The Influence of Heat Input Ratio on Electrical Power Output of a Dual-Core Travelling-Wave Thermoacoustic Engine

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Abstract

This paper presents an analytical and experimental investigation of an electricity generator that employs a two-stage looped tube travelling-wave thermoacoustic prime-mover to deliver acoustic power from heat energy, a loudspeaker to extract electricity from sound energy and a tuning stub to compensate the changes in the acoustic field within the engine to enable close to travelling wave operation at the loudspeaker. Furthermore, the paper explains how to enhance the output power utilizing different heat input ratios through the engine cores. A well-known thermoacoustic design tool called DeltaEC is used to simulate the wave propagation through the different parts of the system. The electrical power predicted from the low-cost prototype was 24.4 W acoustic power which confirms the potential for developing low-cost thermoacoustic electricity generator for heat recovery from low-grade heat sources. The electrical power can be increased to 31.3 W using different heating power percentages through the two units. The verified experimental data shows good agreement with DeltaEC results.

Keywords: Regenerator, thermoacoustic, acoustic power, loudspeaker as a generator, DeltaEC

Background

The development of new techniques utilizing low-temperature waste heat and renewable energy sources have drawn enormous attention worldwide in recent years. There are many sources of such low-grade heat that, if they could efficiently and economically be harvested, would decrease carbon footprint significantly. One application where it has the potential to make significant changes to the standard of life is in the generation of electricity in low-income rural areas of the world. Over three billion people in the developing world use open fires for cooking process and one billion do not have access to electricity. An estimated 4 million people die prematurely by the smoke from open fires, mostly women, and children, making this one of the serious health threats facing people in developing countries [1]. The target of this research is to provide healthy cooking and electric power for the households of Sudan and South - Sudan countries by means of thermoacoustic technology.

Thermoacoustics is a new promising technique that uses heat to produce high-intensity sound waves which can, in turn, produce electricity. A thermoacoustic engine (TAE) eliminates the majority of mechanical moving parts by its simple construction, which comprises an acoustic resonating tube and a section of porous media in between two heat exchangers [2]. The well-known torus configuration travelling-wave engine developed by Backhaus and Swift has demonstrated a high efficiency of 30% which corresponds to 41% Carnot efficiency using 30 bar pressurized helium at a high operating temperature of 725°C [3], which is comparable to the efficiencies from petrol and diesel engines, but at lower temperatures, although efficiency is much lower when a flame is used as heat [4]. At these high temperatures travelling wave thermoacoustic engine has to compete with other conventional devices such as Stirling engine. However, clearance sealing is an issue in conventional Stirling engine at high temperature.
Several variations of systems have been attempted to convert the acoustic power to useful electric power, utilizing different system configurations and transduction mechanisms [5, 6]. Thermoacoustic stoves have been shown to be a cheap option compared to others in situations where hydropower is not available, but since the technology is relatively new, and these low temperature systems are subject to non-linear affects that are not well understood, present work is concentrating on understanding the non-linear effects and minimising the losses.

The idea of thermoacoustic power has been proved over the last 20 years since the first working engines were produced. A number of designs have been developed that can achieve good efficiencies relative to Carnot for. An early thermoacoustic engine was designed for space application using a flexure-bearing linear alternator, the electrical power produced from this engine was 39 W with 18% thermal-to-electrical efficiency [7, 8]. A novel three-cylinder double-acting thermoacoustic Stirling electricity generator was developed and tested [9], using 3.12 KW heating power from each heater block and three alternators to extract the electric power. 5 MPa pressurized helium was adopted as the working gas and the system produced a maximum electrical power of 1570 W. The performance was highly degraded due to the significant difference in the performance of the engines and the alternators. Another investigation on generating electricity using multiple- stage travelling-wave thermoacoustic engines was undertaken by Kang et al.[10]. In this case, the total electric power output had a maximum value of 204 W using 1.8 MPa helium and 6 kW total heating power (with the same input through the two heaters). The parasitic heat loss in the experiments was very large and there was non-linear behavior in the system due to the high-pressure amplitude. Most recently, a three-stage travelling-wave thermoacoustic electricity generator was proposed by Bi et al. [11]. This prototype achieved a maximum electric power of 4.69 kW with thermal-to-electric efficiency of 15.6% using 6 MPa helium gas. The heat transfer was again poor and there were large flow losses and friction losses from the alternator which dropped the power rate.

The conversion of the acoustic field to electrical output is mostly carried out using linear alternators, although more recently bi-directional turbines have shown some potential in improving performance [12]. Linear alternators purpose-designed for thermoacoustic systems are expensive, which limit the advantages of the thermoacoustic heat engines for low-cost energy conversion applications and therefore, it is possible to consider low-cost commercial available loudspeakers to convert acoustic power gain into electricity. In these low cost applications the main driver is the cost of the system, not the transduction efficiency [13, 14]. In 2012, SCORE project (www.score.uk.com) developed and tested two low-cost double-regenerator traveling-wave thermoacoustic electricity generators, to produce electricity using waste heat energy from cooking stoves. A propane-driven stove delivered approximately 15 W of electricity. While, a wood burning cooking stove was successfully demonstrated 22.7 W of electricity. The performance of the devices was low due to the high acoustic losses and the inefficient linear alternators being used [15], but also because, at these low temperatures, the system is very sensitive to losses. Understanding this and minimising losses is important if we want to reach the commercially needed target of producing at least 100 W of electrical power from a cook-stove that costs less than £200,

Many of the configurations that have been tested use multiple stages and it has been the practice to input the same amount of heat in each exchanger. In this paper, a new operational methodology using different percentages of thermal energy is employed for the optimization of the system for the first time. This paper will look at whether there is a strategic advantage in varying the heat power ratio.
Modeling of the system

To further understand the behavior of the thermoacoustic system considered in this research and to predict the performance of the existing build engine, a design software code referred as DeltaEC (Design Environment for Low-amplitude ThermoAcoustic Energy Conversion) is utilized [16]. DeltaEC integrates numerically the wave equation and other equations such as the energy equation throughout the whole system in one spatial dimension based on a low-amplitude “acoustic” approximation and sinusoidal time dependence of the variables [17]. The governing equations used in DeltaEC as follows:

\[
\frac{dp_1}{dx} = -\frac{i\omega \rho_m}{A_g(1 - f_v)} U_1
\]

\[
\frac{dU_1}{dx} = -\frac{i\omega A_g}{\gamma \rho_m} (1 + (\gamma - 1)f_k)p_1 + \frac{(f_k - f_v)}{(1 - f_v)(1 - \sigma)} \frac{1}{T_m} \frac{dT_m}{dx} U_1
\]

Where: \( p_1 \) pressure amplitude of oscillation (Pa), \( U_1 \) volumetric velocity amplitude (m³/sec), \( \omega \) angular velocity which equals \( 2\pi f \) (rad/sec), \( \rho_m \) mean density (kg/m³), \( P_m \) mean pressure of the working gas (Pa), \( T_m \) mean temperature of the working gas (K), \( \gamma \) is the ratio of the specific heats of the gas, \( f_k \) is the thermal spatially averaged diffusion function, \( f_v \) is the viscous spatially averaged diffusion function, \( \sigma \) is Prandtl number, \( A_g \) is the cross-sectional area of the system considered in this research.

This model was validated against experimental results shown below to confirm the findings.

Explanation of test-bed apparatus

The SCORE system comprises a two-stage thermoacoustic engine operating in mainly travelling wave mode, with two tuning stubs and a loudspeaker as shown in Figure 1. Which is based on the loop-tube configuration. This arrangement gives an advantage of using low-temperature heat source with a lower temperature gradient through each stage [18, 19]. Both stages comprise an ambient heat exchanger (AHX), regenerator, hot heat exchanger (HHX), thermal buffer tube (TBT) and a secondary ambient heat exchanger (SAHX) as in Figure 1(b). The AHX is made out of the core of a commercial low-cost car radiator, suitably modified to fit the thermoacoustic engine. A thermos-siphon water circulation method was applied to take heat from the system, so a pump isn’t required in the system. To maintain a low cost for the engine core and to achieve a quick warm-up time, a low-mass convoluted stainless steel plate design has been adopted for the HHX. The HHX is 233 × 307 mm and is made out of 3 mm thick Stainless steel plate. The plate was welded to a flange that designed to be directly bolted to the engine housing. The regenerator is sandwiched between the AHX and the HHX and was formed by stacking 50 pieces, 80-mesh Stainless-steel wire mesh machined to a required size of 20 × 20 mm. The mesh wire has a diameter of 95 μm and a pitch of 250 μm. The AHX and the HHX are clamped between upper and lower housings [5]. The TBT is simply a section of stainless steel pipe and is located below the HHX to separate the SAHX from the hot gas and thus minimizing parasitic heat losses. A SAHX is introduced after the TBT to cool the air before it flows to the alternator. The stages are connected using 70 mm diameter standard PVC pipes and fittings. Two extra pipes perpendicular to the feedback loop “denoted as tuning stubs” are introduced in the loop to enhance the impedance matching between the acoustic wave and the linear alternator and to maintain the phase angle between the velocity and the pressure in a travelling-wave condition through the regenerators. To extract the electric power from the circulating acoustic power, a low-cost commercial loudspeaker (model JL 6W3v3-4) was used as a linear alternator and is connected in series in the loop. This arrangement allows suppressing the acoustic streaming which could cause heat dissipations from a HHX. To simulate more
closely to the final application, two custom-made electrical heaters are used to supply the heat to the HHXs. For temperature measurements, eight thermocouples (Type-K) were placed in different locations to monitor the hot and the cold temperatures of each regenerator unit as well as the temperatures the cooling water. Three absolute pressure transducers (model IMPRESS) were distributed along the feedback pipe and a differential pressure sensor (model ABPMJJT015PGAA5) was used to capture the volumetric flow rate across the loop. The readings of the thermocouples and the pressure transducers were collected by a Data Acquisition system (NI cDAQ 9172) which is connected to a data logger system. To harvest the electrical power from the system, a wide range variable resistor (model VISHAY®) was adjusted to the optimal electrical load for the loudspeaker. The voltage and the current from the alternator are measured using a power analyzer (model KintiqPPA2530).

![Diagram of the two-stage thermoacoustic electricity generator](image)

Figure 1. The two-stage thermoacoustic electricity generator. (a) Photo of the system. (b) Functional diagram

In order to address the performance of the system, it is important to estimate the flow of the acoustic power which is defined as a time-average energy flux accompanied by pressure oscillations and velocity of the working gas. The most common method to measure the acoustic power is the so-called two-microphone method [20]. Conceptually, this method employs two absolute pressure sensors to obtain the velocity of the oscillating gas. However, one of the drawbacks of this technique is obtaining the high accuracy of the phase angle between the pressure and the velocity. Therefore, to get a more durable way of measuring the acoustic power, an alternative method referred as “gradient method” is used in the current system. It employs one absolute pressure transducer and one differential pressure sensor to directly calculate the mass of the air between the two sensors, the acoustic velocity, and the acceleration. The distance between the two sensors is small compared to the two-microphone method. Therefore, no empirical correction for acoustic loss is required. The acoustic power propagation in the feedback loop can be given as [21]:

\[
P_{Ac} = A \cdot \hat{p}_1 \frac{\Delta p_1}{2 \omega \rho_m \Delta x} \sin \phi
\]

Here: \(A\) is the cross-sectional area of the feedback loop, \(p_1\) is the pressure amplitude (Pa) which is the signal from the absolute sensor, \(\Delta p_a\) is the output signal of the differential pressure sensor (Pa), \(\Delta x\) is the distance between the two probes of the differential sensor (m), \(\phi\) is the measured phase between \(p_1\) and \(\Delta p_1\), \(\omega\) is the angular velocity (rad/sec), \(\rho_m\) is the mean density (kg/m³), \(p_m\) is the mean pressure (Pa).

Since the application is for the developing world, air at atmospheric pressure is used as the working gas. The maximum hot and the cold temperatures were set to 650 °C and 90 °C, respectively and the total heat input power was varied between 2.1 - 3 kW. This was split at
different ratios between the two stages. DeltaEC model had predicted that changing the heat ratio to each core could affect the performance, so in the experiment the heat was inputted as 40%-60%, 50%-50%, 55%-45%, 60%-40%. The system operates at working frequency of 73 Hz. To verify the numerical results with the lab data, the load resistance of the loudspeaker was adjusted to 35.5 Ohm. In most applications the heat input would be split between the two cores evenly, providing Q/2 W to each core. In this paper we have investigated whether the results of the model which suggested that a 60% - 40% split would improve performance. These results are used to validate the numerical model.

Results and discussion

The schematic diagram of the model used in DeltaEC simulation is presented in Figure 1 (b). The model was constructed using the same design parameters of the existing prototype and using some of DeltaEC segments [17]. The model starts at x = 0 which is located at the hot end of the first AHX and goes anticlockwise until it returns. The pressure amplitude, the volumetric velocity amplitude, and their phases are adjusted so that they match at the start and the end of the model. The acoustic power flow is indicated by the blue arrows, Figure 2 demonstrates how the key acoustic parameters obtained from DeltaEC vary around the system. The 4 curves correspond to varying heat input into the two cores, with 40%, 50% 55% and 60% of the heat being directed to core 1, which is just before the linear alternator, and the power in core 2 being adjusted to that the total energy input was a constant. No other variables were adjusted. It is clear that the curves have the same trend among the four heat supply percentage. In Figure 2(a), the pressure amplitude drops at each of the two regenerators due to their flow resistance. It also decreases across the linear alternator due to its acoustic resistance. The two stubs don’t influence the pressure amplitude. The standing wave ratio in the system is approximately around 2.97 due to the reflections where the feedback pipe area changes.

These numerical results demonstrate that using 60% of the heat in the first HHX resulted in higher pressure drop across the alternator diaphragm which indicates better extraction of the electric power. In other words, the electrical power output increased from X to Y when the balance of heat went from 50% to 60%, an X% increase. It can be seen that the pressure antinodes altered location slightly in the four heat supply ratios, particularly near the end of the feedback loop due to the slight change in the operating frequency. There is a high decrease in the flow at the location of the stub which indicates that the stub removes part of the volumetric flow from the loop. In contrast, the volumetric velocity increases significantly along the two regenerators due to the sharp temperature gradient across them. Between the alternator and the SAHX, there is a part of connecting pipe where the volumetric velocity increases due to the change in the area. The acoustic impedance Figure 2(c) has high values at the cold end of the two regenerators which led to \([Z] \times A/a \times \rho_m\)~7 & 12 at regenerator 1 and regenerator 2, respectively. In travelling-wave thermoacoustic engines, a common practise is to set the absolute value of the regenerator impedance in the range of 10-20 time the gas characteristic impedance [19]. At the locations of the tuning stubs, the impedance decreased due to the constant pressure amplitude at the junction between the stub and the feedback tube. The acoustic loop power Figure 2(d) increases when adding higher heat in the first HHX. Again for all the cases, the curve has the same characteristics, but it is clear that there is higher acoustic power when the ratio of heat input is 60% / 40%. Considering the case where the total heat splits eventually between the two heaters, the results revealed that, around 58.4 W of the acoustic power from the resonance tube is introduced into unit 1 and only about 1 W is dissipated within its AHX, leading to an amplification of 57.4W. This is then fed into the cold side of the regenerator where the acoustic power is amplified to 77.5 W. Minor acoustic loss of 1.8 W occurred through the HHX, the TBT and the SAHX of the first unit. The alternator
delivered 24.4 W electrical power with a thermal-to-acoustic efficiency of 2.3%, and thermal-to-electrical efficiency of 0.98%.

Figure 2. The variation of the key performance parameters through the loop using different percentages of the total heat input: $Q_1$ in heater 1 and $Q_2$ in heater 2 (a) Pressure amplitude (b) volumetric velocity (c) acoustic impedance (d) acoustic power. * Numbers from 1 to 6 correspond to the defined ones in Figure 1

The results of the numerical modelling were surprising, thus the performance of the experimental rig was assessed using the same concept. Figure 3 compares the lab results of several percentage of the heat power (range 2.1 to 3 kW). Both the acoustic power and the electric output increase linearly with the total heat input. Extra power could be gained by simply supplying a higher heat percentage to the first HHX. This can be justified by the location of the loudspeaker which is immediately after the TBT of the first engine. Using 2.5 kW power with 50% $Q_1$, 50% $Q_2$ generated 48.4W acoustic power. This power is raised to 68 W when using 60% $Q_1$, 40% $Q_2$, which resulted in an extra 6.5 W electric power (10% increase). However, DeltaEC models predict loop power as high as 0.1-2.8 percent, and electric power as high as 0.4 to 3.7 percent which indicates that the system isn’t quite efficient in converting heat energy into acoustic power and the heat dissipation is potentially an issue. The alternator in this system is installed next to the SAHX of the first unit. At this location, the acoustic impedance has a low value. In fact, almost a maximum alternator stroke is reached at 3 kW thermal power. Therefore, if more electrical power is to be extracted, the alternator should be placed in a high-impedance zone to avoid the stroke limitation.

Figure 3. Performance of the engine under four heat input ratios. (a) Acoustic power (b) Electrical power
The thermal-to-electric efficiency reached a maximum value of 1.25% when using 60% $Q_2$, which is indeed much lower than that noted in Ref [8], where the linear alternator acted as a mechanical resonator as well as a transduction mechanism. In the current design, two reasons are contributed to the poor efficiency. The first one, using a linear alternator instead of resonating tube minimizes the acoustic losses where the long resonator dissipated a considerable amount of the loop power. The second reason, the transduction efficiency of the loudspeaker is quite low (about 34%) compared to the linear alternator which was approximately around 90%. However, the linear alternator is expensive and this counteracts the affordability of the system. Therefore, the loudspeaker is a viable competitive candidate for developing a thermoacoustic generator.

The onset temperature is also important. Low onset temperatures can help improve efficiency. Therefore, the electric power against the temperature difference across the two regenerators is plotted in Figure 4 for several heat input percentages. Clearly, the amplification in the second core decreases when the heat input into the core decreases and the onset temperature increases. However, in the first core, the reverse happens. In fact, the onset temperature of the first core drops significantly and by much more than the increase in the second core. Reversing the heat ratio results in reduced performance. Further study is required to find out why this occurred. The onset temperature difference and the steepness of the power against temperature curve are indicators of the performance of a thermoacoustic system. A low onset temperature means low loss and adequate acoustic matching between the various components of the system. A steep temperature curve reflects good heat transfer of the ambient and the hot heat exchangers and also indicates low acoustic dissipation [19]

![Figure 4. Electric power relation with the temperature difference across the regenerator](image-url)

**Summary**

In this paper, the influence of the heat input ratio into a looped-tube thermoacoustic engine was discussed. The engine converts acoustic power to electrical energy using a commercially available low-cost loudspeaker. DeltaEC is used to simulate the acoustic field within the system. DeltaEC results reflect that the electrical power output from the system equals 24.4 W from 2.5 kW heat input. An extra 7 W of electricity could be obtained by applying 60% of the heat into the first hot heat exchanger. DeltaEC models predict acoustic loop power as high as 0.1-2.8 percent, and electric power as high as 0.4 to 3.7 from the lab data percent which indicates that the system isn’t quite efficient in converting heat energy into acoustic power and the thermal dissipation is potentially an issue.

**References:**
