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Thermodynamic measurement and analysis of dual-temperature thermoacoustic oscillations for energy harvesting application

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ABSTRACT

The present work considers energy harvesting by implementing both thermo- and piezo-electric power generation modules on a bifurcating tube, which produces dual-temperature thermoacoustic oscillations. The present system distinguished from the conventional standing-wave one does not involve heat exchangers and uses two different energy conversion processes to produce electricity. To measure and analyze the sound waves generated, an infrared thermal imaging camera, hot wire anemometry, and two arrays of K-type thermocouples and microphones are employed. It is found that the total electric power is approximately 5.71 mW, of which the piezo module produces about 0.21 mW. It is about 61% more than that generated by a similar conduction-driven thermo-acoustic-piezo harvester. In order to gain insight on the heat-driven acoustic oscillations and to simulate the experiment, thermodynamic laws are used to develop a nonlinear thermoacoustic model. Comparison is then made between the numerical and experimental results. Good agreement is obtained in terms of frequency and sound pressure level. Finally, Rayleigh index is examined to characterize the conversion between thermal and sound energy. In addition, energy redistribution between different thermoacoustic modes is estimated. It is found that lower frequency thermoacoustic oscillations are easier to trigger.

1. Introduction

Fossil fuel exhaustion and greenhouse gas emission are increasingly urgent issues. However, waste heat generated by burning fossil fuel is released to the atmosphere in industry, which is harmful to the environment and energy wasting. To recover waste heat, there is a need for energy conversion techniques. Thermoacoustics [1–6] is a research field which deals with the conversion from thermal to acoustical energy [7,8]. For refrigeration, heat should be transferred into the working gas of a thermoacoustic system during the expansion [7], and dumped from the gas during compression. A thermoacoustic heat engine (also known as prime mover) operates on a thermodynamic cycle in the direction opposite to that of the refrigeration cycle. Theories and models have been developed and reviewed for thermoacoustic phenomenon and devices [2,5,7].

Thermoacoustic engines are more attractive than the traditional Stirling engines [9] involving pistons, due to the fact that they lack moving parts, require little maintenance and last long. However, these engines [10,11] provide lower efficiency, little reliability, and high fabrication cost. For example, the traveling-wave engines [11] have high efficiency and high reliability, but have high fabrication costs due to the presence of regenerator and heat exchangers. The standing-wave engines are reliable, and cheaper to fabricate; but they are inefficient. Typically, a thermoacoustic engine is one of the thermofluidic oscillators in which thermodynamic oscillations are generated and sustained by external temperature differences [12] achieved by heat exchangers that play critical roles in producing such oscillations. However, implementing such heat exchangers causes not only additional energy consumption but also increased manufacturing cost.

Thermoacoustics systems involve the energy conversion from heat to sound or other form of mechanical work [13–15]. Optimization of the energy conversion process was studied by several researchers [6,15]. Various forms of input energy have been tested such as solar power [13] and concentrated laser pair [16]. A miniature thermoacoustic engines were developed [17]. Recently, a thermo-acoustic-piezo system was designed and tested to achieve energy conversion from heat-to-sound-to-electricity [18]. It was shown that the output power was very low (approximately 0.128 mW) and two heat exchangers were used.

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In this work, a thermal energy harvesting system is designed and experimentally tested. For this, a cylindrical tube splitting into two bifurcating daughter branches is designed. As a heat source is placed inside the mother tube, it provides a mechanism to produce both 'hot' and 'cold' thermoacoustic oscillations (also known as Rijke–Zhao oscillations). To achieve energy harvesting in the Y-shaped tube, a piezoelectric diaphragm is implemented to the bifurcating branch with 'cold' oscillations. And a thermoelectric power generation module is attached to the end of the other bifurcating branch with 'hot' oscillations. The experimental setup is described in Section 2. Thermodynamic measurements are then conducted. This involves measuring the temperature and monitoring the sound fields, as described in Sect. 3.1. The performances of the piezo- and thermoelectric modules are then measure and compared, as described in Section 3.2. Finally, in Section 4, thermodynamic laws are used to develop a nonlinear thermoacoustic model to gain insight on the heat-to-sound energy conversion and to simulate the experiment. Comparison is then made between the numerical and experimental results. In addition, Rayleigh index and sound energy redistribution are examined to characterize the energy conversion, and the energy redistributed between different eigenmodes.

2. Experimental setup

A non-axisymmetric bifurcating tube with a thermo- and piezoelectric diaphragm attached is designed and tested to demonstrate the possibility of harvesting thermal energy by using two different energy conversion processes, as show in Fig. 1. The angle between the bifurcating branches is 2α and $0^\circ < \alpha < 90^\circ$. As a heat source (flame or solar heater et al.) is placed inside the mother tube of length 0.3 m, it provides a mechanism to produce dual-temperature thermoacoustic oscillations [19,20]. It is worth noting that the oscillations generated in the present system are convection-driven ones, which are different from the conventional conduction-driven standing- or traveling-wave prime movers [1,7]. T-shaped junctions protruding from the bifurcating branches are designed for placing thermocouples, microphones or hot wire anemometry. Before the thermodynamic measurements are conducted, the microphones are calibrated by using a piston phone (124 dB at 250 Hz). The measurement error is about ±0.1 dB. The hot wire anemometry is calibrated by using a Pitot-static tube. The thermocouples are connected to a Pratos K-type digital thermometer (DE305) and compared with the measurement from our National Instrument PXIE4353 thermocouple module.

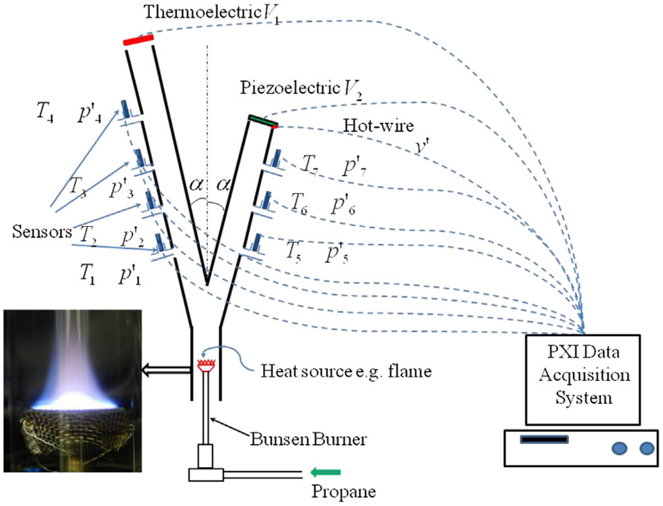

Fig. 1. Experimental setup of dual-temperature thermoacoustic system with a piezoelectric and thermoelectric power generator attached.

The thermoelectric module as shown in Fig. 2(a) and (b) is a $40(W)\times40(L)\times3.8(T)$ mm square diaphragm (GM250-127-14-16). Its technical data is shown in the top row of Table 1. The piezoelectric module is a circular diaphragm (Piezo Systems Inc. T216-A4NO-573X) made of Lead–Zirconate–Titanate, as shown in Fig. 2(c) and (d). It has thickness of 0.41 mm at resonant frequency of 290 Hz. It's technical data is shown in the bottom row of Table 1.

3. Experimental results

3.1. Thermodynamic measurements

To measure the temperature distribution in the bifurcating branches, an infrared thermal imaging camera is used. It captures the quartz tube surface temperature spectrum. However, it can characterize the 'hot' status of the oscillating flow inside each branch. The camera is set to operating range of 0 to 500 °C. Fig. 3(a) shows the measured temperature contour of the present setup in comparison with the temperature measurement of a conventional Rijke-type thermoacoustic system as shown in Fig. 3(b). It can be seen that the present system is associated with two different temperature 'exhaust' flows. The surface temperature of the upper short branch is around 26 °C, indicating that the air flow inside the branch is very close to room temperature, while the other upper branch is associated with 'hotter' air flow. However, the conventional Rijke-type system involves with only 'hot' exhaust oscillating flow, which limits the application of a piezoelectric generator due to the high temperature. Thus our present thermoacoustic system is unique in terms of producing dual-temperature oscillations, and providing a platform to apply energy harvesters with both thermoelectric and piezoelectric energy conversion processes.

To validate the temperature measurement, two arrays of K-type thermocouples are implemented on the bifurcating tube: one array with 4 thermocouples connected to the longer upper branch of length 0.9 m, the other with 3 thermocouples attached to the shorter branch of length 0.5 m. The measured temperatures are summarized in Fig. 4. It can be seen that one branch is with a 'hot' flow, while the other one is at ambient temperature. These measurements are consistent with the infrared camera measurement. The measurement difference between the infrared camera and the thermocouples is approximately ±2 °C.

The presence of the thermoacoustic oscillations can be confirmed by measuring the pressure fluctuations along the bifurcating branches, since they cause the air pressure fluctuating. For this, two arrays of microphones (B&K Type 4954) are implemented and placed side by side to the thermocouples. The measurements are shown in Fig. 5(a) and (b). It can be seen that there are intensive pressure oscillations in both bifurcating branches, and the maximum sound pressure level is about 137 dB. The dominant mode of the thermoacoustic oscillation is at around 180 Hz. And it has several harmonics (see Fig. 5(a) and (b)), which indicates the nonlinearity of the system. This frequency corresponds to the fundamental mode with a wavelength twice of the total length of the bottom stem and the upper longer branch, while a conventional Rijke-type system with total length of 0.8 m is associated with around 230 Hz oscillations, as shown in Fig. 5(c). The 'oscillating' nature of thermoacoustics in the bifurcating branches is further confirmed via direct measurement by using a HWA (hot wire anemometers) near the exit (about 0.5 cm) of the 'cold' branch, as shown in Fig. 5(d). This confirms that the present setup is a reliable system to produce dual-temperature oscillations.

It is worth noting that the angle α between the two bifurcating branches plays an important role in producing dual-temperature