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An acoustically matched traveling-wave thermoacoustic generator achieving 750 W electric power

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ABSTRACT

TWTEG (traveling-wave thermoacoustic electric generator) is promising in efficiently converting the heat of fuel combustion, solar energy, industrial waste heat, etc. into electricity with a very scalable power output. Based on the decoupling method and theoretical analysis, the acoustic impedance requirements of the TWTE (traveling-wave thermoacoustic engine) and LAs (linear alternators) to reach an efficient and powerful operation state were studied quantitatively. A 1 kW level traveling-wave thermoacoustic electric generator was then built for experimental study. Good matching conditions of acoustic impedances were then experimentally demonstrated by modulating the working frequency, load resistance, and electric reactance of the thermoacoustic electric generator, which agreed well with the theoretical analysis. A maximum electric power output of 750.4 W and a highest thermal-to-electric efficiency of 0.163 have been achieved by the acoustically matched thermoacoustic electric generator with helium of 3.16 MPa as the working gas. This work would be instructive for the acoustic matching and designs of high-performance thermoacoustic electric generation systems.

1. Introduction

The continuous exhaustion of conventional energy resources and their environmental impacts have intrigued an increasing interest in the utilization of solar energy and thermal energy existing in industrial waste throughout the world. Various types of energy harvesting technologies and devices have been developed in the past decades, such as those based on photovoltaic effect [1], thermomagnetic effect [2], piezoelectric effect [3], and thermoelectric effect [4] etc. Thermoacoustic effect, which was first theoretically explained by Rayleigh [5] in 1878 and later efficiently utilized to convert thermal energy into acoustic power by Swift et al., in 1999 [6], is among the most attractive and promising energy conversion phenomena.

When oscillating gas is exposed to a large temperature gradient along a porous medium, thermal energy can be converted into acoustic power through thermoacoustic effect. The appropriate acoustic field for energy conversion is typically formed by a resonant acoustic network system simply consisting of acoustic pipes. Due to the unique features of simple structure, high reliability, and intrinsically high efficiency, dozens of thermoacoustic energy conversion systems [7–15] have been manufactured in recent years. For practical applications, the acoustic power generated by TEs (thermoacoustic engines) has to be converted into electricity via acoustoelectric converters, such as LAs (linear alternators) [16–20], loudspeakers [13,21], piezoelectric transducers [22], magnetohydrodynamic generator [23], and ferrite core coil with variable inductance [24], etc. The power outputs of the latter four thermoacoustic electric generation systems are typically in the range from several milliwatts to tens of watts, and may supply electricity for low-power electrical elements. TWTEGs (traveling-wave thermoacoustic electric generators), which are composed of a TWTE (traveling-wave thermoacoustic engine) and LAs, are very promising in higher power solar energy exploitation, waste heat recovery, and combined heat and power systems, etc. For the potential to achieve large power output and high efficiency simultaneously, TWTE has attracted considerable attention recently [16–20]. The first TWTEG was developed by Backhaus et al. for electricity generation aboard spacecraft in 2004 [25,26]. It was

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capable of providing an electric power of 39 W. Similar systems were later built by Sunpower [27] and Wang et al. [20]. Wu et al. built several TWTEGs with various configurations recently, including a TWTEG with a resonator [17,28], a TWTEG with double-acting alternators [18], and a TWTEG with resonant tubes [29]. The power outputs ranged from hundred watts to kilowatts, showing a good application prospective.

In the small-scale TWTEG developed by Backhaus et al., the long gas resonator, which acts as an acoustic inertance for the acoustically capacitive thermoacoustic torus in a TWTE, was totally replaced by a pair of LAs [25,26]. LAs were thus operated at an inertance state, i.e. a phase difference between pressure and velocity of around 80°~90°. To meet the requirement of the large volume flow rate out of thermoacoustic torus, the piston diameters of LAs were designed to reach a large swept volume of 21 cm^3, which is comparable to the size of the torus. However, it would be a big challenge for LAs to be individually coupled with a traveling-wave thermoacoustic torus with an output capacity of ~kilo watts, due to the conflict between the large volume flow rate required and the limited swept volume of LAs. For example, the peak volume flow rate of TWTE built by Backhaus and Swift [6] is as high as 0.3 m^3/s, which is far beyond the limits of most available LAs. Gas resonator, which is usually a long inertance tube together with a reservoir in a TWTE, is capable of providing a stable standing-wave acoustic field with a large volume flow rate at almost a constant frequency. Therefore, it is more feasible to couple LAs together with a gas resonator to a thermoacoustic torus so as to bypass the large volume flow without pushing LAs out of the limit in larger scale systems. Up to now, several TWTEGs of this type have been built and studied. In 2011, a TWTEG with a maximum electric power of 481.0 W and a highest thermal-to-electric efficiency of 15.03% was reported by Luo et al. [17]. Later, they built a prototype of 1 kW TWTEG [28]. In the experiments, 4.5% argon–helium mixture at 4.0 MPa was used as the working gas. However, the achieved acoustic impedance of the LA did not meet the requirements for the efficient operation of the TWTE. The effects of some important parameters, such as electric load resistance and electric capacitance, on the acoustic matching were not studied yet.

In a power circuit, the impedance of an electric load should be matched to the circuit to get optimal power output and high efficiency simultaneously. Similar to the electric load in the power circuit, LAs and the gas resonator are two acoustic loads to the thermoacoustic torus—the acoustic power source. Therefore, the characteristics of the acoustic impedances of them are very important to electric power generation and the control of acoustic power dissipations. For example, a real gas resonator always has an unavoidable resistance impedance apart from the dominant inertance one, and will cause considerable acoustic power losses if the acoustic impedance distribution between the gas resonator and the LA is not designed elaborately. However, the acoustic coupling mechanism between LAs and TEs and the effective approaches to acoustically match them have not yet been clearly addressed from the perspective of acoustic impedance in previous studies. Large space is still left for further improving the performance of TWTEGs. In 2012, we experimentally studied the effects of acoustic transfer line, electric loads and resonance characteristics of a TWTEG [16,30]. By making the system both electrical and mechanical

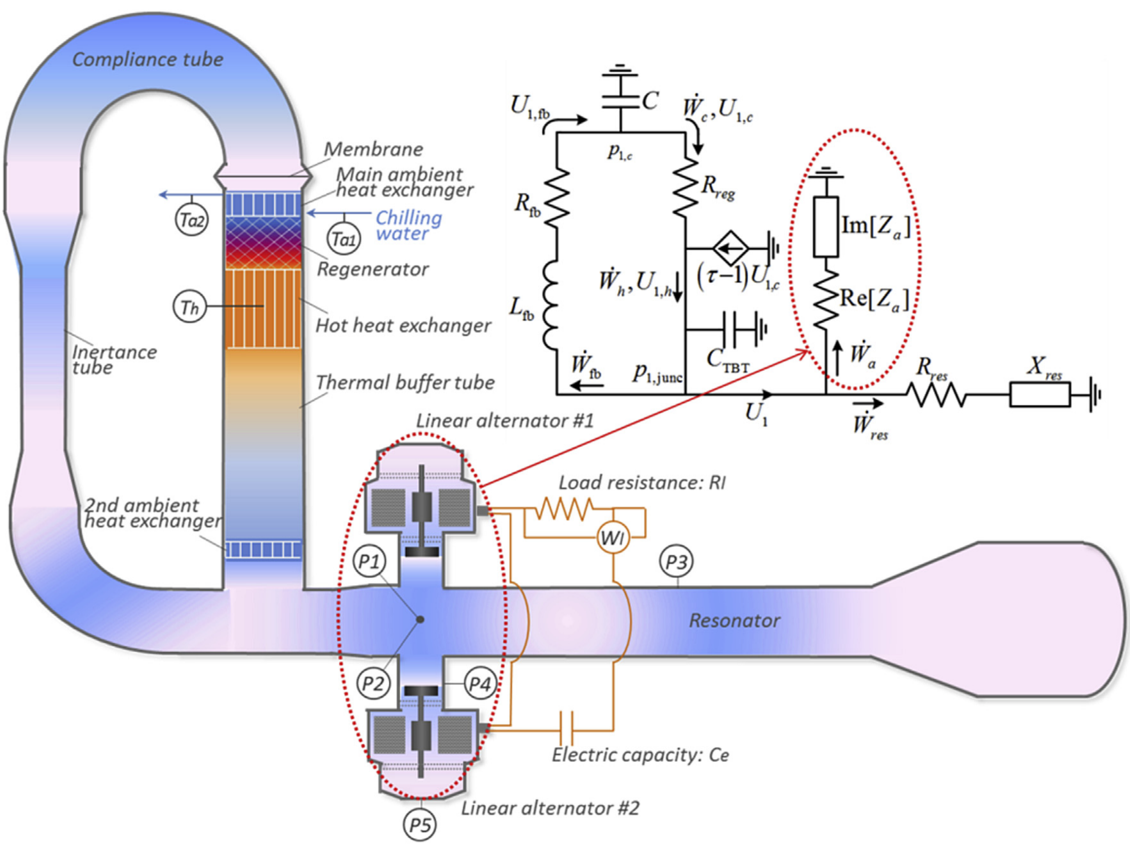

Fig. 1. Schematic diagram of traveling-wave thermoacoustic electric generator and the equivalent electric circuit network. *P1* denotes the location of a piezoresistive pressure sensor, and *P2–P5* denote that of piezoelectric pressure sensors. Heating temperature T_h, temperatures of the inlet T_{a1} and outlet T_{a2} of chilling water were measured by K-type thermocouples. The coils of the linear alternators are connected in series with a variable electric R-C load to extract electric power. Electric power W_l was measured by a power meter.