

SMALL-SCALE THERMOACOUSTIC ENGINE DEMONSTRATOR

Konstantin I. Matveev, Najmeddin Shafiei-Tehrany, Cecilia D. Richards

School of Mechanical and Materials Engineering,
Washington State University, Pullman, WA, USA

Abstract: The construction and testing of 58-mm and 93-mm long standing-wave thermoacoustic engines is described in this paper. The engines are made of commonly available materials and employ atmospheric air as the working fluid. The engines generate sound at 250-350°C temperature difference imposed between the hot and cold parts of the system. Approximate estimations for produced acoustic power and internal thermoacoustic efficiencies of these engines are 20-70 mW and 2-4%, respectively. A simplified thermoacoustic theory gives reasonable estimations for the onset of the system self-excitation.

Key words: thermoacoustic energy conversion; heat engines; miniature power systems.

1. INTRODUCTION

The development of miniature power systems is critically important for broadening applications of MEMS, sensor networks, and other small-scale and remote systems. A lot of research efforts have been undertaken in miniature energy sources [1]. Traditional and recently developed small-scale power systems are not generally satisfactory. For example, energy densities of batteries are small, and scaled-down rotating machinery is challenging to fabricate. A recently proposed promising candidate for small-scale electricity generation is a thermoacoustic engine coupled with an electroacoustic transformer [2]. Thermoacoustic systems are environmentally friendly and potentially highly reliable due to simple structure and minimal number of moving parts.

Thermoacoustic processes involve heat and sound interactions, such as the thermal-to-acoustic energy conversion and heat pumping by sound [3]. A schematic of a simple standing-wave thermoacoustic prime mover is shown in Fig. 1. The heart of the system is the so-called stack (a piece of porous material), where acoustic power is generated in the presence of sufficiently large externally maintained temperature gradient. Heat is supplied and rejected via two heat exchangers located on the sides of the stack. The resonator geometry defines the acoustic modes. Under appropriate conditions, heat is added to gas parcels oscillating inside the stack at the moment of their compression and extracted at the moment of their rarefaction. According to Rayleigh criterion [4], the acoustic power is generated and, therefore, acoustic modes can be excited. The addition of an electroacoustic transformer will convert some of the acoustic power into electricity. This transformer can be installed, for example, at the open end of the tube shown in Fig. 1.

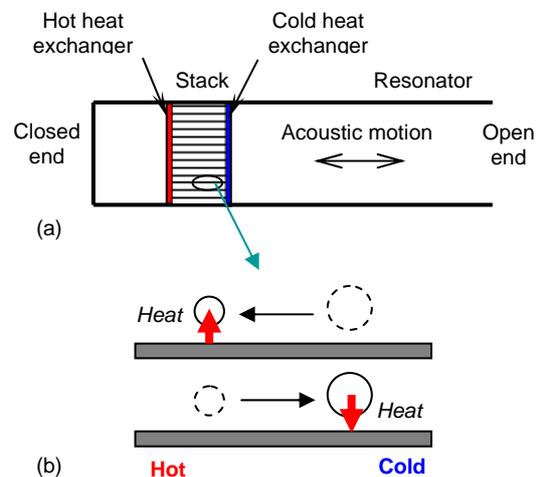


Fig. 1: (a) Schematic of a standing-wave thermoacoustic engine. (b) Thermal interaction between a gas parcel and a stack plate.

The main goals of the present study are to experimentally demonstrate a feasibility of a robust small-scale thermoacoustic engine of several centimeters in size and to evaluate its performance. The open-closed tube system is adopted as a simple standing-wave configuration. The development of this device is described in the following section. Measured parameters, including the critical temperature difference across the stack and the sound power radiated from the open tube end, are reported and compared with a simplified theory. The system has not yet been optimally integrated with a combustor and electroacoustic transformer into an electric generator package, although some initial theoretical and experimental efforts in this direction were initiated and presented elsewhere [2,5].

2. SYSTEM DEVELOPMENT

A modular engine arrangement was chosen for a possibility to modify the system and to optimize its performance. A general schematic of one configuration (with the shortest length) is shown in Fig. 2. Two flanged tube sections and a stack holder form a constant-diameter cylindrical resonator with one end closed and the other end open. The tubes were made of copper for efficient heat addition and rejection. Additionally, copper mesh layers were placed on the stack sides to provide more uniform temperature distribution across the tube section. A butane torch was used as a heat source at the closed end of the resonator, and a cooling water jacket was placed around the open-end tube section.

To minimize the heat conduction leak between these sections, a ceramic stack holder was placed between the copper tube sections. The system is held together by bolts going through the flanges. It was found that elimination of tiny gaps between the system components was critically important. For this purpose, thin graphite gaskets capable of sustaining high temperature were placed between the flanges.

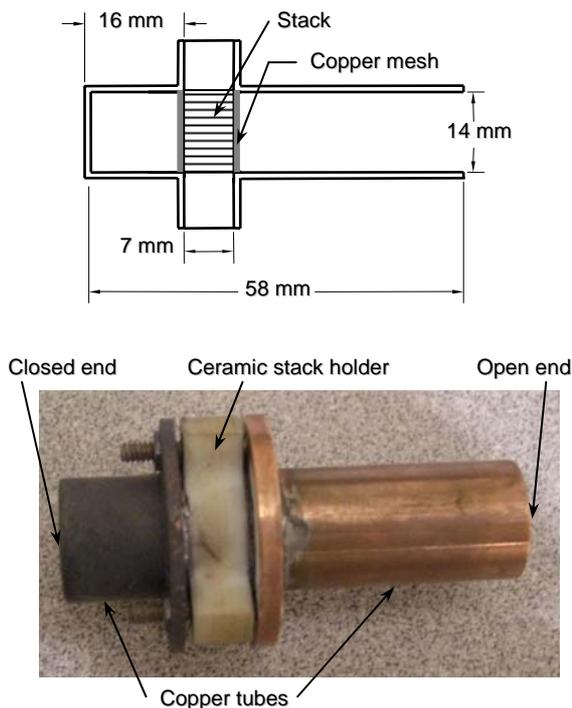


Fig. 2: Schematic and photograph of thermoacoustic engine

The most important component of thermoacoustic engines is the stack. It is known that for efficient performance the pore size in the stack should be equal to a few thermal penetration lengths [3], which is defined as follows

$$\delta_k = \sqrt{2\kappa/\omega}, \quad (1)$$

where κ is the thermal diffusivity of the fluid and ω is the angular frequency of acoustic oscillations. In the quarter-wave resonators, such as shown in Fig. 2, the angular frequency can be estimated as follows

$$\omega = \pi c/2L, \quad (2)$$

where c is the speed of sound and L is the resonator length. In small-scale resonators the sound frequency is high and, therefore, the thermal penetration depth is small. Therefore, desirable pore sizes become a small fraction of a millimeter, out of the range of commercially available regular-geometry porous structures. However, materials with random porosity at this scale are available, such as fine metal wools and reticulated vitreous carbon (RVC). Although it is likely that randomness increases viscous losses in the stack and reduces efficiency of thermoacoustic energy conversion, these materials are found to perform well in some thermoacoustic systems [6]. In a rough approximation, the porosity and characteristic sizes (pore or fiber radius) of random porous materials can be used for estimating the spacing and solid surface area of a corresponding parallel-plate stack, which can be modeled using a well-established theory [3].

In our tests, three types of stacks with random porous materials resulted in sound generation. These materials include RVC with 80 and 100 pore-per-inch (ppi) specifications given by the manufacturer, Energy Research & Corporation, Inc., and a super-fine steel wool with fiber diameter 50 μm . Systems made with 100 ppi RVC stacks were the most efficient. The shortest resonator tested in our study was 58 mm long, such as shown in Fig. 2. However, similar systems but with longer open-ended tube section (up to length of about 11 cm) produced sound as well.

The main measured variables in our tests include temperatures at the hot and cold sides of the stack and the acoustic pressure outside the engine. For temperature measurements, two thin type-K thermocouples were embedded between the ceramic stack holder and the copper tube flanges into the copper mesh layers on the stack sides. A direct acoustic pressure measurement inside the resonator was not carried out, because of the small size of the engine and additional integration with the heat source and sink. The pressure amplitude of the sound emitted from the open end was measured by a LinearX M-52 microphone positioned at 30 cm from the engine. This placement does not affect the boundary conditions at the open tube end and can be used as an approximate estimate for the radiated sound power [7], neglecting reflected sound. Pressure readings at different positions of the microphone around the engine were obtained for estimating the total radiated power.

3. RESULTS

The constructed engine produces sound under favorable conditions. The flame is applied to the closed end, and the open-end tube section is water-cooled. An example of evolution of temperatures measured at two sides of the 100-ppi RVC stack in the 58-mm engine is shown in Fig. 3. The corresponding acoustic pressure amplitude measured outside the engine at 30 cm from the open end is also given in Fig. 3. After about one minute of operation, the temperature difference reaches a critical value within 300-350°C. The system becomes self-excited, and audible sound is generated. The temperatures and acoustic pressure amplitude approach the steady-state conditions in about two minutes. The sound frequency in the steady state is about 1.4 kHz. This stable operating regime does not show significant variations even when the system is run for much longer times, for example, 15 minutes.

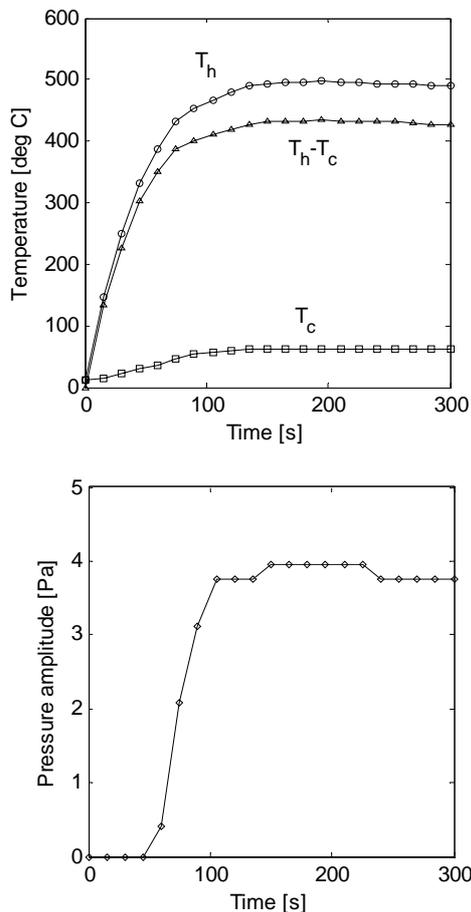


Fig. 3: Temperatures measured at the stack and pressure amplitude recorded at 30 cm from the open end on the resonator axis. T_h and T_c are the temperatures on the hot and cold sides of the stack, respectively. The engine length is 58 mm.

In the 93-mm long engine, the critical temperature difference is significantly smaller, about 250°C. The corresponding temperature and pressure amplitude histories for this engine length are shown in Fig. 4. The measured sound frequency in that engine is about 1.0 kHz.

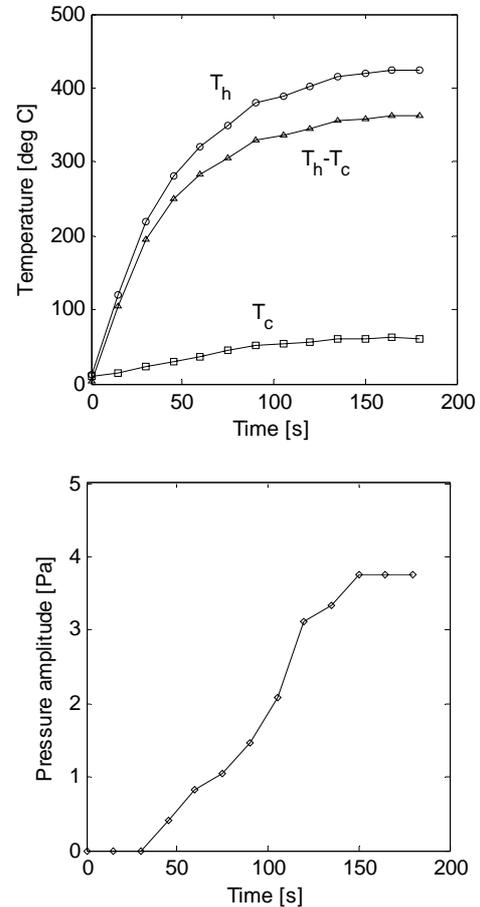


Fig. 4: Temperatures at the stack and pressure amplitude outside the engine. The engine length is 93 mm.

A simplified mathematical model based on the energy balance [8] is applied for estimating the critical temperature difference. For simplicity, it is assumed that the stack consists of fibers aligned with the engine axis, and thermoacoustic processes on the surfaces of these fibers are similar to those on the parallel plates. Since the cooling jacket surface was present close to the open end of the 58-mm engine, the radiated acoustic power is estimated assuming the flanged tube ending. The steady-state sound frequency is used in the computations. The critical temperature difference for the 58-mm engine is calculated to be about 304°C. Hence, the simplified model predicts ΔT_{crit} similar to the value observed experimentally. However, the temperature difference in the experiment was increased at a finite rate, so the oscillation onset in the

quasi-static conditions (as in the model) might be different. For the 93-mm engine, the theory predicts the temperature difference threshold 222°C. The unflanged open tube end was assumed for this engine length. The lower ΔT_{crit} for 93-mm engine is explained by reduced acoustic damping mechanisms at lower operating frequency. It can be also noted that the ideal critical temperature differences for an inviscid fluid correspond to about 57°C and 48°C for the engine with lengths 58 mm and 93 mm, respectively.

A simplified steady-state energy analysis in the excited regime is also carried out for the engine with 100-ppi RVC stack and resonator lengths 58 and 93 mm. Measured temperature differences across the stack and sound frequencies and estimates for the radiated acoustic power are given in Table 1. The corresponding values for generated acoustic power, heat supply rates, and thermoacoustic energy conversion efficiency are calculated. The acoustic power generated in the stack is found to be 20-70 mW. The efficiencies of conversion of heat to acoustic energy inside the engine resonator are about 2-4%, which are reasonable values for miniature power systems. However, a significant heat leak (~15 W) due to conduction between the hot and cold tube flanges occurs through the stack holder and bolted connections outside the resonator. This suggests future developments aimed at optimizing the entire engine structure and focusing on the overall system efficiency.

Table 1: Engine characteristics in steady-state regimes

Resonator length	58 mm	93 mm
<i>Measured parameters:</i>		
Temperature difference at the stack	412°C	354°C
Frequency	1.4 kHz	1.0 kHz
<i>Estimated parameters:</i>		
Radiated acoustic power	0.011 W	0.011 W
Generated acoustic power	0.024 W	0.069 W
Heat supply rate	1.06 W	1.60 W
Thermoacoustic efficiency	2.3%	4.3%

4. CONCLUSION

A small-scale standing-wave thermoacoustic engine is developed using available random porous materials for the stack. This engine demonstrates robust performance with the critical temperature difference in the range 250-350°C. Approximate estimations for the acoustic power generated by the

engine in the steady state and corresponding internal thermoacoustic efficiencies are about 20-70 mW and 2-4%, respectively. A simplified theory gives a satisfactory estimation for the temperature difference threshold. With possible applications of more optimal stack materials and special gas mixtures, the thermoacoustic efficiency of the engine can be further increased. For more accurate determination of acoustic parameters a pressure measurement inside the resonator is desirable. Other directions for the system improvement include a reduction of the heat leak through the stack holder, an implementation of the traveling-wave configuration, and a development of a sealed device with high mean pressure inside. The integration of the engine with compact and efficient combustors and electroacoustic transformers can open a possibility for developing practical miniature power systems with high energy density.

REFERENCES

- [1] Evans JD 2007 Powering the integrated microsystems *DARPA Microsystems Technology Symposium (San Jose, CA)*
- [2] Matveev KI, Wekin A, Richards CD, Shafiei-Tehrany N, 2007 On the coupling between standing-wave thermoacoustic engine and piezoelectric transducer *ASME International Mechanical Engineering Congress & Exposition. (Seattle, WA) ASME paper IMECE2007-41119*
- [3] Swift GW 2002 *Thermoacoustics: A Unifying Perspective for Some Engines and Refrigerators (Sewickley, PA, Acoustical Society of America)*
- [4] Rayleigh JWS 1945 *The Theory of Sound (New York, Dover Publications)*
- [5] Shafiei-Tehrany N, Lin CS, Ahn J, Matveev KI 2008 Development of combustion-driven small thermoacoustic engine *Spring Meeting of the Western States Section (Los Angeles, CA, The Combustion Institute)*
- [6] Adeff JA, Hofler TJ, Atchley AA 1998 Measurements with reticulated vitreous carbon stacks in thermoacoustic prime movers and refrigerators *Journal of the Acoustical Society of America* **104** 32-38
- [7] Garrett SL 2005 *Acoustic Laser Kit Instructions (Penn State)*
- [8] Swift GW 1988 Thermoacoustic engines *Journal of the Acoustical Society of America* **84** 1145-1180