Development and performance evaluation of a single stage travelling-wave thermo-acoustic generator

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***Abstract*— Thermo-acoustic systems are being considered as a potential solution for electricity generation. This work describes the construction of a single stage travelling-wave thermo-acoustic generator. Secondly, an experimental investigation into the effect of the heat source on the potential of the device for electricity generation is performed. The magnitude of the sound generated by the engine, the onset time and the magnitude of electricity generated by the linear alternator have been considered as performance indicators for the device developed. This paper provides clarity on the potential for thermo-acoustic system for sound-to-electricity conversion. Clear trends showing the effect of inputs parameters on device performance have been disclosed. The minimum/maximum amount of heat that has produced a sound was 339/634ºC corresponding to sound of 114.0/114.13 dB and a voltage of 278/319 mV. Although the efficiency of the sound-to-electricity conversion was low, this work proves the viability of thermo-acoustic as the alternative solution for electricity generation.**

Keywords—Thermo-acoustic, travelling-wave, design, construction, temperature, generator, electricity.

I. Introduction

Thermo-acoustic systems are being considered as a potential solution for electricity generation where the sound wave generated by a thermo-acoustic engine (Fig. 1) can be used for electricity generation through a linear alternator. Thermo-acoustic is actually a field of science that is concern with the interaction between thermal energy (heat) and acoustic energy (sound) with the purpose of inducing cooling or generate electricity [1, 2]. Major research on thermo-acoustic commenced in the years of the 1980s and has significantly expanded over the last few decades. Recently, there have been a significant increase in the development of thermo-acoustic refrigerators as well as thermo-acoustic generators with limited to no moving parts involved. [3, 4]. Thermo-acoustic devices could be classified based on their application, the sound-wave type or the geometrical configuration as shown in Table 1.

Standing wave-devices have the stack as the heart of the engine with one end closed and one end open (Fig. 1). Travelling wave-device has the regenerator as the main component and forms rather a looped tube [2, 5] (Fig. 2). Travelling wave devices have exhibited promising results regarding their performance as compare to standing wave thermo-acoustic systems and therefore this study focuses on the traveling-wave thermo-acoustic generator.

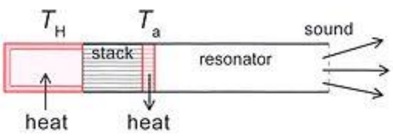

Fig. 1. Schematic diagram of a typical thermo-acoustic engine

TABLE 1. Classification of Thermo-acoustic System

Application Type	
Thermo-acoustic Refrigerator	Thermo-acoustic Generator
Wave Type	
Standing-wave device	Travelling-wave device
Geometrical configuration	
Single stage configuration	Multi-stage configuration

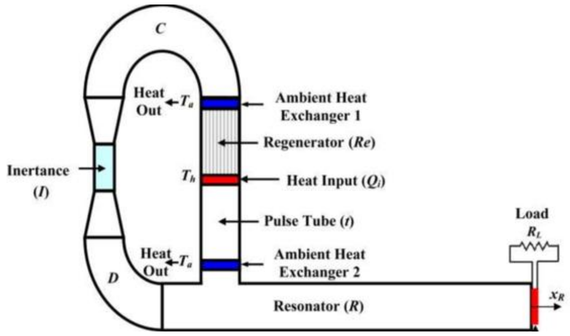

Fig.3. Typical travelling-wave thermo-acoustic generator

The working of thermo-acoustic systems make them suitable for application that incorporate solar powered energy, waste heat recovery devices and small low-cost systems in rural or remote areas without access to the electricity grid. The lack of moving parts and low material requirements favors thermo-acoustic devices to be inherently robust, economic and simple to produce [6]. These devices requires little to no maintenance at all, and their simplicity and reliability makes them attractive for isolated equipment.

Through the travelling wave devices there is possibilities to utilize the temperature differences obtained from a solar vacuum or waste heat in the range of 70-200°C in order to drive thermo-acoustic engines. In order to reach such low onset temperature difference and apply this technology, a hybrid configuration made up of multiple thermo-acoustic cores placed close together can be utilized in one engine to lower its onset temperature without depressing the power density [4]. A multi-stage travelling-wave was proposed by De Blok in 2010. Using helium and argon as the working fluid, this multi-stage device was able to achieve the lowest onset temperature of 46 K and 26 K respectively. De Blok pointed out that a two stage engine system had a higher efficiency than a four stage system [7].

A traveling-wave thermo-acoustic electric generator consisting of two linear alternators was constructed by Wang et al. [8]. The experiment aimed at studying the electric power and thermal-to-electric efficiency of this prototype under different working conditions. A maximum electric power of approximate 474W and thermal-to-electric efficiency of approximately 15% were achieved. Interestingly, the optimization of the load resistance, the increase of the working pressure and the improvement of the coupling engine-alternator were suggested as means to improve the performance of the system. A three-stage looped thermo-acoustic electric generator consisting of three thermo-acoustic engines and a linear alternator, was developed and built by Yang et al. [9]. A thermal-to-electric efficiency of approximatively 1.5% corresponding to a temperature range of 120 °C–170 °C is reported.

Timmer, et al. [6] thoroughly review the approaches available for the conversion of acoustical energy to electrical energy. For each of these conversional methods, they review its design aspect, the operational characteristics and the method used to calculate as well as optimize its performance individually. The approaches reviewed are the piezoelectric devices, the electromagnetic transducers, the magneto hydrodynamic devices as well as the bidirectional turbines as summarized in Fig. 4. This study has pointed out that electromagnetic transducers are the most effective thermal-to-electricity converters capable of generating power within the kilowatt range. The bidirectional turbine were found to be good alternative for relatively higher output power.

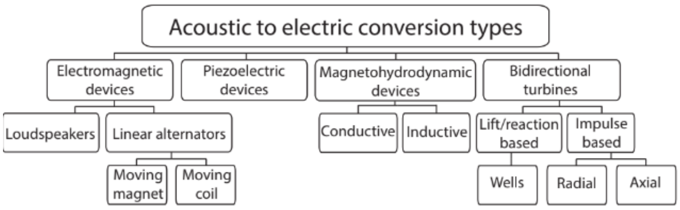

Fig.4. Hierarchal structure of acoustic-electric methods (Adapted from Ref. [6])

The main objective of this research is to contribute to the current available knowledge on "thermal-to-electricity" conversion by developing and analysing a travelling-wave thermo-acoustic generator. The general trends of performance indicators will be used to make recommendation for future refinement of the device proposed in this study.

II. System Design and Construction

This research has two parts. The first part provides details of the design and construction of a single-stage travelling-wave thermo-acoustic generator. The second part describes the experimental investigation conducted in order to evaluate the onset temperature, the generated sound level and the frequency as well as the amount pf power generated.

A. *Design and Construction*

A looped tube single-stage travelling-wave thermos-acoustic engine was developed. A commercial loudspeaker was used as linear alternator in order to assess the potential for sound-to-electricity conversion. The engine consists of the regenerator (REG), a cold heat exchanger (CHX) and a hot heat exchanger (HHE). In addition, the engine core is only component made of steel material, whereas the looped tube and the resonator are made of poly vinyl chloride (PVC) pipes as depicted in Fig. 4. These components are described in details in the following sections.

Fig. 5. Experimental setup

B. Thermo-acoustic engine

This unit has three components namely the HHX, the regenerator REG (the heart of the engine) as well as the CHX as shown if Fig. 6. The HHX consist of three cartridge heaters inserted on copper strip for equal distribution of heat and the CHX is a cooling system consisting of seven copper pipes. Fig. 6 point out the geometrical configuration adopted for the construction of the HHX and the CHX respectively. A readily available ceramic regenerator of 400 cells per square inch (CPSI) was used. The properties of the regenerator are listed in Table 1. The heat-to sound conversion takes place within the regenerator. The engine is 500 mm long with an internal cross-sectional area of 75 mm x 75 mm and is made of steel material in order to withstand high temperatures.

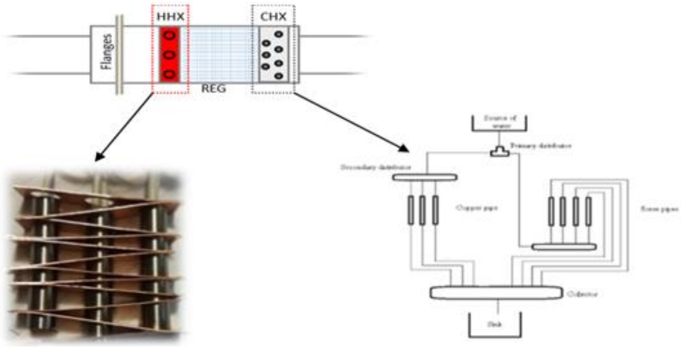

Fig. 6. Thermo-acoustic Engine module

TABLE 2. Properties of the regenerator

Material	**Ceramic**
Pore size range	400 CPSI
Density	2500 kg/m^3
Specific heat	1047 J/kgK
Melting point	1450ºC
Height/Width	75 x 75 mm
Length	40 mm

C. The Looped Tube and Resonator

PVC Material was selected for the rest of the looped tube that completes the travelling wave of the system because it is readily available, less expensive and can withstand up to sixty degrees Celsius. The total length of the looped tubed is 2100 mm with an internal diameter of 50 mm and the additional resonator tube is of same diameter with a length of 900 mm (Fig. 7).

Fig. 7. Looped tube travelling-wave geometry

D. Linear alternator (Loudspeaker)

Linear alternators are devices that convert mechanical (acoustical) energy to electrical energy. A commercial loudspeaker was adopted in this study because it is cheap and readily available although inefficient. To minimize the acoustic power losses during the coupling of the loudspeaker and the engine, a case was created using plexiglass as shown in Fig. 8. Table 3 gives the properties of the loudspeaker considered in this analysis.

Fig. 8. Kenwood Loudspeaker

TABLE 3. Properties of the Kenwood Loudspeaker

Peak power	210 watts
Rated power	21 watts
Resistance	4 ohms

III. EXPERIMENTAL INVESTIGATION

A. *Instrumentations and testing*

Fig. 9 depicts all instruments used to conduct the experimental investigation and measure the performance of the device developed in this study. The power supplier (1) is a variable transformer used to provide voltage to the cartridge heater in the HHX. The personal computer (2) was used for the visualization of temperatures at the HHX and the CHX and the frequency of the sound produced. A multi-meter was used to record the output voltage resulting from the sound generated. The signal processing and visualization of data from the prototype were performed with the National Instrument (NI) DAQ data acquisition (3) (for the temperatures), the NI myDAQ (4) attached to the sound level meter (5) (for the frequency measurement) using the software Labview.

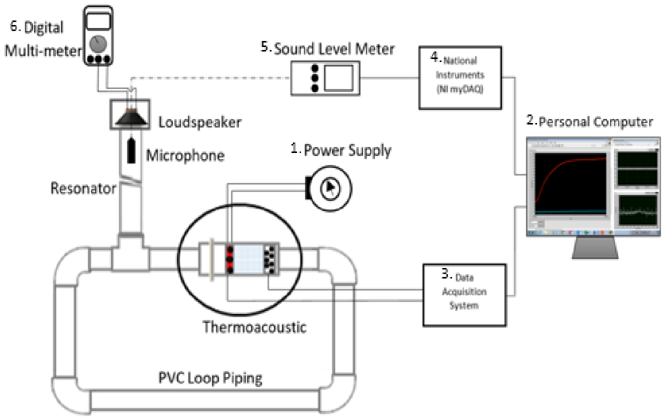

Fig. 9. Schematic diagram of experimental setup

B. *Experiment process*

The prototype was set up to use air at atmospheric pressure as the working fluid. The Cooling system had flowing water at a rate of roughly 0.141 litre/s. The cartridge heaters on the HHX were connected to the transformer that would supply the voltage. The process starts when the cartridge heaters are fed with power and ends when the temperature measured by two K-type thermocouples doesn't change significantly. The cooling system (CHX) was run before powering the HHX. As the tests were conducted attention was particularly paid to the system reaching stability. The onset temperature (Hot and Cold) was recorded for each setting of the power supply. Similarly, the magnitude of the sound and its frequency as well the time taken for the engine to produce a sound were recorded. However, not much attention was given the time taken for the device to reach stability. Cconversely all readings (onset temperature, sound magnitude, frequency and voltage) achieved were only recorded when the device has reached stability. The system stability refers to when the hot temperature on the HHX is no longer changing significantly. The main variable of this experiment was the temperature of HHX through voltage supplied to the cartridge heaters, therefore voltage range of 190 volts – 120 volts were examined.

IV. RESULTS AND DISCUSSIONS

A. *Evolution of the temperature across the regenerator*

The temperature difference across the regenerator was measured using two K-type thermocouple. This Figure shows a significant increase of the temperature at the HHX using cartridge heaters. The CHX appears to be stable suggesting that the construction of the CHX was adequate. The temperature differences reported in this study were recorded once the temperatures at the hot and cold side were relatively constant.

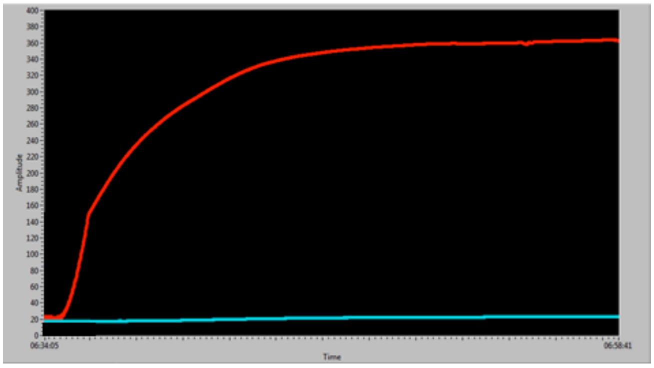

Fig. 10. Temperature difference across the regenerator (blue line: Tcold and red line: Thot)

B. *Frequency*

The frequency of the sound generated was not affected by the input voltage to the cartridge heater. Irrespective of the input voltage, the frequency of the generated sound was approximately 110 Hz. Fig. 11 shows a typical frequency spectrum of the sound wave screenshotted from Labview.

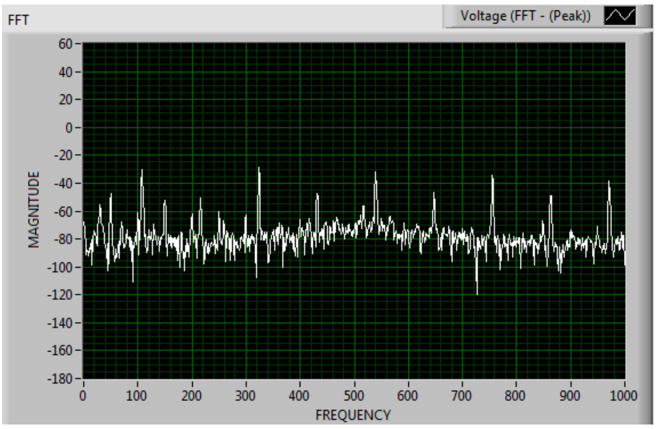

Fig. 11. Frequency spectrum of the sound output

C. Temperature difference across regenerator, sound level, generated voltage as a function of the input voltage

Table 4 provides a summary of the results obtained from the investigation conducted in this study. The temperature difference across the regenerator, the magnitude of the sound produced, the corresponding voltage on the loudspeaker as well as an observation of the time taken to produce the sound were captured in Table 3. These results have been presented graphically in Fig. 12 and 13 for meaningful interpretation.

TABLE 4.Table of Results

Voltage supply [V]	Temperature difference[ºC]	Sound level [dB]	Output voltage [mV]	Onset time [min]
190	634	114.3	319	3
180	569	114.3	317	4
170	478	114.2	311	8
160	424	114.1	306	8
150	399	113.9	296	10
140	352	113.9	289	11
130	339	114.0	287	13

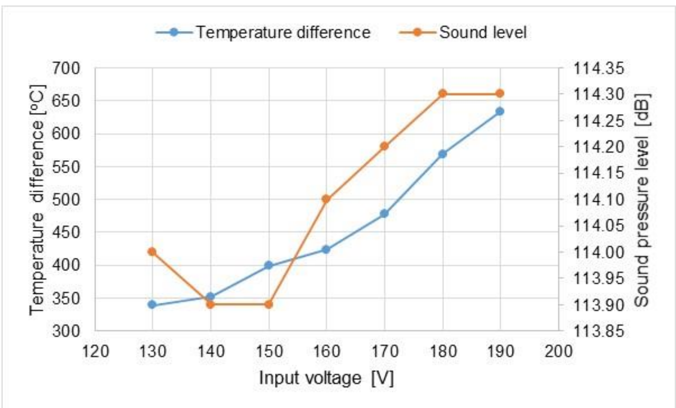

Fig. 12. Temperature difference and sound pressure level as a function of the input voltage

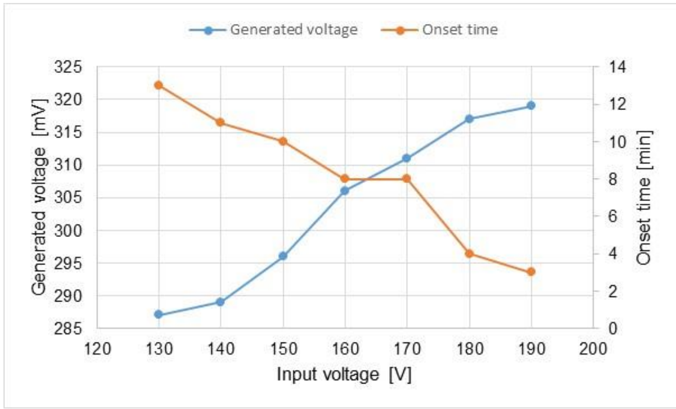

Fig. 13. Generated Voltage and onset time as a function of input voltage

From the results, the highest temperature difference across the regenerator reached by the device at stability was 634ºC with a sound magnitude and corresponding voltage of 114.3 dB and 319 mV respectively. The minimum temperature that could produce a sound was 339ºC with a sound magnitude and corresponding voltage of 114.0 dB and 287 mV respectively. As the input voltage to the cartridge increases, the temperature difference across the regenerator increases as well, which is expected. Interestingly, the magnitude of the sound generated was not significantly affected the amount of power provided to the heat source as suggested in Fig. 12. However, the magnitude of the electricity generated by the loudspeaker was proportional to the magnitude of the heat input with the highest output voltage of 319 mV corresponding to the input voltage of 190 V as shown in Fig. 13. Interesting, the higher the voltage, the shorter the time required to reach the onset temperature and generate a sound wave.

V. CONCLUSION

This paper discussed the design and construction of a single stage travelling-wave thermo-acoustic generator as well as its performance. The prototype was designed and successfully constructed. The experiments were carried out and performance indicators were measured and assessed. Results obtained were the onset temperatures, the magnitude of sound produced and corresponding power (voltage) that is generated on the loudspeaker due to the sound. According to the result obtained, the influence of the input power to the cartridge heaters doesn't affect significantly the magnitude of the sound generated for the range considered in this study. However, the power (voltage) generated on the loudspeaker was significantly affected by the change in the temperature difference across the regenerator. The lowest temperature difference was 339ºC with the sound of 114.0 dB and a corresponding voltage of 287 mV. Although the efficiency of the thermal to electrical power conversion was low because of the mechanical losses within commercial loudspeaker, this work demonstrates the potential of thermo-acoustic technology for electricity generation.

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