Performance investigation and construction of a traveling wave thermo-acoustic engine

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Abstract

The current development of thermo-acoustic devices suggests that there is a possibility to enhance their performance even further. This technology could potentially contribute to the effort to swap conventional pollutant energy refrigerators/generators with environmental friendlier systems in the forthcoming years. The configuration of the regenerator is so far believed to be one of the factor that could contribute to the improvement the performance of the engine. This paper aims to investigate the behaviour of a designed thermo-acoustic engine when changing the porosity of the regenerator. It also aims to provide guidance on the construction, from mostly scrap and cheap materials, of a traveling wave looped-tube thermo-acoustic engine capable of generating higher sound level. The design is conducted using a code program named Design Environment for Low-Amplitude Thermo-acoustic Energy Conversion that helps to simulate in fine details the performance of the device. Three ceramic substrate blocs of different porosities have been considered as regenerators during the simulation. The results showed that the smaller porosity produced higher acoustic power. The higher performing bloc was subsequently used to develop and test a physical prototype. The constructed looped-tube thermo-acoustic engine produced a sound level of 121.4 decibel, just above the minimum auditory pain threshold.

Keywords
Thermo-acoustic, traveling-wave, engine, looped-tube, DELTAEC.

1. Introduction

The escalation of the human lives on earth is contributing to the stress the planet is facing with respect to the management of its resources and the mitigation of environmental issues resulting from it. The potential damage of pollution has resulted in the prohibition of ozone depleting substances such as chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) by the Montreal Protocol. The latter is now forbidden in developed countries and is planned to be phased out by 2030 in developing countries (Montreal protocol, 1987). Anyanwu (2012) study provides details on the danger human health and ecosystems are exposed to from the pollution caused by chlorofluorocarbons (CFC) used as refrigerants in the refrigeration systems.
The development of thermo-acoustic devices could potentially reduce air pollution. The devices consist of either a thermo-acoustic engine, also called prime mover (Power producer device); or a thermo-acoustic refrigerator (TAR), also called heat pump (Power consumer device). The former convert thermal energy from waste heat, such as solar and furnace heat, into acoustic energy by inducing a temperature difference across a porous material (regenerator). The latter utilises the generated acoustic energy to oscillate sound inside the small channels of a porous material and induce cooling. It pumps heat from the cold heat exchanger side to the ambient heat exchanger side, thus, converting acoustic energy into thermal energy. Configuration types of thermo-acoustic devices can be arranged into two major groups according to their external shapes: The standing-wave and the travelling-wave configurations. Existing

literatures suggests that the performance of travelling-wave thermo-acoustic device is relatively higher in comparison to standing-wave device.
In this study, we focus on the looped tube traveling-wave thermo-acoustic engine (TWTAE). A program named Design Environment for Low amplitude Thermo-acoustic Energy Conversion (DELTAEC) has been used as a simulation code to design the engine and predict its performance. The acoustic energy generates the cooling effect without intervention of toxic coolants and lubricants. The acoustic energy could be used to induce cooling or generate electricity in some applications. This is a sustainable way, waste heat, released in the atmosphere, could be recovered for a better use. Its simplicity means low manufacturing and low maintenance costs. The present TWTAE consists of a hermetically sealed looped tube (resonator), a porous material (regenerator) where the temperature gradient is created by two heat exchangers. A thermo-acoustic effect can be well explained by a working principle of a TAR provided by Swift (2003). In Figure 1 an illustration of looped tube TWTAE is shown. The peaks and other points of the wave move spatially in travelling wave devices. The phase difference between the pressure and the velocity approaches 0º.

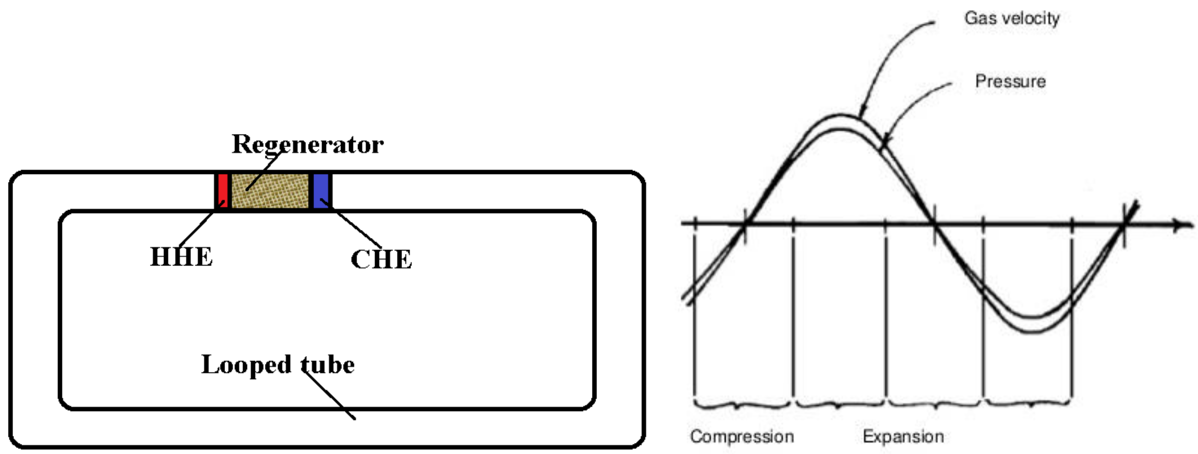

Figure 1. (a) Travelling-wave thermo-acoustic engine (b) Pressure and velocity variation with time in a travelling-wave thermo-acoustic device (Adapted from Ceperley, 1979)

2. Material choice and motivation

The environmental and cost benefits of thermo-acoustic devices and their potential to replace conventional energy generators have led researchers around the world to intensify effort to improve the performance of the thermo-acoustic devices. Previous studies have shown that the efficiency of thermo-acoustic devices depends on the material and the geometrical configuration of the stack/regenerator (Balonji et al., 2017) (Tourkov and Schaefer, 2015). The regenerator is generally made of ceramic substrate materials with regular channels. It is used as a catalytic converter in exhaust systems. When compared to other materials such as metals, it offers many advantages, including, low cost, high mechanical strength at high temperature, thermal stability, uniform porosity, availability, low thermal conductivity, high melting point and high heat capacity.
This paper illustrates how the material and the geometrical configuration of the regenerator affects the performance of the engine. For a particular case of study, we have chosen to focus on the effect of porosity among other geometrical configurations. Three regenerators made of different materials: ceramic, stainless steel and Mylar have been used in the simulation of TWTAE. The most performing regenerator have been identified. Subsequently, three different porosities have been investigated namely 230, 300 and 400 CPSI. The regenerator that produced high acoustic power has then been used in the construction of a prototype of a TWTAE in order to test experimentally the potential of TWTAE for sound generation.

3. Simulation with DELTAEC

The DELTAEC (Design Environment for Low-Amplitude Thermo-acoustic Energy Conversion) is a design program that, numerically integrates wave equations in a gas according to arrangements defined by the user as a sequence of segments such as duct, regenerator, heat exchangers (Hx). This software is used more and more for its aptitude to update dependent values after every amendment, to complete design of apparatus at required performances, to integrate differential equations for each segment with pressures and other variables, and to display results using user interface, built-in graphics displays, or a spreadsheet (Ward et al., 2012). It is readily available from the Los Alamos National Laboratory website (http://www.lanl.gov/org/padste/adeps/materials-physics-applications/condensed-matter-magnet-science/thermoacoustics/computer-codes.php).

3.1. Effects of the regenerator material on the acoustic power in a travelling-wave thermo-acoustic engine: Simulation 1.

In this section, the influence of the material selected to construct the regenerator of the TWTAE have been analysed. Three different regenerator materials (The ceramic, the stainless steel and the Mylar) have considered while most of the other geometrical parameters have been kept unchanged. The length of the regenerators is varied in the interval of 84 to 104 mm and the results obtained have been recorded and compared.

3.1.1. Identification of main parameters

The length of the resonator (*Ls*) was set to be 2700 mm. For a travelling-wave thermo-acoustic device, the resonator length is equal to the wavelength (λ = L). The operating parameters are: Mean temperature (Tm), dynamic Pressure (Po), frequency (f) and mean pressure (Pm). The gas parameters are: Dynamic viscosity (μ), thermal conductivity (K), sound velocity (a), specific heat (Ɣ), density (ρ); The stack parameters are: stack length (Ls), plates spacing (2yo), stack position (Xs), porosity (ϕ), plates thickness (2l), cross section (A), thermal conductivity (Ks); density (ρ), specific heats (Cs), Stack diameter (Ds). Tables 1 and 2 depict the summary of parameters used to define the working condition of the engine:

Table 1. Operating parameters considered for simulation 1

Operating & gas parameters	Pm bars	Po bars	f Hz	Tm K	µair20º Kg/ms	Kair20º W/(mk)	a air20º m/s	Ɣair20º KJ/(KgK)	ρair20º Kg/m³
Values	1.7	0.15612	± 300 Guessed	± 125 Guessed	± 125 Guessed	0.0257	343	1.005	1.205

Table 2. Geometrical parameters considered for simulation 1

Geometrical parameters	Regenerator diameter mm	Regenerator length mm	Porosity CPSI	Heat exchanger thickness Hot/Cold	Length mm
Values (range)	60	84-104	200	27/22	2700

3.1.2. Illustration of the simulation procedure

The parameters defined previously were used as input parameters in the DELTAEC models and kept the same for all the experiments. The regenerator length has been varied in an interval of 84 to 104 mm, and its influence on the performance of the thermo-acoustic engine was investigated for an engine two heat exchangers. The results obtained were compared and the best performance was identified.

3.1.3. DELTAEC model design, analysis and results

The DELTAEC was used to numerically integrates wave equations in a gas according to patterns defined as a sequence of segments such as duct, stack, heat exchangers (Hx) as shown in Figure 2.

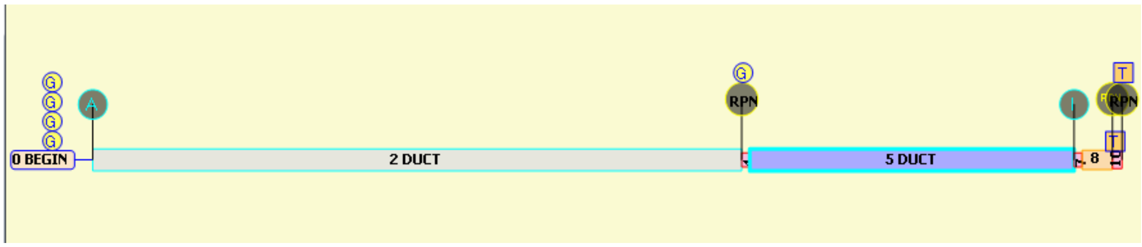

Figure 2. Pictorial representation of DELTAEC refrigerator for operating pressure variation

The simulation has been conducted varying the regenerator's length in the interval of 84 to 104 mm to find the acoustic Power of three engines with two cold heat exchangers and different materials. The equation below has been incorporated into the DELTAEC program and a reverse polish notation (RPN) has been used to perform algebraic calculations.

$$\dot{E} = \frac{1}{2}\mathrm{Re}[p_1.\tilde{U}] \qquad \text{Equation 1}$$

Dry air has been used as gas. Five parameters (The frequency, the flow, the operating pressure, the angle phase and an RPN) have been used as "GUESSES" and five others (The temperature of the solid and 4 RPN) as "TARGETS". Input parameters are shown in the Table 3.

Table 3. DELTAEC input parameters for single and double cold heat exchangers

Regenerator materials	Cell density CPSI	Operating pressure Bars	Porosity %	Wall spacing mm	Plate spacing mm	Input heat W	Net cooling power W
Ceramic Mylar Stainless steel	200	1.7	0.75111	0.1	0.65	201	80

The results obtained, show that the acoustic power of the engine depend on the regenerator materials as illustrated in Figure 3. The results obtained clearly shows that higher acoustic power of the engine is expected with regenerator made of Mylar. Mylar regenerator has reached a higher maximum acoustic power of 28.644 W, ceramic regenerator has achieved 24.002 W, while stainless steel could only reach at 2.9673 W. This result is well understood as the Mylar has a relatively low thermal conductivity. But in practice it can not be used to sustain higher temperatures generated by engine's heat exchanger because of its low melting point. Therefore the ceramic regenerator has been selected in this study.

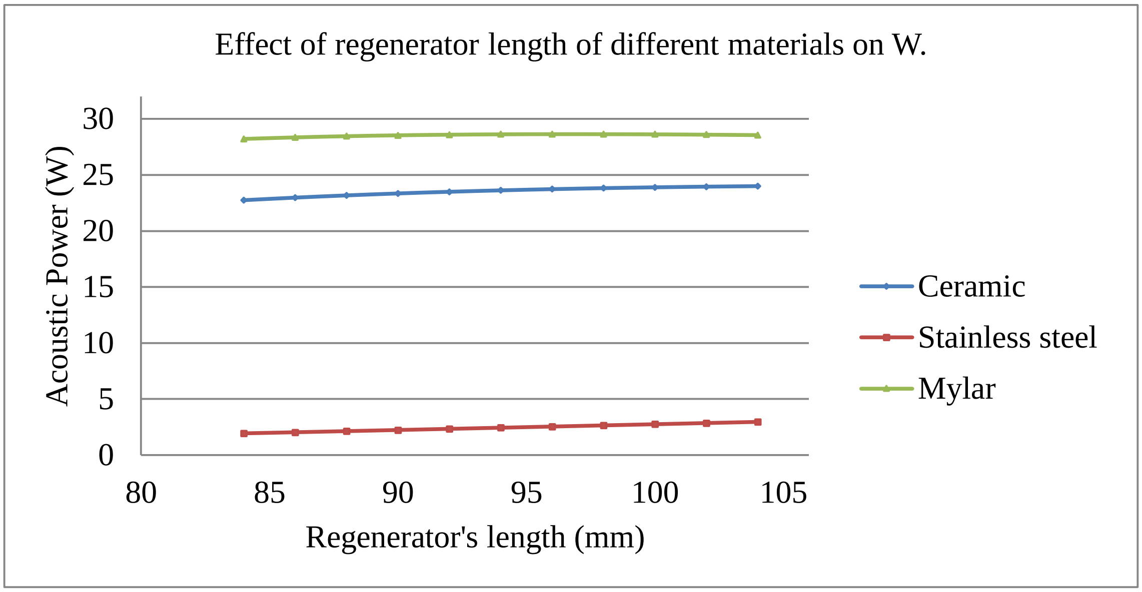

Figure 3. Effects of the regenerator material on the acoustic Power in a travelling-wave thermo-acoustic engine.

3.2. Effect of regenerator's porosity on the acoustic power in a travelling-wave thermo-acoustic engine: Simulation 2

This section aims at investigating the influence of the porosity of the regenerator in a travelling-wave thermo-acoustic engine. The simulation was performed with DELTAEC. This simulation has been used to predict the performance of regenerator in travelling-wave thermo-acoustic engine. In particular the DELTAEC code provided guidance on:

- The selection of parameters capable of achieving an acoustic power at a frequency to possibly produce the highest sound level;
- The selection of the most performing among the three different regenerators of various porosities before the engine manufacturing.

The parameters computed in this section have been used to construct the travelling-wave thermo-acoustic engine presented in the next section.

3.2.1. Identification of main parameters

The length of the resonator (*Ls*) was set to be 1.95 mm. For a travelling-wave thermo-acoustic device, the resonator length is equal to the wavelength (λ = L). Table 4 and 5 depict the summary of parameters used to define the working condition of the device:

Table 4. Operating parameters

Operating & gas Parameters	Pm (bars)	Po (bars)	f Hz	Tm K	µair20º Kg/ms	Kair20º W/(mK)	aair20º m/s	Ɣair20º KJ/(KgK	ρair20º Kg/m³
Values	1.0	0.0859 guessed	± 150 Guessed	303	18.2	0.0257	343	1.005	1.205

Table 5. Geometrical parameters

Geometrical parameters	ϕ CPSI	Regenerator diameter mm	Regenerator length mm	Gas A/A %	Resonator length mm	Heat exchanger thickness mm Hot/Cold
Values (Range)	230 300 400	73.4 73.4 73.4	75 75 75	72.65 68.7 63.03	1950	17/26

3.2.2. Illustration of the simulation procedure

The parameters defined previously were used as input parameters in the DELTAEC models and kept the same for all simulations. The regenerator porosity has been varied in a range of 230 to 400 CPSI, and its influence on the performance of the thermo-acoustic engine was investigated. The results obtained were compared and the best performance was identified and considered for construction.

3.2.3. DELTAEC model design, analysis and results

The DELTAEC was used to numerically integrates wave equations in a gas according to patterns defined as a sequence of segments such as duct, stack, heat exchangers (Hx) as shown in Figure 4.

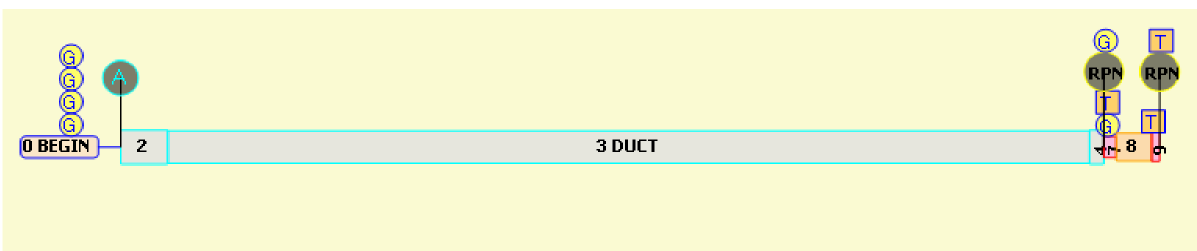

Figure 4. Pictorial representation of DELTAEC Travelling-wave thermo-acoustic engine

The simulation has been performed for each regenerator to find the acoustic power of each travelling-wave thermo-acoustic engine. Dry air has been used as gas, five parameters (The frequency, the flow, the operating pressure, the angle phase and an RPN) have been used as “GUESSES” and five others (The temperature of the solid at cold side, temperature of the solid at hot side and 3 RPN) as “TARGETS”.
The results showing the acoustic power of the engine for each regenerator is reported in Table 6. The results obtained clearly shows that higher acoustic power of the engine is expected with the 400 CPSI regenerator producing 31.456 W at 159.18 Hz. The 300 CPSI regenerator has produced 9.7447 W at 158.48 Hz and the 230 CPSI regenerator has produced 5.8263 W at 158.10 Hz . Lager density of pores has resulted in higher acoustic power. Hence, a 400 CPSI has been selected for construction.

Table 6. Acoustic power as function of regenerator porosity

Regenerator porosity	230 CPSI	300 CPSI	400 CPSI
Acoustic power	5.8263 W	9.7447 W	31.456 W

The following conclusion was drawn from the investigation conducted in this section. With respect to the effect of the regenerator material on the acoustic power in a travelling-wave thermo-acoustic engine: higher acoustic power of the engine was obtained with regenerator made of Mylar. But Mylar can not be used in higher temperature engine because of its low melting point. The ceramic substrate has been adopted for this study; With respect to the effect of regenerator’s porosity on the acoustic power in a travelling-wave thermo-acoustic engine: higher acoustic power of the engine was obtained with regenerator of smaller porosity. Therefore the 400 CPSI ceramic regenerator has been chosen to be used for the engine prototype construction.

4. Construction and experimental investigation of a looped tube thermo-acoustic engine

A looped tube thermo-acoustic engine has been built according to the specification described in the previous simulations. The prototype consists of a looped tube with a core located somewhere along the loop. Air at atmospheric pressure has been used as working gas. The operating frequency was between 140 and 200 Hz. The regenerator is the 400 CPSI ceramic substrate with square channels, 75 mm long and 64 mm square section. The resonator is made out of steel and PVC pipes to form a looped tube. The hot heat exchanger is made of 300 Watts heater cartridges fitted at one side of the regenerator. The cold heat exchanger is a two directions network of copper tubes circulating cold water at the other side of the regenerator.

4.1. Designing of parts and manufacturing procedures

The resonator has a length of 1.95 meters. It is composed of a metallic and PVC parts as shown in Figure 5. The outside and inside diameters are 76 mm and 71 mm respectively.

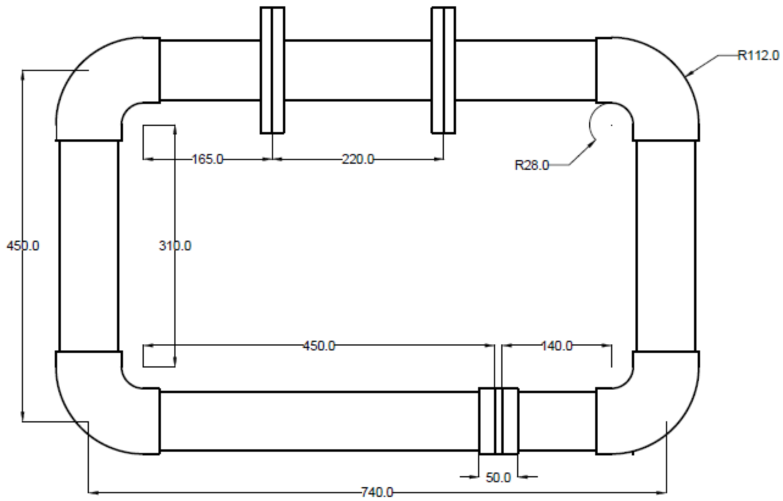

Figure 5. Resonator configuration

Figure 6. The core

In the present work, the core (Figure 6) is a scrap material made out of a 205 mm long square tube with outside and inside dimensions: 75 × 75 mm and 65 × 65 mm respectively. It is the part of the engine that encloses the regenerator and heat exchangers. The chosen hot heat exchanger (HHE) is a set of three cartridge-heaters fitted in a foil as shown in Figure 7. The outside diameter of each cartridge heater is 10 mm, the length is 65 mm with a rating of 300 watts. The foil is made out of a copper sheet (780 mm long, 15 mm large and 0.5 thick). It has been folded, then perforated to fit in the cartridge heaters as shown in Figure 7. Six feed-ins have been designed to carry out the three pairs of heaters lead wires, while insuring that the resonator is hermetically sealed to keep the pressured air from escaping.

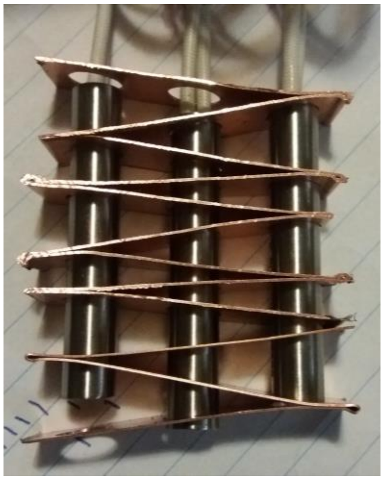

Figure 7. Heater cartriges

Figure 8. Copper cold heat exchanger

The preferred cold heat exchanger (CHE) for the present project is a tubular-fin heat exchanger (Figure 8). This gas-to-liquid heat exchanger consists of an array of copper tubes in contact with the copper fins. The fin is a 1 meter long, 25 mm width and 0.5 mm thick copper sheet, perforated on two columns, and folded into 16 foils in zigzag pattern inside a square channel. The tubes are made of copper material similar to those used in conventional refrigerator systems. They are ¼ inch outside diameter and 0.74 thick. They are 10, aligned in 2 columns of 5 and welded and slide in the perforated holes of the foils. The schematic view in Figure 9, describes the circuit of the water cooling system. The assembly of different part has been a meticulous work as it aimed to form a hermetic system. A kind of silicone product called 'hot-gum ' has been used for its glue-like property and its ability to resist high temperatures. Figure 10 shows the assembly work in progress.

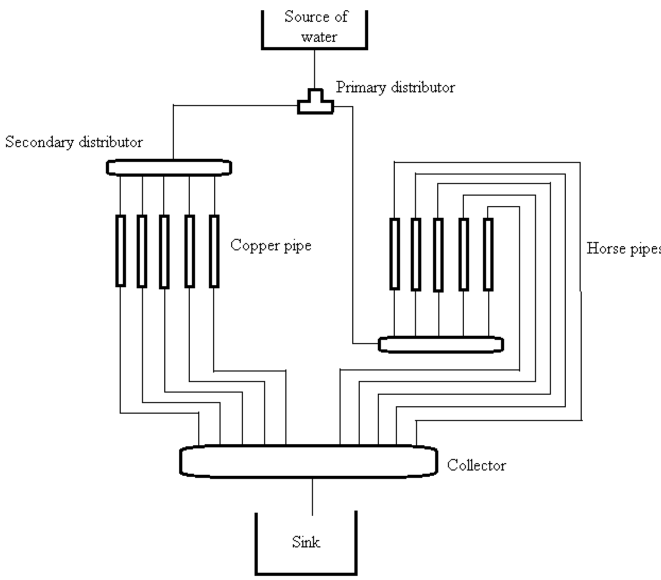

Figure 9. the circuit of the water cooling system

Figure 10. View of TWTAE assembled

4.2. Instrumentation

Thermocouples were used to measure the temperature at both side of the regenerator. The thermocouples are made of chromel and alumael and have a temperature range of 0 – 800 ˚C. The accuracy of the thermocouples is ±2.2˚C. The signal processing, analysis and visualization were performed through the use of a NI DAQ (9211A) data acquisition and Labview. The frequency of the sound was measured using a NI myDAQ attached to the sound level meter (SL-4013). The pressure gauge reads the pressure inside the engine and is positioned at 1.70 meter from the cold heat exchanger.

4.3. Experimental process

The model has been set up to use air as operating gas at atmospheric pressure. The cold heat exchanger (CHE) was receiving water from the tap and was rejecting it in the tank at a rate of 0.141 liter/s. The hot heat exchanger was connected to a 220 volts power supply. The process starts when the cartridge heaters power supply is switched on and it ends when the acoustic level returns to its initial value. Before the engine starts, running water was flowing through the pipes passing through the cold heat exchanger. Afterward the heaters were powered while the behaviour of the temperatures (cold and hot), the frequency of sound, the sound level and the time elapsed to reach the maximum sound level were being observed. Particular attention was paid to the resonance period during which the acoustic power was generated. During this process, we have monitored the temperatures (cold and hot), the frequency of sound, its magnitude and the time taken for the engine to reach its full potential.

4.4. Results and discussions

The results obtained from this experimental test, namely the temperatures, the frequency and the sound level, are described in the following section.

Temperatures: Figure 11 provides an illustration of the temperature changes across the regenerator within the thermo-acoustic engine. It shows the hot side temperature (red line) and the cold side temperature (blue line) while the heat is provided by the cartridge heaters. During the first part of the experiment (up to around 600ºC), no sound was generated irrespective of how high the heat provided were. As highlighted in Figure 11 (in blue), a sudden increase of the magnitude of the sound-wave was observed around 610ºC resulting in a small turbulence as suggested by the trend of the hot temperature. This temperature constitutes the onset temperature described as the minimum temperature required to generate a sound wave. This sound-wave was sustained, once initiated, during the entire period of the testing. This is quite an important finding with respect to the applicability of heat-to-sound conversion in thermo-acoustic engine. Recent researches suggest the possibility of decreasing the onset value through the use of a multi-stage configuration (Zhang et al., 2016).

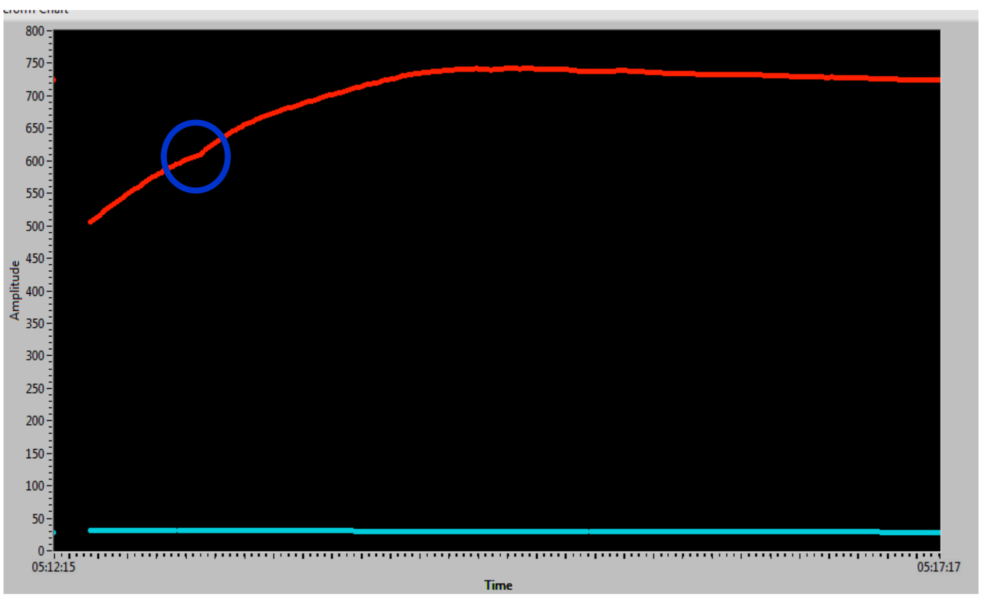

Figure 11. Experiment results for temperatures during resonance period

In order to assess how sustainable the sound-wave generated was, with respect to the supplied heat energy, the influence of the hot side temperature was investigated. Figure 12 highlights the minimum hot side temperature below which the sound died off. This temperature was estimated to be around 350ºC. Below this value, the sound wave, which has reached a maximum value during resonance dies off. Interestingly, this value was not similar to the onset value identified previously. The cold heat exchanger has proven to be very efficient looking at how stable the temperature at the cold side appear were (Figure 11 and 12).

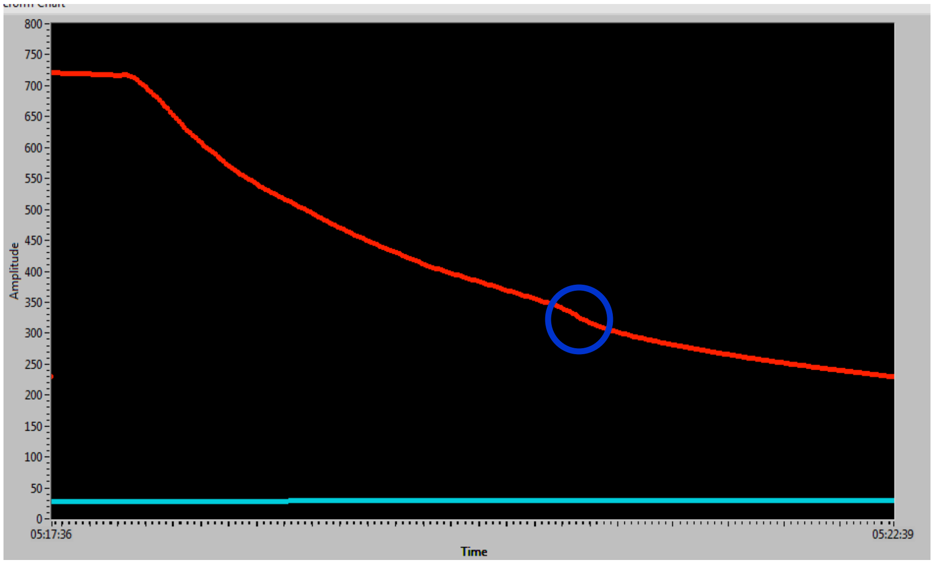

Figure 12. Experiment results for temperatures after resonance period

Frequencies: Figure 13 shows the fast Fourier trasformation (FFT) representing the fundamental frequency and the harmonics of the sound wave generated during resonance. These frequencies were evaluated to be around 158 Hz, 316 Hz and 474 Hz corresponding to the three pics highlighted.

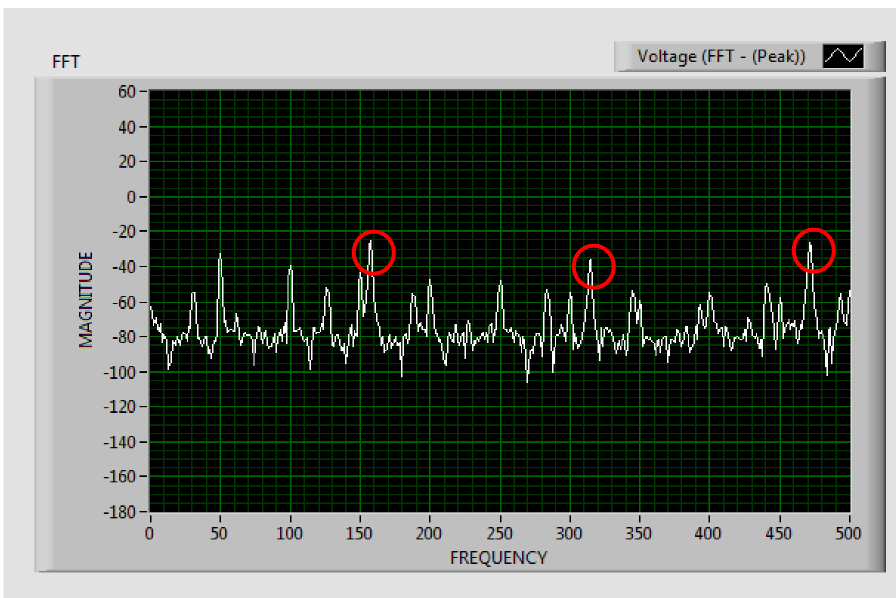

Figure 14. Sound wave frequencies with peaks at interval of 158Hz

Sound levels: A sound level of 121.4 dB corresponding to a temperature difference of 577.6ºC has been generated with the model considered in this experimental test of the travelling-wave thermo-acoustic engine. The onset time, which is considered to be the time taken for the sound wave to start, was estimated to be 121 sec.

5. Conclusion

This work has analysed the performance of a looped tube thermo-acoustic engine with a main focus of providing clarity on the influence of the regenerator's geometrical parameters on the performance of the device. A numerical simulation has also been performed to predict the performance of the engine with the most effective regenerator to be used in the construction of a travelling-wave thermo-acoustic engine. Material and geometrical parameters of the regenerator have an impact on the travelling-wave engine's performance. Mylar regenerator has shown great performance over the stainless steel and the ceramic ones. But the latter has been chosen because of its ability to stand high temperatures. The 400 CPSI ceramic has been used in the built prototype as it has performed better than the 300 and the 230 CPSI. From the experimental test performed on a travelling-wave engine, constructed with scrap and cheap materials, a sound level of 121.4 dB, corresponding to a temperature difference of 577.6ºC across the 400 CPSI regenerator considered in this experiments, was measured. Although the onset temperature reported in this study was relatively higher, the results reported have undoubtedly demonstrated the potential for travelling-wave thermo-acoustic engine for sound generation.

6. Acknowledgements

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7. References

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8. Biographies

Balonji Serge is a Master's degree candidate at the University of Johannesburg in South Africa. He earned a Bachelor degree of technology at the University of South Africa. He has 16 years' experience in manufacturing of Joy Mining works and components design. He published a conference paper on thermo-acoustic refrigeration. His research interests include thermo-acoustic, manufacturing, design and analysis, optimisation, modeling and simulation. He is member of SAIMechE.

Lagouge Tartibu is a senior lecturer in the department of Mechanical Engineering Technology at the University of Johannesburg in South Africa. He has been a Lecturer for Cape Peninsula University of Technology (2007-2012) and Mangosuthu University of Technology (2013-2015). He holds a Doctorate degree in Mechanical engineering from Cape Peninsula University of Technology (2014) and a Bachelor degree in Electromechanical Engineering from the University of Lubumbashi (2006). His primary research areas are thermal science, electricity generation and refrigeration using thermo-acoustic technology, mathematical analysis/optimization and mechanical vibration.

Tienchen Jen is a professor in the Department of Mechanical Engineering Science at the University of Johannesburg in South Africa. He holds a Doctorate degree in Mechanical and Aerospace Engineering from the University of California. Prof Jen has made extensive contributions to the field of mechanical engineering, specifically in the area of machining processes. Examples include, but not limited to, environmentally benign machining, atomic layer deposition, cold gas dynamics spraying, fuel cells and hydrogen technology, batteries, and material processing. His current interest centers on cutting-edge hydrogen energy generation and storage.