew substantially after Xiao et al. (2008) from Tsinghua University reported a flexible thermophone with an active element composed of a CNT sheet. CNTs are nanoscopic or nanoscale cylinders of carbon atoms arranged in a hexagonal lattice (much like a piece of wrapped chicken wire) that can have exceedingly high aspect ratios.

For example, CNTs used in thermophones have a diameter on the order of 10 nm (about 1/10,000 the thickness of a human hair) but are hundreds of microns in length. A CNT "sheet" useful for thermophone applications is made from a CNT "forest" (a highly oriented dense vertical array of CNTs) made by a process called chemical vapor deposition (CVD). The CVD process for growing the CNTs now used in thermophones was adapted by Zhang et al. (2005). Catalyst nanoparticles are deposited on a silicon wafer and individual CNTs grow vertically from these catalyst particles during the CVD process as a heated feedstock gas is passed over the wafer. With careful adjustment of various growth parameters, the edge of the resulting forest can be mechanically pulled into a less dense porous sheet of horizontally aligned CNTs (**Figure 3**). The roughly 50-μm-thick CNT sheet can be con-

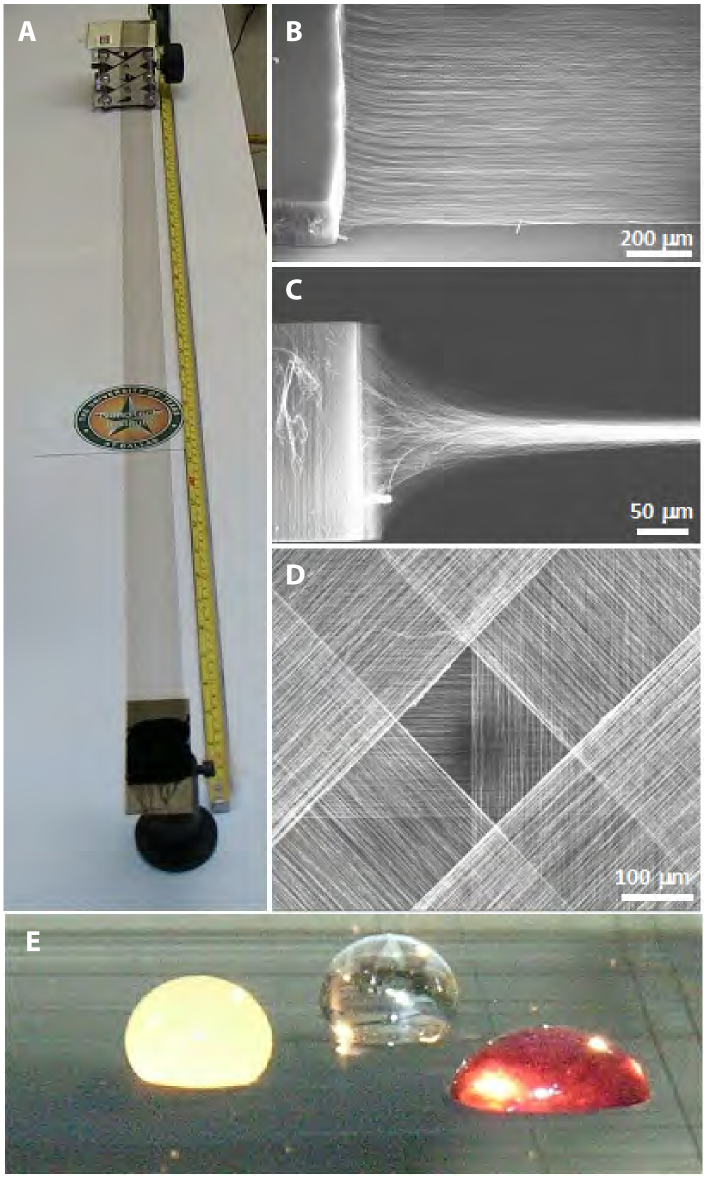

***Figure 3. A**: 1–meter-long freestanding carbon nanotube (CNT) sheet pulled from the edge of a CNT forest by Zhang et al. (2005). **B** and **C**: scanning electron microscope images of the interface between the horizontally aligned sheet and the vertically aligned forest, respectively. **D**: layering or stacking of CNT sheets at various angles. **E**: hydrophobic CNT sheet can support droplets from various aqueous solutions. Images reprinted from the AAAS, with permission.*

tinuously drawn from the forest and, if desired, spun into fibers. Individual CNTs can be semiconducting or metallic, depending on their chirality (i.e., the relative orientation of the 2-D lattice to the angle in which the lattice is "wrapped" on itself), but, statistically speaking, a random array of various chirality CNTs is electrically conducting (Saito et al., 1998). The high porosity of CNT sheets affords them a much larger interface with the surrounding gas and results in more efficient acoustic thermophones than those that utilized thin platinum wires or gold leaf, although this efficiency is still well below that of most conventional transducers.

Although CNT sheets are considered to be very mechanically robust by certain metrics (and can support droplets of liquid 50,000 times the weight of the sheet itself), their extreme porosity leaves them vulnerable to damage by even small macroscopic natural events such as a droplet of water falling on the sheet or a moderate gust of air. In an attempt to remedy this problem, other thermophone heaters that have been manufactured and examined include graphene sponges (Fei et al., 2015), CNT sponges (Aliev et al., 2015), carbonized electrospun polymers (Aliev et al., 2016), and carbon fiber (Dzikowicz et al., 2017). These denser but also more manageable materials highlight the tradeoff between mechanical robustness and thermoacoustic efficiency.

Another parameter thermophone designers must take into consideration is device scalability, which asks how quickly and efficiently these materials and devices can be manufactured and assembled in a repeatable fashion. Since Shinoda et al. (1999), various other thermophone active elements have been produced using VLSI technology such as multilayer (Tian et al., 2011a) and single-layer (Suk et al., 2012) graphene sheets, tungsten thin films deposited by atomic layer deposition (Brown et al., 2016), and thin gold (Dutta et al., 2014), silver (Tian et al., 2011b), and aluminum (Niskanen et al., 2009) wires.

The group from Tsinghua University who published the first CNT-based thermophone element described, in a patent submitted shortly thereafter, sound produced from such a device when submerged just beneath the surface of water (Jiang et al., 2008). Aliev et al. (2010) drew the conclusion that such an effect is possible underwater because carbon nanotubes are hydrophobic and sustain a thin layer of air that then thermally expands on heating as opposed to relying on the thermal expansion of water, which is quite negligible below vaporization. Although sound can be discerned from a pristine CNT thermophone that has been submerged just below the surface of the water, removing the CNT sheet from the water results in physical damage to the element.

An alternative to producing more robust thermophone elements is to shield the fragile element from the external environment. To protect CNT sheets, Aliev et al. (2010, 2014b) and Mayo (2015) have encapsulated them between various materials ranging from polyimide film and mica sheets to ceramic and metal plates. Introducing the encapsulation media results in a mechanical system with resonances that

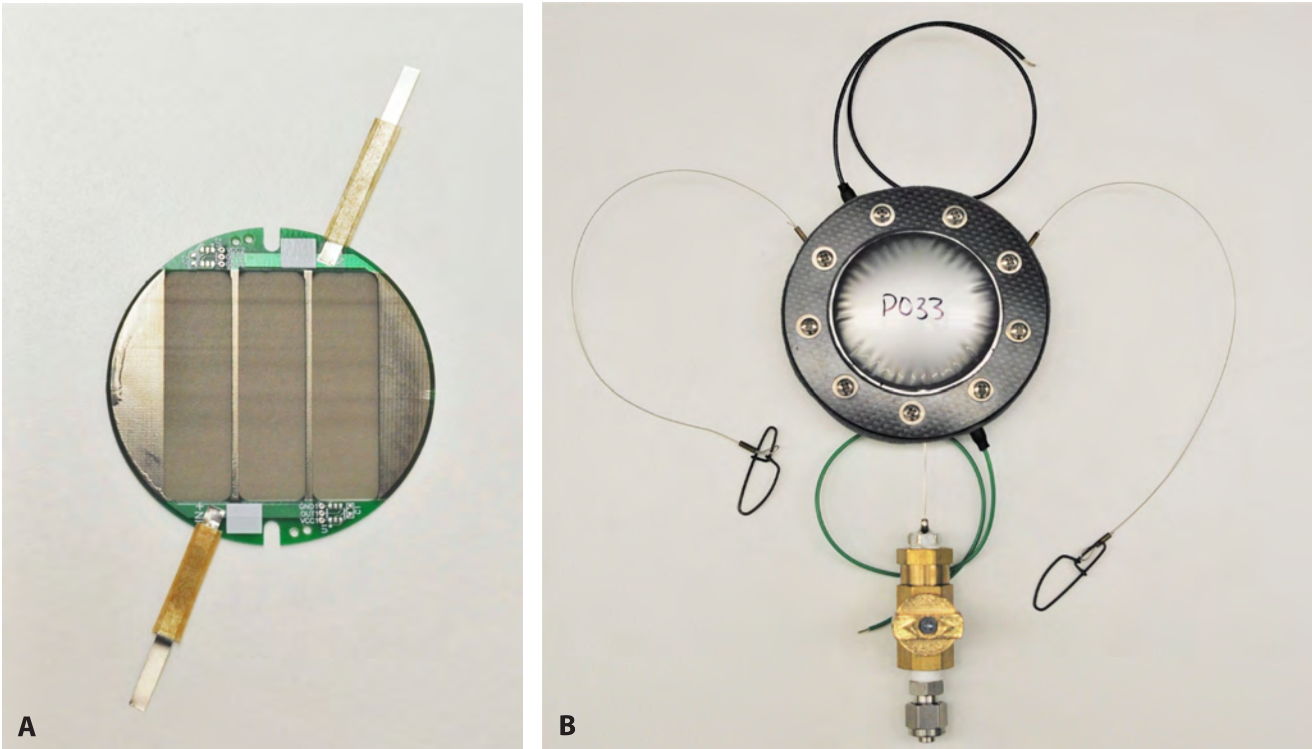

*Figure 4. A: 6.35-cm-diameter G10 circuit board substrate populated with CNT sheets. The device resistance is specified by the separation gap and height along with the number of overlapped CNT sheets. B: fully assembled aluminum laminate thermophone pouch (labeled P033) inflated with argon gas and supported along its perimeter by a black carbon fiber ring. The **black** and **green** leads have been soldered to the positive and negative tabs, respectively. The needle port along with the brass valve below the pouch allows the pouch to be pressurized with inert gas. The two metal wires with clips loosely connect the thermophone to a rigging apparatus (not shown) for calibrated acoustic testing.*

can be tuned by choice of the properties and dimensions of the encapsulation media. The advantage of the thermoacoustic approach is that these mechanical resonances are independent of the properties of the active material.

Aliev's encapsulated thermophones drew interest from the US Navy, who have worked to evaluate and adapt the technology for use in underwater sonar applications. Recent free-field acoustic calibration presentations have looked at the usefulness of various aluminum laminate thermophones as underwater projectors (Howarth et al., 2016). One such adaptation (**Figure 4**) is something of a cross between the thermophones used for microphone calibration (**Figure 2**) and bubble transducers demonstrated by Sims (1960). These thermophones consist of a CNT-active element suspended across a substrate (**Figure 4A**) that is then housed inside an aluminum laminate composite and pressurized in an inert gas environment (**Figure 4B**). These devices act as low-frequency resonating-bubble projectors that allow them to achieve relatively large source levels for their small package size (143 dB re 1 μPa at 1.4 kHz from a single 6.35-cm-diameter thermophone). When the inert gas within the pouch is replaced with a liquid, the bubble is removed and the device becomes a broadband projector (Mayo et al., 2017).

The main selling point of thermophones is just that, their cost. The simplicity of thermophone design (you could literally make one with a fine wire and a power source) and the small amount of active material required puts a very low cost floor on production. Thus, thermophones can be made very thin and lightweight, use no rare earth metals, and can easily conform to most surfaces. In contrast, although piezoelectric ceramics dominate the underwater projector market due to their high electroacoustic conversion efficiencies, most use lead or other heavy metals and require complex processing steps to manufacture high-quality material such as single crystal ceramics.

Theory

Arnold and Crandall (1917) along with Wente (1922) were the first to significantly develop a theory for thermophone transduction as a precision source of sound. Their calculations predict an acoustic pressure that is proportional to the square root of the driving frequency (of a biased system). More recent models of CNT thermophones in free space were published by Xiao et al. (2008), Vesterinen et al. (2010), and Aliev et al. (2013). Each of these models differ slightly, but under the same basic assumption of a negligible active-element heat capacity, the far-field acoustic pressure is linearly proportional to its frequency and reduces to

$$p = \frac{f\ P_{el}}{2\sqrt{2}\ r\ c_p\ T_{amb}} \quad (1)$$

where p is the acoustic pressure at a distance r from the monopole source that is driven with an electrical input power P_{el} producing an acoustic signal at frequency f in an ambient gaseous environment at temperature T_{amb} with gas-specific heat capacity at constant pressure c_p. Therefore, in the "absence" of the thermophone active element, the thermoacoustic transduction process is only determined by the drive power, frequency, and properties of the surrounding gas.

These formulations are limited in scope to sources small with respect to the acoustic wavelength and the ability of the thermophone to maintain its background ambient temperature. At high power, the acoustic pressure will thermally saturate as the background temperature approaches the surface temperature on the heater, eventually causing the active element to degrade, either burning or melting in extreme cases (Aliev et al., 2014a). Both Xiao et al. (2008) and Aliev et al. (2015) have proposed that the difference in the frequency dependence between various thermophones is due to a more substantial heat accumulation of the active elements used in the early 20th century compared with the CNTs often utilized in thermophones today.

Models for the far-field acoustic pressure of encapsulated thermophones are studied less and, although few exist, none appear robust enough to predict the performance of devices that vary significantly in dimension or housing composition. Even fewer models of underwater thermophone projectors exist, an area much in need of development for any practical implementation of thermophones in naval applications.

The largest criticism of thermophones by far is their low efficiency. People often think, "can you just make a better nanomaterial that converts heat to sound more efficiently," but often it isn't the element itself that is the problem. At the current stage of development, the efficiency of a thermophone open to its environment (i.e., not encapsulated) appears to be limited by the properties of air rather than the active element.

To complicate things further, it is difficult to provide a comparison of thermophone performance to that of conventional transducers. Most transducers operate within a region of essentially constant efficiency no matter what power is provided to the device. Thermoacoustic devices are completely different, and the conversion process is similar to that of a car engine or power plant that has a behavior limited by Carnot's cycle in which the efficiency is dependent on the temperature difference between the "hot" fluid and "cold" reservoir. Therefore, so long as the background temperature of the "cold" reservoir surrounding a thermophone is maintained, an increase in input power provides a proportional increase in efficiency. For acousticians, this translates to a 6 dB increase in sound pressure level (SPL) for each doubling of input power as opposed to the 3 dB increase seen in conventional devices.

As discussed, thermophone efficiency may be greatly increased by operating at a higher frequency and higher power and by creating resonant devices. However, efficiency still remains orders of magnitude lower than in conventional devices, and each of these requirements limits application potential. It is for this reason that commercialization of thermophones at this point has been stymied.

Conclusions

Thermophone transducers generate acoustic signals by modulating the temperature of an active element via Joule heating. Heat transfer to gas adjacent to the element causes thermal rarefactions and compressions producing an acoustic wave. The historical origins of these transducers are entangled with the invention of Bell's telephone and scientific observations that followed, leading to the development of photoacoustic spectroscopy, thermoacoustic engines, and thermoacoustic refrigeration. Arnold and Crandall (1917) developed the theoretical foundation for sound projection by thermophones that enabled their use as a precision source of sound for microphone calibration. Decades went by with relatively few developments in thermophone technology until highly porous nanoscopic materials such as porous doped silicon and carbon nanotubes were utilized in the late 1990s and 2000s, respectively. The discovery that such materials significantly improve thermophone efficiency has led to a resurgence in interest as well as new theoretical models and potential use cases.

Overall, low efficiency, the mechanical fragility of highly porous thermophone heaters, and an effective lack of receiving capability has limited thermophones from making their way into any practical commercial devices. Still, a few niche use cases exist in which thermophones could outshine their traditional counterpart projectors due to their broadband response and low manufacturing cost. Use as an underwater sound projector place thermophones in an ideal environment where they can be run in their most efficient regimen at high power with ample cooling capability.

Moreover, most thermophone technologies are easily upscaled with various active heating elements being produced using VLSI processes. New materials are being explored as more mechanically robust thermophone elements, although freestanding CNT sheets currently remain the most efficient transduction material. Thermophone encapsulation provides a means of protecting the relatively fragile active material from harsh environments but also results in a resonant device. This resonance can be tuned independently of the active material that is usually suspended from a substrate. Thermophone elements are usually arrays of wires or planar films that are suitable for making large area projectors that are very thin and lightweight.

The future of thermophone projectors is still largely unknown. The ability to generate sound without any mechanically moving parts makes thermophones a fascinating technology to study for potential applications. However, modern thermophones are still a relatively new technology and are certainly not an end-all replacement for conventional devices. Indeed, an inspection of recent thermophone publications shows that most studies on the topic have been conducted from a physics or materials science perspective and not for direct applications. Thus, additional evaluation and critique by trained acousticians and engineers is sought to more rigorously quantify thermophone performance and help progress this exciting technology. Along with developing the theoretical foundation of thermophones, input from biologists, sonar technicians, medical doctors, and many others is needed to highlight the various niche areas in which the advantages of these projectors can be utilized. Only time will tell as to what other practical devices this technology can produce. In the meantime, it continues to provide a very curious tabletop demonstration for students.

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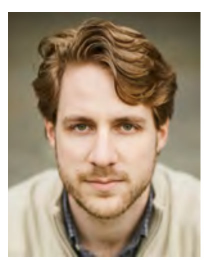
BioSketch



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