INFLUENCE OF FEEDBACK LOOP CHARATERISTICS ON THE PERFORMANCE OF A TRAVELLING WAVE THERMOACOUSTIC ENGINE

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Abstract: A method to find experimentally the equivalent effective length of the Thermoacoustic (TA) Core of a TA Engine (TAE) was proposed. The TAE is first operated with various Feedback Loop (FL) length configurations. For every configuration, the frequencies of the sound waves were recorded to determine the wavelengths. These wavelengths are compared with the measured FL lengths and a constant deviation was observed, which gives the effective length of the TA Core as 55cm. This effective length is used in the calculation of a FL Ratio and the optimum FL Ratio was found to be 3.4.

1. Introduction

In 1979, Ceperley explained the fundamental principles of a Travelling Wave TAE and its potential of achieving higher efficiency compared to Standing Wave TAE [1]. However, it is until 20 years later only did this potential was significantly demonstrated by Backhaus and Swift [2]. By placing the regenerator in a toroid tube connected to a resonance tube, the Travelling Wave TAE designed by Backhaus et al. operated at 41% of Carnot efficiency, which was at least 50% higher than the best Standing Wave TAE at that time. Despite demonstrating that high efficiency is achievable, the design and operating conditions of this TAE is not feasible for many real world applications. Biwa et al. has shown that increasing the number of regenerators in the toroid is able to reduce the onset temperature of the TAE, thus increasing the possibility of different heat sources to the TAE [3]. Also, De Blok suggested that the regenerator in the toroid shape has to overcome large acoustic losses when connected to the resonance tube [4]. To overcome this, the resonance tube is removed entirely and the regenerators are connected in a complete loop, which is denoted as the FL. De Blok's design involves 4 regenerators positioned at quarter wavelengths apart so that the impedance of the TA core matches the impedance of the FL in a similar manner as a quarter wave impedance transformer, thus eliminating reflection in the FL [5]. The minimum onset temperature difference achieved by this engine is 30K [5]. These works have encouraged developments of multi-stage travelling wave TAEs.

In the University of Nottingham (UoN) and University of Nottingham Malaysia Campus (UNMC), together with the collaboration of the SCORE project [6], a two stage travelling wave TAE was designed and manufactured by Baiman et al. [7]. This TAE has two identical TA cores connected by the FL. Thus, the FL is separated into two sections. The lengths of these two FL sections are intended to be a quarter wavelength and three quarter wavelength to match the impedance of the TA core and the FL. However, the dimensions of the parts in the TA core also contribute to the length of the FL. Together with the complicated design in the TA core, it was found to be very challenging to obtain the optimum length configuration of the FL to achieve the quarter and three quarter wavelengths configuration.

This paper describes an experimental investigation conducted to obtain an equivalent length contributed by the TA core and subsequently obtain the optimum length configuration of the FL. An offset between the theoretical and measured length of the FL indicates the equivalent length of the TA core. If is found that the TA core of the TAE has an equivalent length of 55cm. This 55cm is included in the calculations of the FL Ratio and the optimum FL Ratio is 3.4. Modifications were made to the experimental set up as part of the future work.

2. Experiment

The Two Stage Travelling Wave TAE mentioned above was used in this experiment. The schematic diagram of the TAE is shown in Fig 1 and a detailed description of the TAE is presented in this paper. [7]. Referring to Fig 1, the FL connects both TA cores to form a closed loop. There are two U-Bends present in the loop. The straight sections of the FL are made by connecting PVC pipes of various lengths until the desired length is achieved. This allows the FL length to be varied and so does the operating frequency. During the experiment, the following data were measured and recorded:

- The frequency, f of the oscillation.
- The Peak Pressures at TA Core 1 and 2.
- The temperatures at the Hot Heat Exchangers (HHX) and Ambient Heat Exchangers (AHX). The difference between both heat exchangers' temperatures will be denoted as Temperature Difference (TD) for the rest of this paper.
- The length of section AB and section CD in Fig 1.

The HHX is heated from room temperature until 400°C, allowing the onset TD of the engine to be recorded. The AHX is kept at room temperature through water cooling. K-Type Thermocouples are attached to both sides of the Regenerator in both TA cores. The Pressure Transducers used are Kulite HKL-375 (M) Series. A self-written Labview Program is used to display the experimental data.

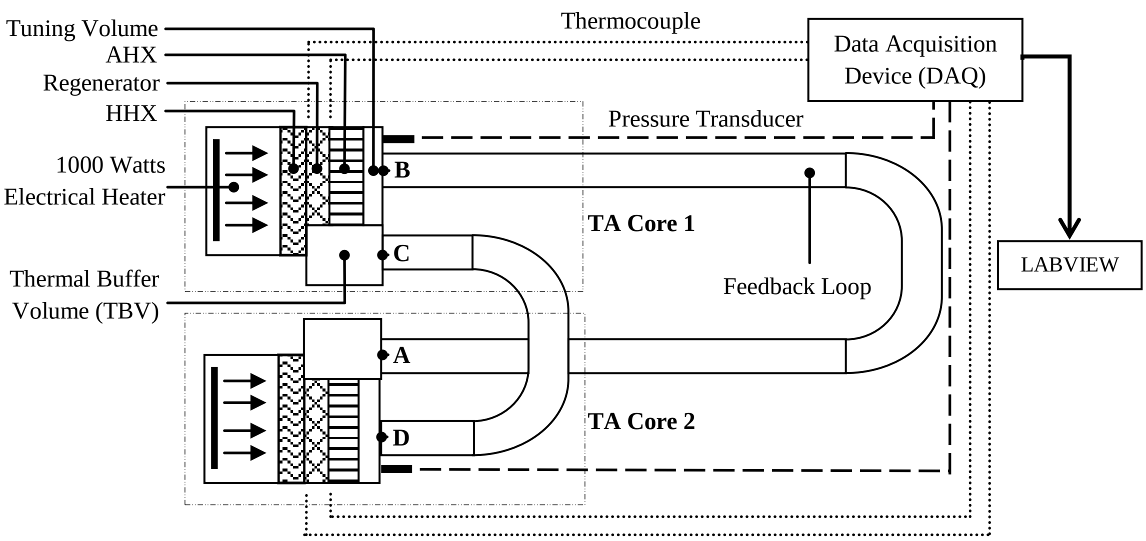

Figure 1: Schematic diagram of the Two Stage Travelling Wave TAE. Both TA cores are identical. Illustration is not to scale.

3. Results and Discussion

The lack of moving parts in a TAE allows the TA core to be designed to facilitate the performance of the heat exchangers. However, this would cause the TA core to be designed with complex geometries, as evident in the TAE used in this work. Due to this, it is very challenging to measure the effective length of the components in the TA core, which contributes to the overall length of the FL. Thus, an experimental investigation was carried out to estimate the effective length of the TA Core. The TAE was first tested at various FL configurations to obtain a range of operating frequencies. Then, by using the following relation,

$$v = f\,\lambda \tag{1}$$

where v is the speed of sound (343 m/s) and *f* is the frequency of the wave in the engine, the wavelength, λ can be obtained. This wavelength is the Theoretical length of the FL. Fig 2 shows the measured and theoretical FL length at various frequencies. From equation (1), it is apparent that the wavelength and 1/*f* has a linear relationship, thus the FL lengths are plotted against 1/*f*. The Measured Length refers to the physically measured length. The lengths of both U-Bend centrelines are measured physically as 57cm. From Fig 2, it is observed that there is an offset of 1.1m between the Measured and Theoretical lengths for every frequency which reveals the length contributed by both TA cores. Thus, ignoring manufacturing tolerances, a single TA core contributes 0.55m.

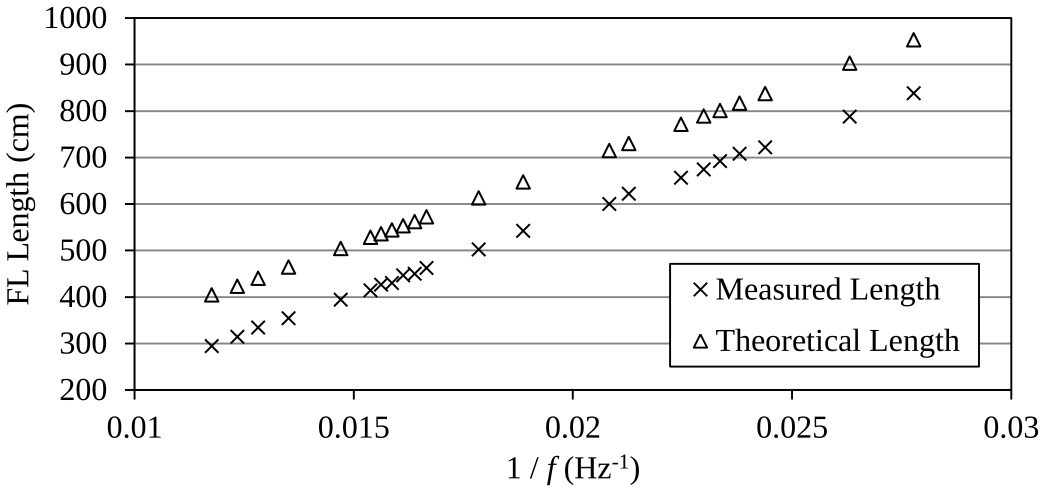

Figure 2: Measured (X) and Theoretical (Δ) FL length at various frequencies, *f*.

By adding 0.55m to the length of section AB and CD, the FL Ratio of every FL configuration was computed by

$$FL\ Ratio = \frac{0.55m + Length\ AB}{0.55m + Length\ CD} \tag{2}$$

The TAE performance at various FL Ratios was compared in Fig 3. The Average Onset TD between both TA cores (left vertical axis) and Peak Pressures at TD of 300 ºC (right vertical axis) are plotted against the FL Ratio. When the TD reaches 300°C, the corresponding Peak Pressures in both TA cores are recorded to give a common point for comparison. The desired performance is for a low Onset TD and high Peak Pressure, which was observed at the FL Ratio of 3.4. Also, notice that at smaller FL Ratios, the Peak Pressure in TA Core 1 is lower than that in TA Core 2, but at larger FL Ratios the Peak Pressure in TA Core 1 is higher. The

FL Ratio that gives the highest Peak Pressures at TD 300 °C occurs when the Peak Pressure at both TA cores are similar, indicating that both TA cores are performing at its optimum at this FL Ratio. At FL Ratio of 3.4, the Length AB and CD are 5.51m and 1.23m respectively. The Onset TD recorded for TA Core 1 and 2 are 167.61 °C and 136.66 °C respectively. However, to achieve the quarter wavelength and three quarter wavelength configuration, a FL Ratio of 3.0 is desired. The TAE performs at its optimum at FL Ratio of 3.4 indicates that a slight impedance mismatch between the FL and the TA core is desired. A slight impedance mismatch will introduce a minor Standing Wave component to the sound wave which has shown to improve the performance of the TAE [8].

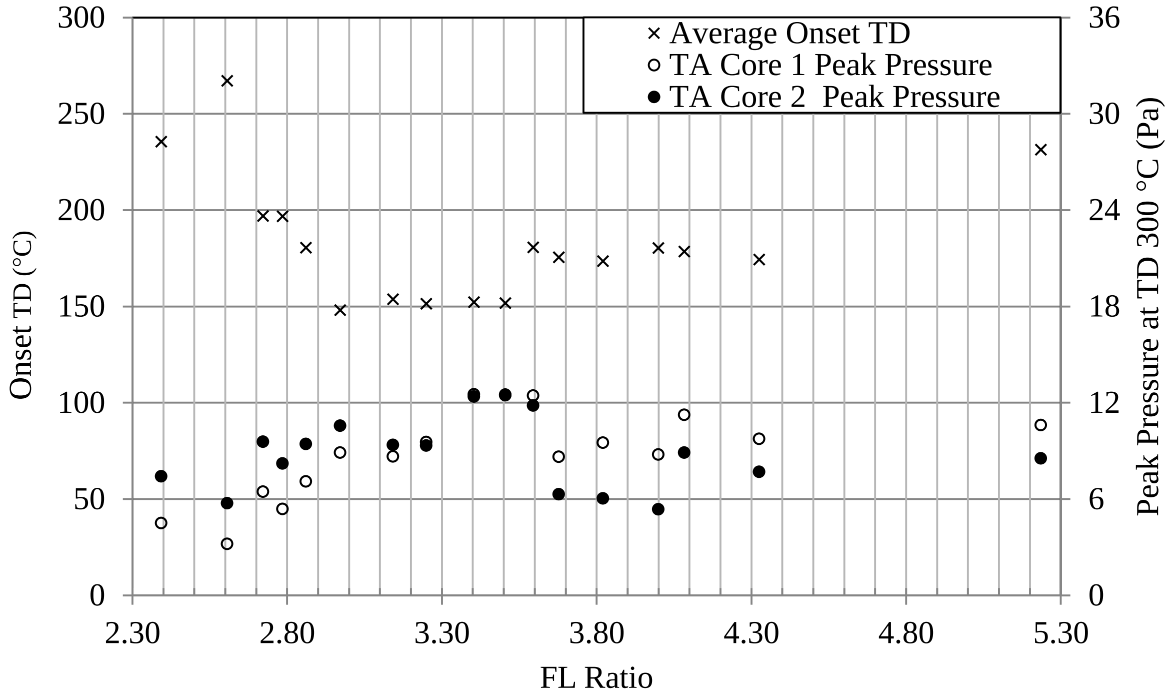

Figure 3: Comparison of the TAE performances at various FL Ratios.

Subsequently, 8 pairs of pressure transducers are added to the FL to investigate the sound wave produced by the TAE. The pressure transducers are 15cm apart in every pairings. The position and Peak Pressure recorded by the pressure transducers are shown by the markers (Δ) in Fig 4. Point A (from Fig 1) is set as the starting position and the position of all the components in the FL are referenced to Point A. The FL Ratio of the FL configuration shown in Fig 4 is 3.95, where the lengths of section AB and section CD are 625 cm and 117cm respectively. From Fig 4, it is observed that the sound wave produced by the TAE is amplitude modulated, indicating a Standing Wave component is present in the sound wave.

Unfortunately, at the time of writing of this paper (March 2014), the Peak Pressure along the FL of other FL Ratio has not been tested. It is intended to obtain the Standing Wave Ratio (SWR) of the sound wave produced by the TAE at various FL Ratios. The intensity of the sound wave along the FL could also be estimated [9]. These will be the subject of future work. The TAE used is still in its development stages and other features in the TA core are still not optimized. The work presented is useful in predicting the optimum length configuration of the FL of the TAE, especially when modifications are made to the TA core. It is also important to note that this experiment was conducted at the TAE's operating conditions.

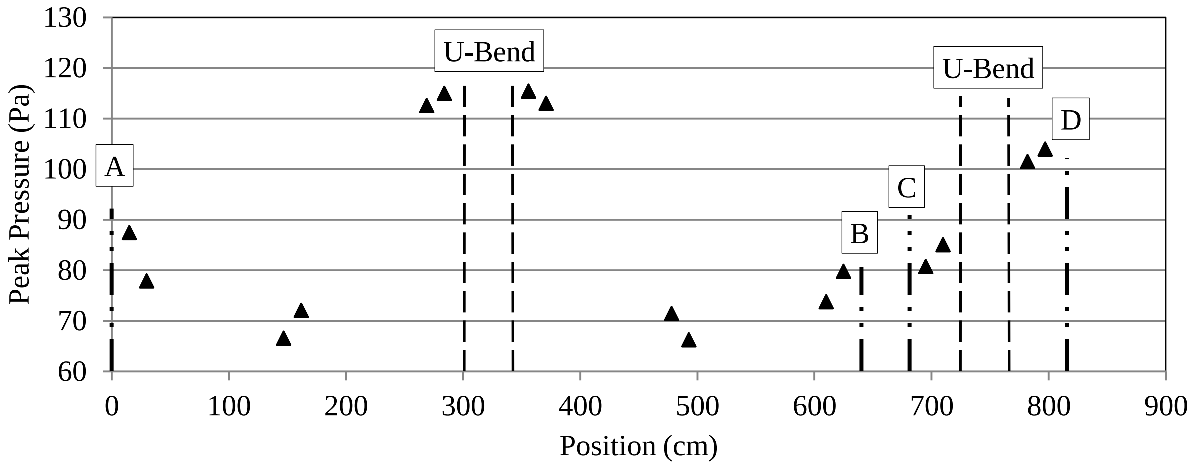

Figure 4: Peak Pressures along the FL.

4. Conclusion

In a Two Stage Travelling Wave TAE developed by the SCORE project, the FL was designed such that the two TA cores are a quarter wavelength apart and three quarter wavelength apart for the remainder of the FL. However, due to the complexity of the TA core, the length of the FL is hard to estimate as the effective length of TA core has to be accounted for as well. An experimental investigation to obtain the effective length of the TA core was explained. The effective length was found to be 55cm and this is then used in the calculations of a FL Ratio. A figure of Onset Temperature Difference and Peak Pressure versus FL Ratio was plotted to compare the TAE performance at various length configuration. It is found that the TAE performs best at a FL Ratio of 3.4.

Subsequently, pressure transducer pairs are added to the FL to measure the Peak Pressure along the FL. The Peak Pressure along FL of other configurations will be analyzed and compared to confirm that the FL Ratio of 3.4 is the optimum for the TAE. This will be included in future work.

5. References

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