Letter

Chinese Science Bulletin

Energy Science & Technology

July 2011 Vol.56 No.19: 1975–1977
doi: 10.1007/s11434-011-4504-1

Experimental investigation of a 500 W traveling-wave thermoacoustic electricity generator

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Received January 21, 2011; accepted April 6, 2011

In this paper, an experimental investigation of a traveling-wave thermoacoustic electricity generator, which consists of a traveling-wave thermoacoustic heat engine and a linear alternator driven by that engine, is presented. Using the results of previous theoretical and experimental research, we designed and fabricated a traveling-wave thermoacoustic heat engine and a linear alternator. In the experiments, 450.9 W of electrical power was obtained with a maximum thermal-to-electrical efficiency of 15.03%, and a maximum electrical power of 481.0 W was achieved with 12.65% thermal-to-electrical efficiency.

traveling-wave thermoacoustic heat engine, linear alternator, thermal-to-electrical conversion

Citation: Wu Z H, Man M, Luo E C, et al. Experimental investigation of a 500 W traveling-wave thermoacoustic electricity generator. Chinese Sci Bull, 2011, 56: 1975–1977, doi: 10.1007/s11434-011-4504-1

Currently, because of the severe energy and environmental problems in the world, searching for new technologies of the renewable energy utilization has become a hot topic for scientific research. Solar energy utilization technologies, especially solar-powered electricity generation technologies, are very important for the renewable energy sciences. Solar-powered thermal-to-electric generation technologies are feasible power generation ways. The traveling-wave thermoacoustic electricity generation system introduced in this paper is a novel device which consists of a traveling-wave thermoacoustic heat engine (TWTAHE) and a linear alternator (LA). In this system, the TWTAHE is based on the Stirling thermodynamic cycle and can convert heat into acoustic work (i.e. mechanical work) with a high intrinsic efficiency. The LA is capable of converting the acoustic power into electrical power. In addition to its high conversion efficiency in comparison with other thermal-to-electrical technologies, the traveling-wave thermoacoustic electricity generator (TWTAEG) greatly improves the reliability and reduces the difficulty and costs of fabrication and maintenance in terms of eliminating the moving parts within the hot end of the device.

At its core, the traveling-wave thermoacoustic electricity generation system consists of a TWTAHE and a LA, which can perform thermal-to-acoustic and acoustic-to-electrical energy transformation processes. The TWTAHE has been studied and developed over the last 40 years [1], but the acoustic power output of the engine was relatively low until at the end of the last century. In 1999, Backhaus and Swift from Los Alamos National Laboratory developed a TWTAHE with a 560 W net output acoustic power and 23.7% net output efficiency (the thermoacoustic efficiency of the engine could be as high as 30% if the acoustic power dissipated in the resonance tube was included) [2]. In 2005, to reduce the large power dissipation in the conventional straight resonance tube, especially for large pressure wave amplitudes, our group proposed an energy-focused TWTAHE with a tapered resonance tube. In the experiments, a 451 W net acoustic power with 15.3% net thermoacoustic efficiency was obtained [3]. After further improvements in the resonance tube (the engine loop was left unchanged), a maximum net thermoacoustic efficiency of

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26.5% (31.8% including the dissipated power in the resonance tube) with 710 W net output acoustic power, and a maximum net output acoustic power of 810 W with 22.7% net thermoacoustic efficiency were achieved [4].

Because the output power and efficiency of the engine have been increased, this presents the possibility for applications in energy conversion. Research on thermoacoustic power generation technology is the first step. In 2004, a TWTAEG, which directly coupled the LA with the TWTAHE loop without a resonance tube, was first developed at Los Alamos National Laboratory. Their experiments yielded electrical powers of 39 W and 58 W at 18% and 15% thermal-to-electrical efficiencies [5]. In 2007, our group used a resonance tube in a TWTAEG system and experimentally achieved an electric power of 100 W [6]. However, the thermal-to-electrical efficiency was less than 4% because of the mismatch between the engine and the LA.

To increase the output electrical power and efficiency and identify the coupling law between the TWTAHE and the LA, we studied the acoustic power output characteristics of the engine as a function of the load impedance and found the proper matching impedance for the engine. Moreover, we developed a new design for the LA to realize this impedance. Using this design, new TWTAHE and LA systems were designed and fabricated.

Figure 1 shows a schematic diagram of the TWTAEG, which includes a TWTAHE loop, a resonance tube and a LA. The thermoacoustic Stirling heat engine loop is about 1.86-m long with a 100 mm inner diameter. It consists of a 1345 mm-long feedback tube, a 50 mm long main ambient heat exchanger, an 80 mm long regenerator filled with 150 mesh stainless steel screens, a 60 mm long heater block containing 12 heat cartridges inserted in, a 240 mm long thermal buffer tube and a 20 mm long secondary ambient heat exchanger. All ambient heat exchangers are cooled using 25°C water. Thermocouples were installed in the heater block and the two ambient heat exchangers to monitor the temperature. Because of the limitations in material strength, the temperature is kept below 650°C. The hot part of the engine, including the regenerator, heater block and thermal buffer tube are covered by thermal insulation materials to reduce the thermal losses. This covering is not shown in Figure 1. The resonance tube is 5.3 m long tube, which consists of a tapered region where the inner diameter gradually changes from 100 to 250 mm and a 1 m long 250 mm inner diameter straight tube with a capped end (partially shown in Figure 1). A power meter was used to measure the heating power of the heat cartridges in the heater block.

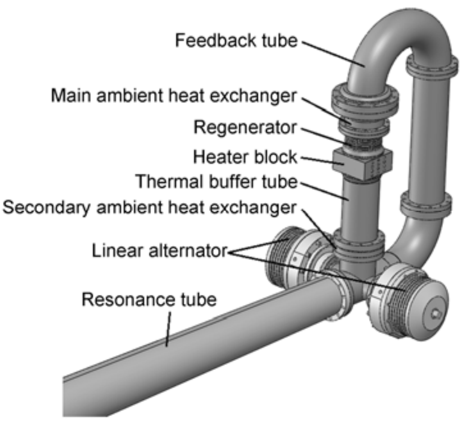

Figure 1 Schematic of the TWTAEG.

To reduce system vibration, the LA uses a dual-opposing motor configuration. The diameter of the two pistons is 60 mm. The main electrical and mechanical parameters of two motors are as follows: 102.2 and 101.3 N/A nominal BL products; 171.0 and 172.4 N/mm mechanical spring stiffnesses (the gas spring stiffness of the motor buffer spaces is not included); 0.93 and 0.94 kg moving masses; 15 N s/m mechanical damping coefficient; 3.73 and 3.72 Ohm winding resistances; and 263.7 and 267.7 mH winding inductances. In the experiments, a rheostat supplied the load resistance for the LA. The voltage and current waves of the rheostat were measured using high-precision voltage and current probes. Meanwhile, high-precision dynamic pressure sensors were installed at the T pipe of the engine loop and at the back space of the motor to monitor the LA during operation.

Figures 2 and 3 show the output electrical power and efficiency for different load resistances as a function of the heating temperature. The output electrical power can be calculated using the measured voltage and current of the rheostat. The efficiencies, including the thermal-to-electrical efficiency, the acoustic-to-electrical efficiency and the thermoacoustic efficiency, are defined as

$$\eta_{\mathrm{te}} = W_{\mathrm{e}}/Q, \tag{1}$$

$$\eta_{\mathrm{ae}} = W_{\mathrm{e}}/W_{\mathrm{a}}, \tag{2}$$

$$\eta_{\mathrm{ta}} = W_{\mathrm{a}}/Q, \tag{3}$$

where W_{e} and W_{a} represent the electrical power and acoustic power, Q represents the heating power. From Figures 2 and 3, it can be seen that an electrical power of 450.9 W was achieved with a maximum thermal-to-electrical efficiency of 15.03%, and a maximum electrical power of 481.0 W was obtained with 12.65% thermal-to-electrical efficiency. The working fluid was 3.54 MPa pressurized helium and the working frequency was 74 Hz.

From Figures 2 and 3, it can be seen that the output elec trical power, the thermal-to-electrical efficiency and theth-ermoacoustic efficiency increase as the heating tempera ture increases. Moreover, a higher output electrical power can be obtained at a smaller load resistance (see Figure 2) when the heating temperature is less than 620°C. However, a greater load resistance yields higher thermal-to-electrical and thermoacoustic efficiencies (see Figure 3). The main reason for this is that the pressure amplitude of the LA and the engine increase when the load resistance of the LA decreases

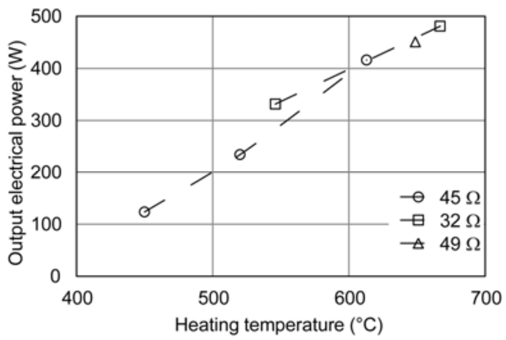

Figure 2 Output electrical power for different load resistances as a function of heating temperature.

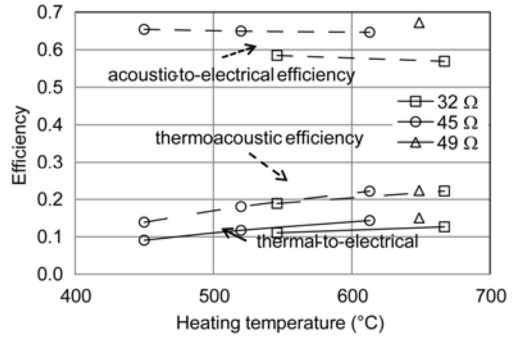

Figure 3 Efficiencies for different load resistances as a function of heating temperature.

for a given heating temperature (see Figure 4). A small increase in the pressure amplitude can result in high losses in the engine because of the strong nonlinear relationship between them. Therefore, there is a trade-off between the maximum output electrical power and maximum thermal-to-electrical efficiency when choosing the load resistance.

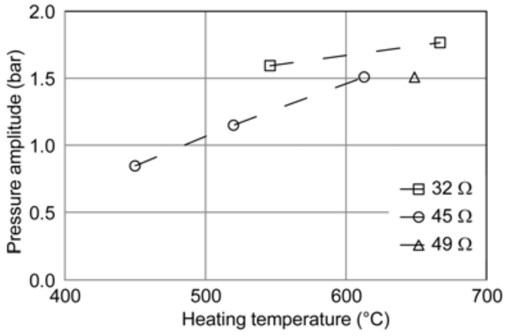

Figure 4 Pressure amplitude for different load resistances as a function of heating temperature.

In our experiments, we determined the resistance value by keeping the pressure amplitude of the LA at about 5.5% of the mean pressure to balance the output acoustic work with the conversion efficiency of the engine.

Also, it can be seen in Figure 3 that the acoustic-to-electrical efficiency slightly decreases as the heating temperature increases for a given resistance. The main reason for this is that the piston velocity increases as the heating temperature increases, which results in greater losses in the motor because of the nonlinear mechanical damping coefficient between the piston and the cylinder wall.

In this paper, a TWTAEG was built and experimentally investigated to identify the coupling law between the TWTAHE and the LA. In our experiments, an electrical power of 450.9 W was achieved with a maximum thermal-to-electrical efficiency of 15.03%, and a maximum electrical power of 481.0 W was obtained with 12.65% thermal-to-electrical efficiency. The output electrical power and thermal-to-electrical efficiency present a possibility for applications. However, because of the limited thermoacoustic efficiency achieved in the experiments, we believe that the coupling mechanism between the TWTAHE and the LA still needs further investigation. However, a large percentage of the acoustic work was dissipated in the resonance tube. This loss could be reduced by finding more efficient coupling methods in the future. Moreover, the acoustic-to-electrical efficiency of the LA can be improved by reducing the mechanical damping coefficient.

This work was supported by the National Basic Research Program of China (2010CB227303) and the National Natural Sciences Foundation of China (50707034). The authors would like to make a special acknowledgment of all the members of the Lihan Company for their technical support on this project.

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