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A two-stage traveling-wave thermoacoustic electric generator with loudspeakers as alternators

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HIGHLIGHTS

- A two-stage traveling wave thermoacoustic generator is introduced.
- Two audio loudspeakers have been used as linear alternators.
- A high electric power output of 204 W has been achieved.
- A thermal-to-electric efficiency of 3.43% has been achieved.

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ABSTRACT

This paper presents the design, construction and tests of a traveling-wave thermoacoustic electric generator. A two-stage traveling-wave thermoacoustic engine converts thermal energy to acoustic power. Two low-impedance linear alternators (i.e., audio loudspeakers) were installed to extract and convert the engine's acoustic power to electricity. The coupling mechanism between the thermoacoustic engine and alternators has been systematically studied numerically and experimentally, hence the optimal locations for installing the linear alternators were identified to maximize the electric power output and/or the thermal-to-electric conversion efficiency. A ball valve was used in the loop to partly correct the acoustic field that was altered by manufacturing errors. A prototype was built based on this new concept, which used pressurized helium at 1.8 MPa as the working gas and operated at a frequency of about 171 Hz. In the experiment, a maximum electric power of 204 W when the hot end temperature of the two regenerators reaches 512 °C and 452 °C, respectively. A maximum thermal-to-electric efficiency of 3.43% was achieved when the hot end temperature of the two regenerators reaches 597 °C and 511 °C, respectively. The research results presented in this paper demonstrate that multi-stage traveling-wave thermoacoustic electricity generator has a great potential for developing inexpensive electric generators.

1. Introduction

Due to the concerns about the depletion of fossil fuels and global warming, the utilization of low temperature heat sources, such as industrial waste heat sources and solar energy, has drawn enormous attention. Different technologies have been developed for energy recovery application at different scales. Several advanced thermodynamic cycles such as the Stirling cycle, Organic Rankine cycle, Kalina cycle, Uehara cycle, and triangle cycle have also been developed in order to generate power from relatively low temperature heat sources. Organic Rankine cycle (ORC) systems that use organic fluid with a low boiling point as the working medium and a turbine as expander have demonstrated a great potential to generate power from waste heat sources at medium and large scale (i.e. 10 kW to several MW). There are also research efforts to develop small-scale ORC systems to generate around 1 kW to meet the energy demand of households, which has not been very successful so far due to the lack of suitable expanders.

Stirling engine is considered as a promising technology for generating power from waste heat source or solar energy at a relatively small scale. However, conventional Stirling engines usually rely on the clearance sealing at high temperature, and thus require high manufacturing costs. Travelling-wave thermoacoustic engine is essentially the acoustic equivalent of the conventional Stirling engine. It uses a compact acoustic network to obtain the proper time phasing within a regenerator to achieve a Stirling-like thermodynamic cycle to convert the thermal energy to acoustic energy.

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A thermoacoustic engine usually consists of several simple parts such as an acoustic resonator, heat exchangers, and a section of porous materials called a regenerator, and thus eliminates mechanical moving components. Therefore, thermoacoustic engines are simple, reliable, and almost free of maintenance [1–8]. However, they also have some drawbacks. Their power density is relatively low as they usually require a large size acoustic resonator. Their efficiency is lower than the conventional Stirling engine or internal combustion engines.

Due to the aforementioned unique features, traveling-wave thermoacoustic engines have attracted a lot of attention in the past decades. Various prototypes based on different concepts have been constructed, tested and reported [1–4]. So far, the most efficient traveling-wave thermoacoustic engine [1] delivered 710 W to its resonator with an efficiency of 0.30 which corresponds to 41% of the Carnot efficiency, when the hot end temperature of regenerator reaches 725 °C. Additionally, it uses 30-bar helium as working gas and the frequency of is 80 Hz. It has a quarter wave-length acoustical resonator that is around 4 m in length.

Linear alternators with flexure bearings and clearance seals can be used to convert thermoacoustic engine acoustic power to electricity, which can achieve a transduction efficiency up to 90% [9,10]. A thermoacoustic generator combines the advantages of a thermoacoustic engine and a linear alternator to generate electricity from low temperature heat sources with high efficiency and high reliability. There have been continuous research efforts to develop traveling-wave thermoacoustic electric generator in the past decade [11–17]. However, the linear alternators are costly, which counteracts the advantages of thermoacoustic engines such as simplicity and low cost. To pave the way for a possible commercialization, the thermoacoustic electric generator based on linear alternator will be in head-to-head competition with the generators based on conventional Stirling engines which have been on the market for a while. Hence, there is a need to develop inexpensive linear alternators to facilitate the development of inexpensive and reliable thermoacoustic generators to meet the fast growing waste heat recovery market. To meet these challenges, research efforts have been made to develop inexpensive linear alternators using conventional audio loudspeaker technologies [3,18].

The audio loudspeakers usually have low acoustic impedance when they are coupled to thermoacoustic engines, which bring new design challenges and considerations. Yu et al. systematically investigated these issues theoretically and experimentally [3]. A low-cost thermoacoustic electric generator prototype was developed by placing an audio loudspeaker in the looped-tube traveling-wave thermoacoustic engine as an alternator [3,18]. Phase tuning techniques (i.e. tuning stub and phase shifter) were developed to correct the acoustic field after the alternator was introduced to the engine. The inexpensive prototype generator using atmospheric air as working gas and a six-inch B&C subwoofer as alternator, produced 11.6 W of electrical power. This shows the potential for developing inexpensive electricity generators for energy recovery from waste heat sources based on thermoacoustic technology. Later, a combustion driven prototype was also developed to fully demonstrate the development of low cost thermoacoustic electricity generators for rural communities that are off the national grid [20,21]. Chen et al. [22] also reported their development of low cost two-stage traveling-wave thermoacoustic generators to generate electricity from waste heat energy of cooking stoves. The propane stove driven thermoacoustic generator produced approximately 15 W of electricity using an audio loudspeaker as the alternator. A wood-burning stove powered thermoacoustic generator was constructed and tested, which generated 22.7 W of electricity [23].

This research continues the effort on the development of inexpensive thermoacoustic electric generators. In order to improve the power density, two stage engines and two alternators are designed in one loop. The modeling and simulation of the system, together with the experimental results, are presented and discussed in this paper. The goal of this research is to further demonstrate the potential of low cost thermoacoustic generator, and ultimately push forward the development of inexpensive thermoacoustic generators.

2. Selecting a loudspeaker as alternator

The modeling and analysis for using loudspeakers as linear alternators have been described and presented in detail in Ref. [19]. The loudspeaker can be simplified and schematically represented by the elements as shown in Fig. 1 of Ref. [19]. The diaphragm has an area of S. The total moving mass is M_m. The stiffness of the suspension system is K_m. The mechanical resistance is R_m. The coil has an inductance L_e and resistance R_e. The force factor is Bl, and the electric load has a resistance R_L. The electrical power extracted by the load resistor can be written as [19],

$$P_e = \frac{1}{2}\frac{|U_1|^2}{S^2}\frac{(Bl)^2 R_L}{(R_e + R_L)^2}. \tag{1}$$

Electric power output reaches the maximum when $R_L = R_e$,

$$P_{e,\max} = \frac{1}{8}|U_1|^2\frac{(Bl)^2}{S^2 R_e} = \frac{1}{8}|U_1|^2\frac{(Bl)^2}{S^2 R_L}. \tag{2}$$

Eq. (2) can estimate the maximum electric output of a given alternator, and therefore is a performance indicator for selecting a suitable loudspeaker as the alternator. According to Eq. (2), the maximum electric power output is proportional to $|U_1|^2$ and $(Bl)^2/S^2R_L$. The volumetric velocity U_1 is determined by the engine parameters and operating conditions, and is limited to certain value for a given engine. $(Bl)^2/S^2R_e$ (or $(Bl)^2/S^2R_L$) is the acoustic impedance of the loudspeaker. It can be found that this acoustic impedance should be increased to increase the electric power

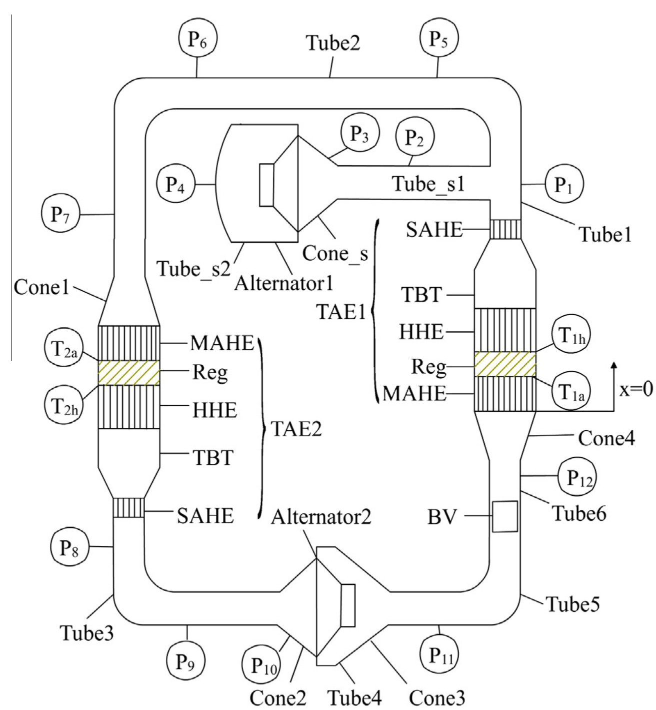

Fig. 1. Schematic of the two-stage thermoacoustic generator prototype.