Experimental investigations of the performance of a thermoacoustic electricity generator

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Abstract. This paper presents the experimental investigation of a two-stage thermoacoustic electricity generator able to convert heat at the temperature of the exhaust gases of an internal combustion into useful electricity. The novel configuration is one wavelength and consists of two identical stages. The identical stages will have out of phase acoustic wave at similar amplitudes which allows coupling a linear alternator to run in push-pull mode. The experimental set-up is 16.1 m long and runs at 54.7 Hz. The working medium is helium at 28 bar. The maximum generated electric power is 73.3 W at 5.64% thermal-to-electric efficiency. The working parameters including load resistance, mean pressure and heating power were investigated.

1 Introduction

Traveling-wave thermoacoustic energy conversion is based on the Stirling cycle. In brief, heat is converted inside the thermoacoustic core into a high amplitude acoustic wave, which is used to generate electricity by driving an electrical linear generator. Thermoacoustic core placed inside a resonator consists of a porous medium having adjacent heat source and heat sink. Thermoacoustic power generation is a vital waste heat recovery method as it is an environmental friendly technology and its applications are maintenance free. Johnson [1] highlighted Thermoacoustics as a potential technology to generate cooling power from waste heat of exhaust gases. While, Jadhao and Thombare [2] highlighted it as a direct electricity generation method from internal combustion engine exhaust gas heat recovery.

Looped-tube traveling-wave thermoacoustic engine is one wavelength loop filled with a noble gas or air as a working medium. Yazaki et al. [3] designed and built the first one wavelength looped-tube thermoacoustic engine to study the spontaneous gas oscillations of a travelling wave. Experimentally, the engine ran at a very low efficiency caused by the low acoustic impedance. Many looped-tube traveling-wave thermoacoustic engines built afterwards aimed to increase the efficiency and acoustic impedance. However, the low acoustic impedance of the looped-tube thermoacoustic engines were an issue.

Multi-stage thermoacoustic engines were proposed as a solution of the low acoustic impedance of the looped-tube engines by de Blok, who has built four novel engines with four identical stages [4, 5]. The identical four stages were presented as feasible from the construction point of view because of having identical components per stage. One of the

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engines generated 1.64 kW of electricity using available waste heat of 20 kW, at working frequency of 40 Hz. Three-stage devices were pioneered by Yang et al. [6] as heat pump applications. Unlike the previous looped tube and multi-stage engines, there is no need to construct the engine to a full one wavelength. The reason behind is the use of a linear motor having dual-opposed pistons in between each of the two stages, which shift the volumetric flow rate by 120°. Li et al. [7] adopted the three-stage configuration and built a three-stage thermoacoustic engine to study the heat to acoustic power conversion. At a mean pressure of 40 bar of helium, each stage of the engine generated 1080 W of acoustic power at 36% total efficiency. Bi et al. [8] improved the engine built by Li et al. [7] and Wu et al. [9], and pushed the power generation to the highest value recorded to date. The mean pressure was 60 bar and the working frequency was 70 Hz. The maximum generated electricity was 4.69 kW at 15.6% of thermal-to-electric efficiency and the highest efficiency was 18.4% at generated electricity of 3.46 kW. Kang et al. [10] successfully constructed a two-stage looped tube engine using two linear alternators. At 171 Hz working frequency, the maximum generated electric power was 204 Watts at 3.41% thermal-to-electric efficiency and a maximum efficiency of 3.43% was obtained at 183 W electric power.

The current research presents an alternative solution to run the two-stage looped tube engine with one linear alternator. The three operational parameters were studied. The experimental apparatus is shown in Section 2 and results are presented and discussed in Section 3.

Fig. 1. (a) Conceptual drawing of the engine; (b) Photo of the thermoacoustic engine reported in this paper.

2 Experimental apparatus

The apparatus consists of two identical stages each having a power extraction point, and a linear alternator connected to these two power extraction points. The conceptual design shown in Figure 1a illustrates the configuration, while figure 1b shows a photo of the device. The identical stages generate acoustic waves having similar pressure and volume flow rate amplitudes which are out of phase by 180° between the two stages. When these out of phase acoustic fields reach the linear alternator, one is “pushing” while the other is “pulling” the piston. Hence, the active acoustic impedance running the alternator is the sum of the two push-pull acoustic fields, and this will increase the power output at a specific acoustic impedance. DeltaEC simulation tool was used to simulate the acoustic field and optimize the dimensions of parts. DeltaEC (Design Environment for Low-amplitude Thermoacoustic Energy Conversion) is a design tool for thermoacoustic applications developed based on the linear thermoacoustic theory (Ward et al. [11]). After a long trade-off optimization process considering the performance and parts availability, a successful model is generated. This

thermoacoustic generator is a 16.1 m long, looped tube thermoacoustic engine, and uses pressurized helium at 28 bar as the working gas. It runs at a frequency of 54.7 Hz.

Figure 2 shows a cross-section of the thermoacoustic core. At the top, there is the ambient heat exchanger. It is a cross flow heat exchanger having staggered fins at both water and helium flow directions. It is made of copper. The diameter of the heat exchanger on helium side is 101.75 mm and thickness is 30 mm. The fins are 0.5 mm in width leaving 1 mm channels. On the helium side the fins are 8 mm long, while they are 5 mm long on the water side. At the right amplitude, the peak-to-peak displacement is roughly half of the heat exchanger length. The porosity of the ambient heat exchanger 31.2%.

Fig. 2. Cross-section of the thermodynamic section, ambient heat exchanger (AHX), regenerator (Reg), hot heat exchanger (HHX), thermal buffer tube (TBT), secondary cold heat exchanger (2ndAHX).

Below the main ambient heat exchanger is the regenerator. It consists of 445 stainless steel mesh screen discs, the length of the “pile” of discs being 73 mm. The diameter of the regenerator is 102 mm. The diameter of the mesh wire is 65 μm and the aperture is 180 μm . On each end of the regenerator, there is a coarse diamond mesh of 1.3 mm thickness, which acts as a spacer. These spacers allow the gas leaving the heat exchangers to mix and spread over the entire regenerator cross section. The regenerator hydraulic radius and the volume porosity have been calculated using the wire diameter, aperture and the amount of packed mesh per unit volume. The hydraulic radius is 60.5 μm and the volume porosity is 78.9%.

The hot heat exchanger has been manufactured from a low carbon steel. It has a 102.2 mm (4 inch) circular face diameter and 40 mm length in the direction of oscillation. It is equipped with pairs of 100 W cartridge heaters. On the helium side, it has comb-like shaped channels of 1 mm width with fins of 7 mm length and 0.5 mm width. The porosity of the hot heat exchanger on the helium side is 34.4%. At the right amplitude, the peak-to-peak displacement is roughly one third of the heat exchanger length. Below the hot heat exchanger is the thermal buffer tube providing thermal buffer between the hot and secondary ambient heat exchangers. It is 162 mm having a conical middle section reducing the internal diameter from 102.2 mm to 77.9 mm. The conical section is expected to reduce the Rayleigh streaming in the thermal buffer tube, as recommended by Swift [12]. The last part of the thermoacoustic core is the secondary ambient heat exchanger. The aim of this part is to prevent heat from flowing beyond the core section. It is made of copper and has a porosity of 38%. The diameter of the heat exchanger on the helium side is 77.5 mm and it is 20 mm thick. The fins are 0.5 mm in width; on the helium side the fins are 9 mm long, and 5 mm long on the water side. At the right amplitude, the peak-to-peak displacement is roughly equal to the heat exchanger thickness.

The acoustic network delivers the acoustic power generated in a thermoacoustic core to the linear alternator branch and the rest is fed to the other thermoacoustic core. The network comprises of a straight standard 1½ inch tube. The last 275 mm of the feedback loop is 1-inch standard tube to adjust the phase difference at the linear alternator, for a better performance.

3 Experimental results

There is an acceptable agreement between the measurements and the calculated results. The circular symbols in Figure 3 show the measured pressure amplitude and acoustic power (calculated using pressure amplitudes and phases difference, Fusco et al. [13]), and the line shows the calculated values along the engine. The experimental measurement of the pressure amplitude and phase difference showed small differences between corresponding points for the two stages. The pressure amplitude and acoustic power profiles are comparable at all magnitudes of load resistance.

Fig. 3. Distribution of pressure amplitude, volumetric velocity and acoustic power along the engine.

3.1 Effect of load resistance

In the experiments, a resistive load was connected to the linear alternator to measure and dissipate the generated electricity. The load value varied from 26.3 Ω to 92.5 Ω . Any value lower than 26.3 Ω damps the oscillations, and load resistance higher than 92.5 Ω does not show a significant effect. The linear alternator piston applies an acoustic load to the acoustic field at each of the linear alternator branches. The value of the load resistance dominates the acoustic load which dominates the acoustic field and performance of the engine. Figure 4a shows the experimental measurements at different load resistances. Increasing the load resistance will decrease the linear alternator acoustic load which allows the piston to oscillate at higher displacement. Higher piston displacement allows higher acoustic impedance at the linear alternator (on one side) as shown in Figure 4a. It also shows that higher acoustic power and acoustic impedance at higher load resistance leads to higher net acoustic power generated in one stage. The electrical output showed a different trend to varying the load resistance. Figure 4b shows the electricity output measured from the load resistance connected to the linear alternator and the predicted values using DeltaEC model. The experimental results are indicated by the symbols, and the line shows the prediction. The circles represent the average of four experimental readings and the error bar their variations. The load resistance, the acoustic pressure amplitude at the linear alternator and the temperature difference across the regenerator measured were applied as the boundary conditions to the DeltaEC model. A maximum electrical power of 62.2 W was measured, and 85.02 W was predicted when the

load resistance is 30.8 Ω (the highest performance of the engine will be shown in Section 3.3). With a further increase of the load resistance the electricity output gradually reduces.

Fig. 4. (a) The generated acoustic power in one stage, the acoustic power on one side of the linear alternator and the piston displacement, (b) the electricity generated by the engine, when the load resistance on the linear alternator is varied.

The electrical power output is a combined result of the acoustic power delivered to the alternator and the transduction efficiency of the alternator. It is concluded that, the transduction efficiency peaks when the load resistance is equivalent to the coil resistance of the alternator (Yu et al. [14]), which is 2 ohm. The electrical power output is also proportional to the square of the piston displacement, which increases continuously as seen in Figure 5b. Figure 5a shows that the acoustic-to-electric efficiency falls from 62.7% to nearly 28.4% by increasing the load resistance from 26.3 Ω to 92.5 Ω. The thermal-to-electric efficiency reaches the maximum of 6.91% at the highest electrical output when applying a load resistance of 30.8 Ω. Figure 5b shows the temperature difference measured across the regenerator (T2 and T4 shown in figure 2) at various load resistances and linear alternator piston displacement. The increase in piston displacement is a sign of increasing the volume flow rate at the linear alternator and along the engine. At the same heating power, the temperature difference on the regenerator reduces gradually with the load resistance, as a result of enhanced heat transfer for the hot to ambient heat exchangers due to high volume flow rate.

Fig. 5. (a) Effect of load resistance on acoustic-to-electric and thermal-to-electric efficiencies; (b) Effect of load resistance on temperature difference across the regenerator and linear alternator piston displacement.

3.2 Effect of mean pressure

The values of the mean pressure typically affect the power density present in the acoustic field. Swift et al. [12] determined the power density factor to be $p_m a A$, where a is the speed of sound, p_m is the mean pressure and A is the cross-sectional area. Higher acoustic power density leads to higher ability of delivering acoustic power. Varying the mean pressure

changes the thermodynamic properties of the gas, e.g. density and thermal and viscous penetration depths which influence the energy conversion process of the thermoacoustic system. The mean pressure was varied in the range of 14–28 bar, at a load resistance of 30.8 Ω and heating power of 900 W. Any mean pressure less than 14 bar leads to a non-harmonic oscillation which failed to maintain itself and was quickly damped.

Figure 6a shows the net acoustic power generated in one stage, the acoustic power delivered to one side of the linear alternator and the piston displacement from the experimental measurements when different load resistances were applied. It clearly indicates that the engine performs better at higher mean pressure, as it provides higher power density and favourable thermodynamic properties of the working gas.

Fig. 6. (a) The generated acoustic power in one stage, the acoustic power on one side of the linear alternator and the piston displacement; (b) the electricity generated by the engine, at different mean pressure.

Fig. 7. (a) Effect of mean pressure on acoustic-to-electric and thermal-to-electric efficiencies; (b) Effect of mean pressure on acoustic wave drive ratio.

Figure 6b shows the measured electricity output and the predicted values using DeltaEC model. The experimental results are indicated by the symbols, and the line shows the prediction. The load resistance, the acoustic pressure amplitude at the linear alternator and the temperature difference across the regenerator measured were applied as the boundary conditions to the DeltaEC model. A maximum electrical power of 62.2 W was measured and 85.02 W is predicted in the model when the mean pressure is 28 bar (the highest performance of the engine will be shown in Section 3.3). There is a clear trend showing that decreasing the mean pressure reduces the generated electricity. Surprisingly, the electricity output increased when the mean pressure reduced from 16 bar to 14 bar. The main reason is the spike increase in drive ratio (pressure amplitude of the acoustic wave to the mean pressure) at 14 bar mean pressure, as shown in Figure 7b. In spite of the working gas having higher power density at 16 bar than 14 bar, the 14 bar case shows an improvement because the higher

drive ratio allows the regenerators to generate higher acoustic power at approximately the same acoustic-to-electrical efficiency, as shown in Figure 7a.

3.3 Effect of heating power

Heating power and oscillation intensity are the two parameters determining the regenerator hot side temperature. However, heating power is the dominant parameter determining the ability to maintain a high temperature difference across the regenerator during the oscillation. In this section, the value of the heating power represents the summation of the equal heating power of the two stages. The heating power was varied from the minimum power able to maintain oscillations of 500 W to a maximum of 1700 W, at 28 bar mean pressure and load resistance of 30.8 Ω. Figure 8a shows the generated electricity at different heating power for both experimental tests and simulation (at the experimental boundary conditions). The generated electricity reached the maximum at 1300 W heating power of 73.3 W at 5.58% thermal-to-electric efficiency, while maximum predicted was 98.1 W. Beyond that heating power, the generated power started to decrease despite the increase of generated acoustic power.

Fig. 8. (a) The electricity generated by the engine; (b) the generated acoustic power in one stage, the acoustic power on one side of the linear alternator and the piston displacement, at different heating power.

Fig. 9. (a) Effect of heating power on acoustic-to-electric and thermal-to-electric efficiencies; (b) Effect of heating power on regenerator temperature difference.

Figure 8b shows that the increase of heating power increases the net generated acoustic power, acoustic power delivered to each side of the linear alternator and the piston displacement. However, the acoustic power phasing becomes unfavourable to the linear alternator (explained in Hamood et al. [15]) at higher heating power as the acoustic-to-electric efficiency decreases with increasing of heating power as shown in figure 9a. The thermal-to-electric efficiency decreases between 700 W and 1300 W, as the rate of generated

electricity is less than that of the heating power. The increase of heating power from 700 W to 1700 W increases the regenerator temperature difference. However, the increase of temperature difference when reducing the heating power from 700 W to 500 W is due to the weaker acoustic intensity at 500 W heating power.

4 Conclusion

A novel configuration of a two-stage traveling-wave thermoacoustic engine was studied in this paper. The configuration of two identical half-wavelength stages allows to couple a linear alternator to two points, and acoustic field will run it in push-pull mode. The working medium of the engine is helium at 28 bar. The three operational parameters were studied. The load resistance was found to have a curtail effect on the performance of the engine, and its optimum value was found to be 30.8Ω . Reducing the mean pressure and the heating power was found to decrease the electricity generation.

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