NEW VARIETIES OF THERMOACOUSTIC ENGINES

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Abstract. Over 100 years ago, Rayleigh understood that heating and cooling could create acoustic power "if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction." Rayleigh's criterion is met in two classes of thermoacoustic engines. In standing-wave engines, a gas oscillates with standing-wave time phasing in a channel with a steep axial temperature gradient, the lateral thermal contact between the gas and the channel wall being deliberately imperfect. In traveling-wave engines, the gas oscillates with traveling-wave time phasing in a channel with a steep axial temperature gradient, the lateral thermal contact between the gas and the channel wall being as perfect as possible. Both classes of engines have been under vigorous development since Ceperley's 1979 realization that Stirling engines are of the traveling-wave class, and, hence, that acousticians could play a key role in the development of powerful, efficient heat engines. Today, throughout the world, the necessary heat exchangers are being imbedded in an interesting variety of acoustic cavities and networks, creating the time phasings and other acoustic conditions needed for the creation of heat engines with the simplicity and elegance of sound waves.

INTRODUCTION

Rayleigh understood that oscillatory thermal expansion and contraction of a gas could create acoustic power "if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction," and that the oscillatory thermal expansion and contraction could themselves be caused by the acoustic wave under consideration, in a channel with a temperature gradient. The spontaneous acoustic oscillations that Rayleigh explained in this way included the Sondhauss oscillation and the Rijke tube [1], which are essentially open tubes with either nothing inside

(Sondhauss) or a simple gauze inside (Rijke), heated at one location by a flame and held elsewhere at ambient temperature.

These oscillations were weak. Extremely powerful and efficient heat-driven acoustic oscillations had to await Peter Ceperley's realization [2] that the efficient Stirling engine, invented over 150 years earlier, requires pressure and velocity oscillations in the thermodynamic working gas to have essentially the same relative time phasing as they do in a traveling acoustic wave. During the subsequent two decades, Ceperley's insight has enabled the elimination of moving pistons from Stirling engines and has inspired research toward comparably powerful and efficient extensions of the Sondhauss oscillation, in which the time phasing is essentially that of a standing wave.

Below, we will describe some of the recent history, physics, and practical characteristics of both standing-wave engines and traveling-wave engines, and then introduce a new hybrid of these two types that has the best advantages of both.

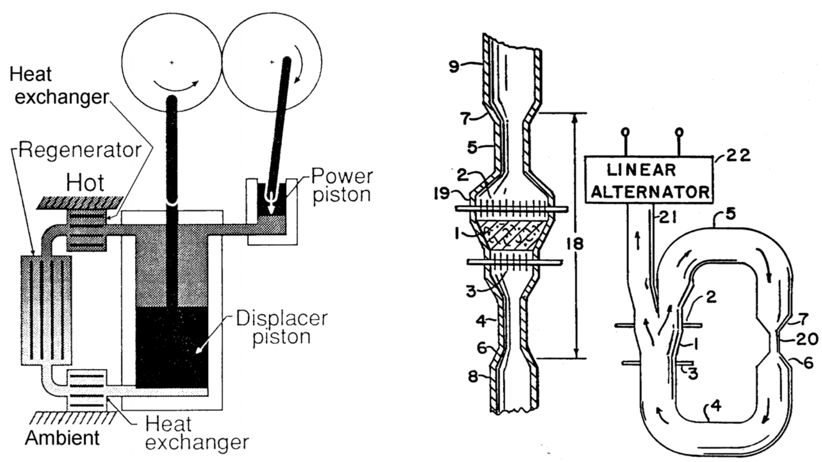

Fig. 1. In a Stirling engine (left), two pistons oscillating with the correct relative time phasing carry a gas in two heat exchangers and a regenerator through a cycle of pressurization, motion from ambient to hot, depressurization, and motion from hot to ambient. Ceperley realized that the underlying phenomena resembled a sound wave, and proposed that the Stirling engine's pistons could be eliminated by imbedding the heat exchangers (2 and 3) and regenerator (1) in a suitable acoustic waveguide (right; from Ref. 2).

STANDING-WAVE ENGINES

Rayleigh's criterion for spontaneous thermoacoustic oscillation—that heat should flow into the gas while its density is high and out of the gas while its density is low—is accomplished in the Sondhauss tube and in other standing-wave engines according to the process illustrated in Fig. 2.

As a typical parcel of the gas oscillates along the axis of the channel, it experiences changes in temperature, caused by adiabatic compression and expansion of the gas by the sound pressure and by heat exchange with the solid wall of the channel. A thermodynamic cycle, with the time phasing called for by Rayleigh, results from the coupled pressure, temperature, position, and heat oscillations. The time phasing between gas motion and gas pressure is such that the gas moves hotward while the pressure is *rising* and coolward while the pressure is *falling*. Deliberately imperfect heat exchange between the gas and the solid wall of the channel is required in order to introduce a significant time delay between gas motion and gas thermal expansion/contraction, so that Rayleigh's criterion is met. The imperfect thermal contact results when the characteristic lateral dimension of the channel is one or more thermal penetration depths in the gas at the frequency of the oscillation.

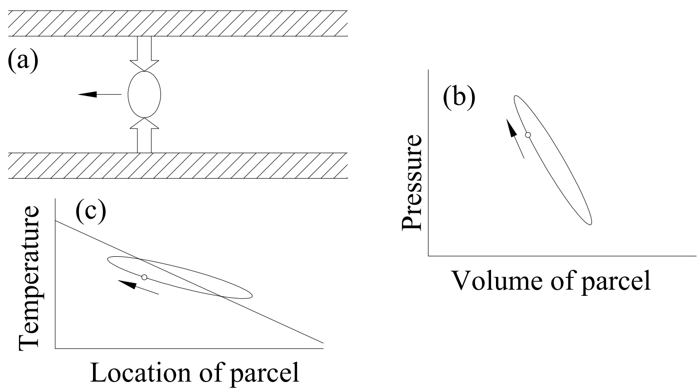

Fig 2. The standing-wave engine process. (a) A parcel of gas oscillating horizontally in a channel. At this instant of time, it moves left (small arrow) and absorbs heat from the channel walls (large arrows). (c) The straight line shows temperature vs position in the channel walls, and the ellipse shows temperature vs position and time of the parcel. (b) Pressure and volume of the parcel trace out a clockwise ellipse as functions of time.

The time phasing described above is that of a standing acoustic wave. Hence, a simple resonator such as a closed-closed $\lambda/2$ or a closed-open $\lambda/4$ resonator, where λ is the acoustic wavelength, can provide the necessary acoustic environment. For the highest efficiency, the tradeoffs among viscous, thermal-relaxation, and thermal conduction losses usually put the stack and its heat exchangers at a location in the wave where $z \sim 5\rho a$, where z is the magnitude of the specific acoustic impedance and ρ and a are the gas density and sound speed.

In the Sondhauss tube, the process shown in Fig. 2 occurs in a single channel, and the temperature gradient is maintained by a heat source outside of one end of the tube and a casual heat sink to atmospheric air along and in the other end of the tube. However, in standing-wave engines, the process occurs in many channels in parallel, all of which contribute to the acoustic power generation. Such a set of parallel channels, now called a stack, was not added to a Sondhauss tube until the 1960s [1,3]. This important development allowed filling a large-diameter tube with small channels, creating a large volume of strong thermoacoustic power production, while leaving the rest of the resonator open and relatively low in dissipation. Heat exchangers spanning the ends of the stack are needed for efficient delivery and extraction of the large amounts of heat needed by a stack. Early use of such heat exchangers was described by Feldman [3] and by Wheatley [4]. Figure 3 shows a recent example of such an engine [5], which produced acoustic powers up to 17 kW and operated at an efficiency as high as 18%. (Here, efficiency is the ratio of acoustic power flow rightward out of the ambient heat exchanger to the heater power supplied to the hot heat exchanger by the combustion of natural gas.)

Although Rayleigh gave the correct qualitative description of the oscillating thermodynamics that is at the core of standing-wave engines, an accurate theory was not developed until Nikolaus Rott [6] derived the wave equation and energy equation for monofrequency sound propagating along a temperature gradient in a channel. These equations first received experimental verification [7] in the context of Taconis oscillations, which can occur when a gas-filled tube reaches from ambient temperature to cryogenic temperature. Rott's work forms the theoretical basis of most of modern standing-wave thermoacoustics.

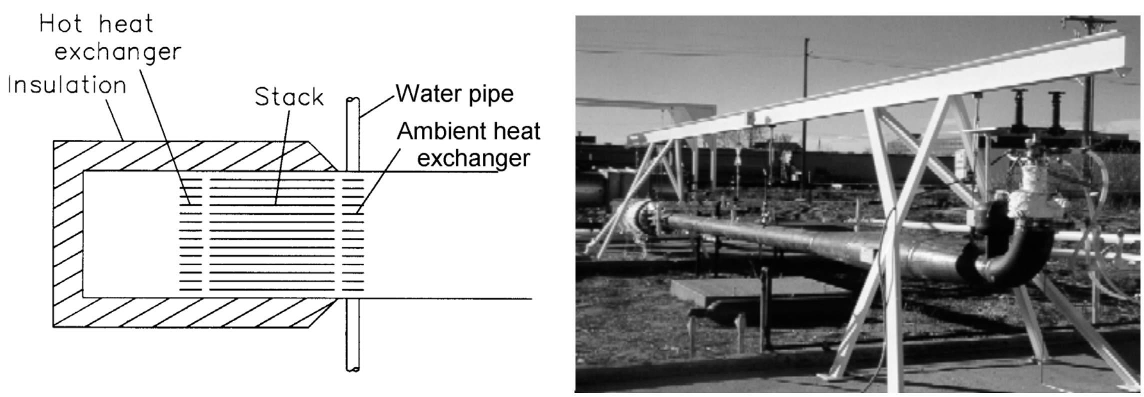

Fig. 3. Schematic and photo of a powerful standing-wave thermoacoustic engine, built at Cryenco in Denver, CO to supply acoustic power to an orifice pulse tube refrigerator. The whole system was a cryogenic liquefier of natural gas, powered by combustion of natural gas. In the photo, the engine (also shown in the schematic) is at the left(background) and the refrigerator is in the foreground. The resonator is essentially $\lambda/2$, with pressure oscillations in the engine and refrigerator 180° out of phase and similar in magnitude.

TRAVELING-WAVE ENGINES

In Stirling engines and traveling-wave engines, the conversion of heat to acoustic power occurs in the regenerator, which smoothly spans the temperature difference between the hot heat exchanger and the ambient heat exchanger and contains small channels through which the gas oscillates. The channels must be much smaller than those of the stacks described above—small enough that the gas in them is in excellent local thermal contact with their walls. A solid matrix such as a pile of fine-mesh metal screens is often used. Proper design causes the gas in the channels to move toward the hot heat exchanger *while* the pressure *is high* and toward the ambient heat exchanger *while* the pressure *is low,* as shown in Fig. 4 (cf. "*while…rising*" and "*while…falling*" in the standing-wave description for Fig. 3). Hence, the oscillating thermal expansion and contraction of the gas in the regenerator, attending its oscillating motion along the temperature gradient in the pores, has the correct time phasing with respect to the oscillating pressure to meet Rayleigh's requirement for power production.

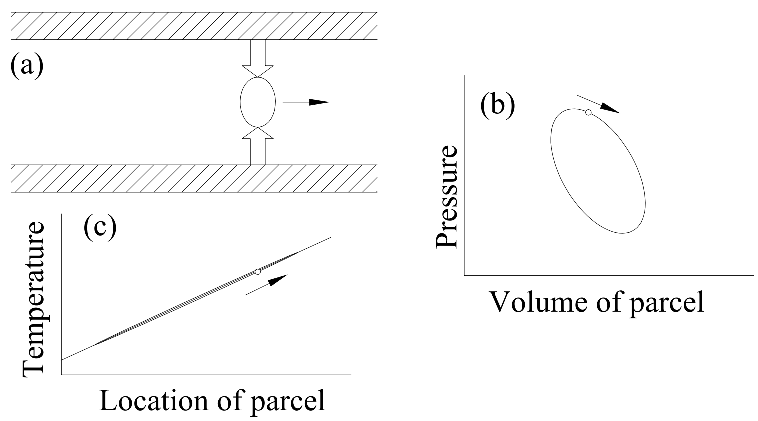

Fig 4. The process in the regenerator of a traveling-wave engine. Note that temperature vs position and time is different from Fig. 2: Good thermal contact creates the clockwise pressure-volume ellipse via traveling-wave phasing here.

The time phasing described above is that of a traveling acoustic wave, which carries acoustic power from ambient to hot. In contrast to standing-wave engines, acoustic power must be injected into the ambient end of a regenerator in order to create more acoustic power; the regenerator is an amplifier of acoustic power. (This point is important for understanding the cascaded engines described below.) A simple, dead-ended resonator cannot provide the ambient power injection, so an ambient piston (Fig. 1a) or toroidal resonator (Fig. 5) is necessary. For the highest efficiency, the tradeoffs among viscous and thermal losses usually put the regenerator and its heat exchangers around a location in the wave where $z \sim 30\rho a$.

Yazaki et al. [8] demonstrated a traveling-wave engine very similar to that first conceived by Ceperley, with the path length around the toroidal waveguide nearly equal to 2λ. At about the same time, deBlok [9] and the Los Alamos group [10] invented a traveling-wave engine with the heat exchangers imbedded in a lumped-acoustic-impedance torus much shorter than λ. Figure 5 shows the Los Alamos demonstration of that concept. The conversion of heat to acoustic power occurs in the regenerator between two heat exchangers, which are structurally and functionally similar to those of a Stirling engine. Proper design of the acoustic network (including, principally, the feedback inertance and compliance) causes the gas in the channels of the regenerator to move toward the hot heat exchanger while the pressure is high and toward the main ambient heat exchanger while the pressure is low. Excellent thermal contact between the gas and the regenerator matrix ensures that Rayleigh's criterion is satisfied as in a Stirling engine, but without moving parts. With a wire screen [10] or parallel-plate [11] regenerator, the engine of Fig. 5 has produced acoustic power of 710 W or 1750 W, respectively, each with an efficiency of 30%.

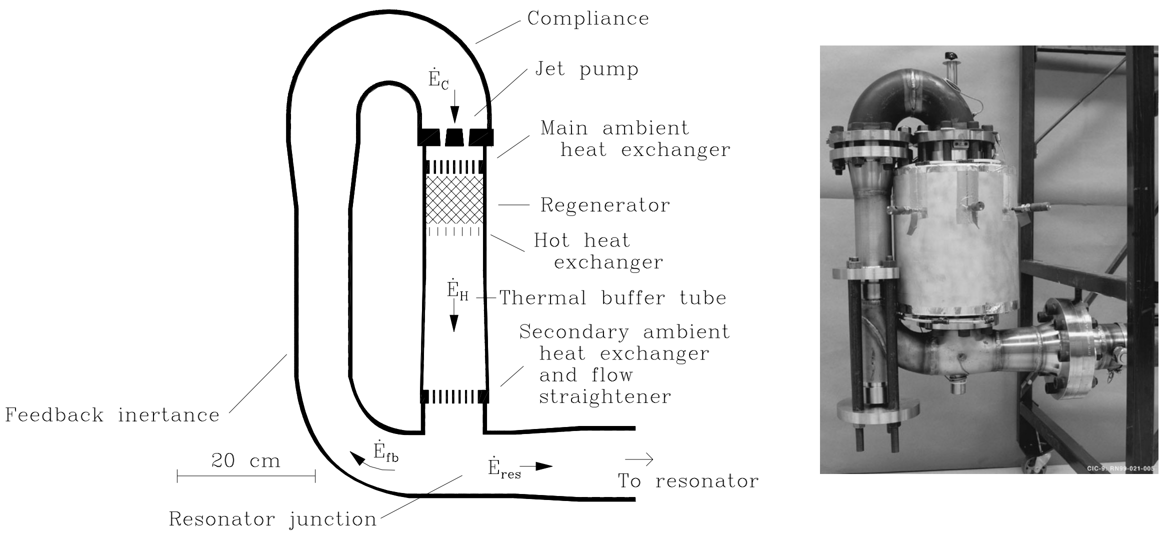

Fig. 5. Thermoacoustic-Stirling hybrid engine, producing 1 kW of power at an efficiency of 30% without moving parts. The $\dot{E}$'s show the circulation and flow of acoustic power.

Several mechanisms might convect heat from hot to ambient without creating acoustic power, thereby reducing the engine's efficiency. A thermal buffer tube (Fig. 5) is needed to thermally isolate the hot heat exchanger from ambient-temperature components below. Ideally, a slug of the gas in the axially central portion of a thermal buffer tube experiences adiabatic pressure oscillations and thermally stratified velocity/motion oscillations, so that this slug of gas behaves like an axially compressible, thermally insulating, oscillating piston. Steady axial internal motion of any portion of the gas in this slug should be avoided, because such motion convects heat from one end of the slug to the other. Such undesirable axial internal motion can be caused by gravity-driven convection, by inadequate flow straightening at the ends of the thermal buffer tube causing jets to extend into the central portion of the thermal buffer tube, or by Rayleigh streaming [12]. The toroidal, pistonless geometry of Fig. 5 introduces the possibility of Gedeon streaming [13], a steady circulation around the entire torus. Hydrodyamic suppression of Gedeon streaming ("jet pump," Fig. 5) has been demonstrated, but it dissipates acoustic power and requires additional parts.

CASCADED STANDING-WAVE AND TRAVELING-WAVE ENGINES

None of the systems described thus far provides high efficiency *and* great reliability *and* low fabrication costs. For example, the traditional Stirling engine (Fig. 1) has high efficiency, but its moving parts (requiring tight seals between the pistons and their surrounding cylinders) compromise reliability and are responsible for high fabrication costs. The thermoacoustic-Stirling hybrid engine (Fig. 5) has reasonably high efficiency and very high reliability, but the toroidal topology needed is responsible for high fabrication costs, for two reasons: It is difficult to provide flexibility in the toroidal pressure vessel to accommodate the thermal expansion of the hot heat exchanger and surrounding hot parts, and some structure or control must be provided to suppress Gedeon streaming around the torus. Finally, the stack-based standing-wave thermoacoustic engine (Fig. 3) is reliable and costs little to fabricate, but its efficiency is only about 2/3 that of a regenerator-based system.

Hoping to enjoy the best features of all these systems, we have begun to build a combination in which one standing-wave engine and two traveling-wave engines are cascaded in series, as shown in Fig. 6. All three engines will be within one pressure maximum in the standing wave, with the stack at a location where $z \sim 5\rho a$ and the regenerators at locations of higher z. The two cascaded regenerator units will provide great amplification of the small amount of acoustic power that will be created by the small stack unit. Only about 20% of the total acoustic power will be created in the stack, so the stack's comparatively low efficiency will have a small impact on the entire system's efficiency. The linear topology simplifies thermal expansion problems and eliminates Gedeon streaming.

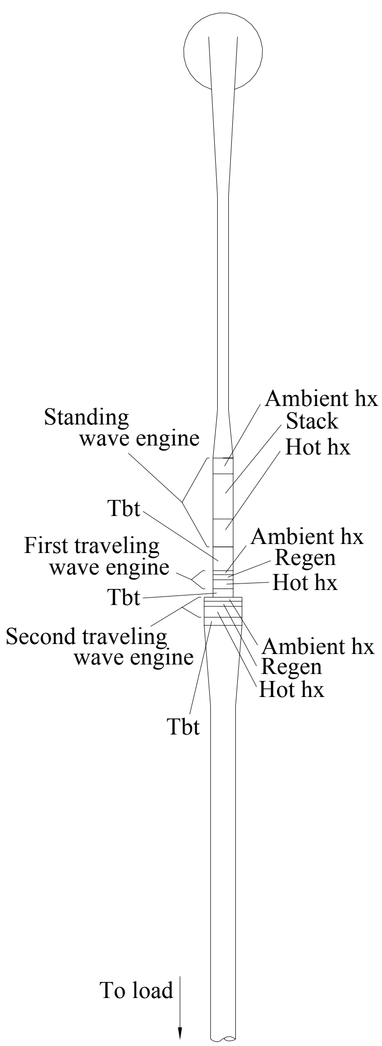

Fig. 6. A cascade of one stack and two regenerators, with the necessary adjacent heat exchangers and intervening thermal buffer tubes, should provide high efficiency in a simple, reliable package. The portion of the resonator shown in the figure is approximately $\lambda/2$ tall. "Tbt" is a thermal buffer tube, and "hx" is a heat exchanger.

SUMMARY

Ceperley's realization that Stirling engines require what acousticians call traveling waves triggered much research activity in the 1980s and 1990s, with both standing-wave and traveling-wave engines under vigorous development. The newly discovered "cascade" combination of standing-wave and traveling-wave engines shows that even more innovation may be possible.

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