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Compact standing wave thermoacoustic generator for power conversion applications

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ABSTRACT

In the past decade, a variety of thermoacoustic engines (TAEs) were devised to convert thermal energy to acoustic power. In this paper, we optimized the design of a standing wave thermoacoustic generator that can provide high intensity acoustic pressure and convert it into electrical power output using a low cost alternator. Three prototypes of standing wave thermoacoustic generator (TAG) were designed to optimize the overall efficiency. The first prototype of standing wave TAG could produce an acoustic pressure of 0.9 kPa (153 dB) with an input thermal power of 210 W. Further, the maximum heat to electrical conversion efficiency was 0.045% with an input thermal power of 250 W. However, the performance of this system was not fully optimized. The performance of TAE depends upon various parameters including stack position, stack length and resonator length. Hence, a new second prototype of tunable TAG was developed to tune these critical parameters in order to improve the overall efficiency. A compact third prototype of TAG was successfully built with optimized parameters and has been tested. In the improved design, high intensity acoustic pressure of 2.9 kPa (163.5 dB) was observed for the same 210 W input thermal power. The maximum heat to electrical energy conversion efficiency was 0.084% with an input of 250 W which is 87% higher as compared to the first prototype. The major reason for the lower conversion efficiency is due to the low efficiency of the alternator. In future, high efficiency alternator designs can be employed along with careful impedance matching to obtain higher conversion efficiencies. The results described in this paper demonstrate the potential of developing compact portable acoustic power and electricity generators for decentralized power applications.

1. Introduction

Thermoacoustic devices deal with the phenomenon of conversion between heat energy and acoustic power. For many years, heat and sound were believed to be two entirely different energy forms not related to each other [1] until Higgins [2] in 1777 recorded the first observations of heat-driven oscillations. He observed that in an open glass tube, acoustic oscillations were excited by suitable placement of a hydrogen flame. Later, Rijke [3] performed similar but more illustrative experiments by placing a heater in a cylindrical tube open at both ends. Continuous supply of heat resulted in high intensity acoustic oscillations. He observed that the maximum amplitude for these oscillations occur when the heater was located at one fourth of tube's length from the bottom. Sondhauss [4,5] started to investigate the observations by Higgins in 1850 and concluded that acoustic frequency and intensity depends on the length and volume of the bulb. The first qualitative explanation for heat-driven oscillations was given in 1887 by Lord Rayleigh [6].

From the understanding of the theory of thermoacoustics, investigation of thermoacoustic devices had begun at Los Alamos National Laboratory (LANL) in 1980 [7]. Wheatley, Swift, and Hofler were the pioneers in designing and testing of various laboratory prototypes of thermoacoustic engines [7–9]. A standing wave engine was constructed and characterized by Swift et al. [7,8].

Rapid advancement in the field of thermoacoustics occurred only during the last two decades [9]. According to the characteristics of the sound waves (pressure oscillations) produced in these engines, they can be categorized into two types: standing wave and traveling wave engines. For the standing wave devices, the phase difference between the pressure and velocity oscillations is close to 90° within the thermoacoustic stack assembly, while for

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traveling-wave engines, the phase difference is close to zero [10]. With a suitably designed transducer such as a linear alternator, the acoustic energy can be converted into electrical energy [1]. Thermoacoustic engine coupled with such an alternator is commonly referred to as a thermoacoustic generator (TAG). Several prototypes of standing-wave TAEs of different sizes and configurations were created by various researchers during this period [11–15]. Standing wave generators though easy to build and compact are not as efficient as traveling wave based designs [7]. The reason for standing wave generators to be much less efficient is due to the phase difference between working gas pressure and velocity [9]. The expression for the average acoustic power as a function of the working gas pressure (p) and velocity (U) is given as:

$$\dot{E}_{st} = 1/2|p||U|cos(\varphi_{pU}) \quad (1)$$

From the above expression, it can be concluded that there will be no power generation at 90° phase difference. Some earlier attempts also show that the system was not able to self-oscillate due to significant mechanical losses present in the system [16]. However, there were several attempts aimed at developing miniature thermoacoustic engines [11] using piezoelectric generators. Nouh et al. [12] used the harvester with a dynamic magnifier to magnify the electric energy harnessed from the piezo membranes. The efficiency of energy conversion using the dynamically magnified thermoacoustic-piezo system was almost doubled for short length resonators. Matveev [13] reported that thermoacoustic engines integrated with piezoelectric elements can be an effective small-scale power sources to convert heat to electricity. A simplified mathematical model is developed and results of sample calculations showed that the efficiencies for the acoustic-electric energy conversion on the order of 10% are feasible. Castrejón-Pita and Huelsz [14] proposed a design for conversion of heat to electricity. He used thermoacoustic prime mover coupled to a magneto hydrodynamic generator. Smoker et al. [15] reported a one-dimensional thermoacoustic-piezoelectric (TAP) resonator to convert thermal energy directly into electrical energy. An acoustic to electric energy conversion efficiency of 9.7% was reported in the paper. In general, designs using piezoelectric generators are less efficient due to low acoustic to electrical conversion efficiencies. Various traveling wave design based TAGs have been reported in literature which can convert thermal power into electricity at high efficiencies [10]. Currently, research is also being focussed toward incorporating the thermoacoustic engines with cooking stoves to utilize the waste heat for electricity generation [17].

This work presents the successful design, fabrication and characterization of a standing wave thermoacoustic generator. The first prototype of TAG was able to convert heat into electricity with a conversion efficiency of 0.045%. Detailed performance analysis was carried out by measuring the acoustic pressure, frequency, voltage, power etc. The second prototype, a tunable TAE was developed to study the effects of various parameters namely stack position, stack length and resonator length on the performance of TAE and to optimize the performance. The performance here was measured in terms of the pressure amplitude generated inside the TAE and the optimum values of the parameters for improved performance were obtained. The third prototype of standing wave TAG was built with the optimized parameters which gave higher efficiency as compared to the first prototype.

2. Standing wave thermoacoustic generator design

Standing wave engines have a very simple linear configuration but relatively low efficiencies [7]. This device can operate with a variety of heat sources, including solar energy, waste heat and combustion of conventional and non-conventional fuels. Scaling down thermoacoustic systems is challenging due to an enlarged role of thermal management, fabrication and manufacturing issues. Other technical challenges include integration of these devices with various heat sources and alternators.

2.1. Design and construction of TAE

A typical TAE consists of a stack sandwiched between two heat exchangers, placed inside a resonator tube. The stack is the porous medium where the fluid undergoes a thermoacoustic cycle. The temperature gradient across the stack results in the amplification of pressure disturbances in the working gas and sound is generated once the acoustic driving exceeds acoustic damping in the engine. At resonance, pressure antinodes are formed at the closed end of the resonance tube. Hence, by positioning the stack near the closed end of the resonator, we can ensure that gas parcels within the pores of the stack experience large acoustic pressure oscillations [18]. However, since large acoustic displacement is also required for the extraction of acoustic power [18,19], the stack should be positioned optimally to ensure high thermal energy to acoustic conversion efficiency. The exact physical mechanism for sound generation can be understood by considering a gas in the vicinity of the walls inside the tube. When the gas is subjected to a sound wave, it experiences cyclic compressions and expansions, and simultaneously, gas parcels move from the hot side to the cold side of the engine [20,21]. Hence, heat is given to the oscillating gas during compression and is removed from the gas during expansion over the course of the cycle. This energy imbalance results in an increase of the pressure amplitude from one cycle to the next, until the acoustic dissipation of the sound energy equals the addition of heat to the system [20,21]. The acoustic power generated by the TAEs can be converted to electricity through a linear alternator [8]. The energy conversion efficiency of TAGs remains relatively lower than conventional engines. Nevertheless, the primary advantage of the thermoacoustic technology is the absence of moving parts in most of the engines conceived till date.

2.2. Design and construction of different components of TAG

2.2.1. Stack

Stack (Fig. 1) is the porous medium that produces acoustic pressure using a thermal gradient. Stack should have high thermal capacity and low thermal conductivity compared to the working fluid. The design and position of the stack have to be optimized in order to achieve high efficiency for the system. Corning® celcore® catalytic substrate with square cross sectioned pores was used as stack for the experiments. The material is extremely brittle and requires careful handling while shaping the stack.

2.2.2. Heat exchangers

Heat exchangers are one of the critical components of any thermoacoustic system. Heat input and output from the device

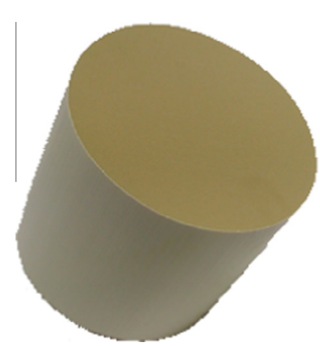

Fig. 1. Circular shaped stack used for the experiments.