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Determination Performance of Thermoacoustic Heat Engine Simulation by Delta EC Software

Irfan Abd.Rahim.[1,2,a], Mohd Zarhamdy Mohd Zain [3,b],
Nor Zelawati Asmuin.[4,c] and Mohd Sazli Mohd Saad [1,2,d]

[1]Green Design and Manufacture Research Group, Center of Excellence Geopolymer and Green Technology (CEGeoGTech), School of Materials Engineering, Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia

[2]School of Manufacturing Engineering, Universiti Malaysia Perlis (UniMAP), 02600 Perlis

[3]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor

[4]Faculty of Mechanical Engineering, Universiti Teknologi Tun Hussein Onn Malaysia (UTHM), 86400 Johor

[a] irfanrahim@unimap.edu.my, [b]zarhamdy@fkm.utm.my, [c]norzela@uthm.edu.my,
[d]sazlisaad@unimap.edu.my

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Abstract. Thermoacoustic Heat Engine probably the most efficient energy source for electronic devices for the next 10 year ahead that require small amount of electrical energy to operate. This study was to simulate the Thermoacoustic Heat Engine (TAHE) standing wave system by conducting a Fluid Structure Interaction (FSI) by using a Thermoacoustic system's software named DeltaEC for better uderstanding on the fundamental of TAHE standing wave system. Some characteristics or parameters in the system that were studied in order to derive the fundamental knowledge of TAHE standing wave system. The thickness of Hot Heat Exchangers (Hot HX) plays the major role in affecting the maximum acoustic power generated, the level of onset temperature difference and maximum pressure amplitude followed by the stack length. Hot HX dimension (thickness) contributes nearly 3.3% changes in maximum acoustic power where the lowest thickness scores the highest maximum acoustic power generated. 2.9% of increment on maximum acoustic power generated by altering the length of the stack by 5 mm.

1. Introduction

The word of thermoacoustic is derived from two different words of "Thermo" and "Acoustic" which are related to heat and sound respectively. Thermoacoustic effect was first observed and recorded by Sondhouss in 1850 [1,2]. Sound can be produced in various ways for instance when a hot glass is in contact with an open-ended cold glass tube. 9 years after Sondhouss' finding on the thermoacoustic effect, Rijke had made a conclusion that when a hot gauze is placed slightly lower in the middle of the open-ended tube glass sound wave will be produced [3] and maximum sound oscillation is observed when the gauze located at L/4 from the bottom surface of the tube glass, where L is the total leghth of the open-ended tube.

In 1802 the first experiment was conducted by Byron Higgins, studying on oscillations produced by hydrogen flame. Experimental works have been carried out to find the practical application of thermoacoustic effects in heat pump and heat engine. 600W of heat source could produce 27W of acoustic power, as reported by Feldman on his PhD dissertation [4]. Investigations on the theory that could explain the phenomena, have been done by later researchers, to find a possible optimization and operations of the actual system [2-9].

Rijke stated that, this phenomenan is due to the expansion of air adjacent to the hot gauze and subsequent contraction of air. Lord Rayleigh released a qualitative description of thermoacoustic phenomena after Rijke's theory failed to explain the magnitude of the oscillation. He stated that " If heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of rarefaction, or abstraced at the moment of greatest condensation, the vibration is discouraged." [10]. Since after the quantitative calcutaion made by Rott in 1960s [11,12], the thermoacoustic effect is widely understood and researchers and engineers begin to benefit the knowledge for sake of the human being [8,14].

2. Principle background

In principle, oscillation by fluid particles near a solid boundary, creates a temperature gradient which is fully developed in that wall, and steady as the solid-fluid heat transfer (thermoacoustic effects) a reaches at the end balanced of the axial conduction within the solid. Material used should posses low conductivity, to reduce the axial heat conduction, which is favourable for the stack design. The distance through which the thermoacoustic effects take place by the thermal penetration depth is, δ_k. Heat loss due to shear stresses by the attenuated viscous penetration depth is denoted as, δv and the desired working fluid should ideally be a fluid with a low Prandtl number, σ. [12, 14].

$$\sigma = \left(\frac{\delta_v}{\delta_k} \right)^2 = \frac{c_p \mu}{K} \qquad [1]$$

where c_p, is the specific heat capacity, μ ,dynamic viscosity, and K, is fluid thermal conductivity of the fluid respectively. However, in this study the working gas selected is air as, it is easily available for the final use in the system. The important parameter is the critical temperature gradients, T_{crit} as recommended by Swift. Detailed design parameter and variables may be obtained in Swift, 2001 [9].

3. Modelling Simplication

On the research methodologies that ware used to study the fundamental of standing wave thermoacoustic heat engine via simulation. Most of the pre-processing process was done on simulation software named Design Environment for Low Amplitude ThermoAcoustic Energy Corversion or known as DeltaEC. The first thing that was done in pre-processing was to design the core element of standing wave thermoacoustic heat engine step by steps using the similar softwares.

Begin with the simulation problems, they will try to maximize the simplification of the design and at the same time minimize the results deviation both from real experimental and simulation. Figure 1 shows the simplification steps from the real design to the simulation design.

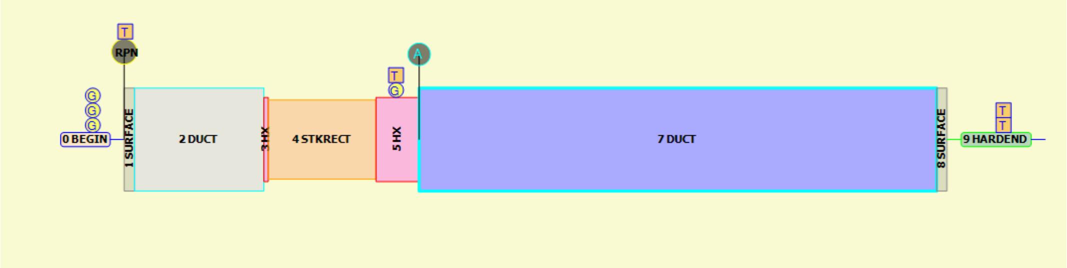


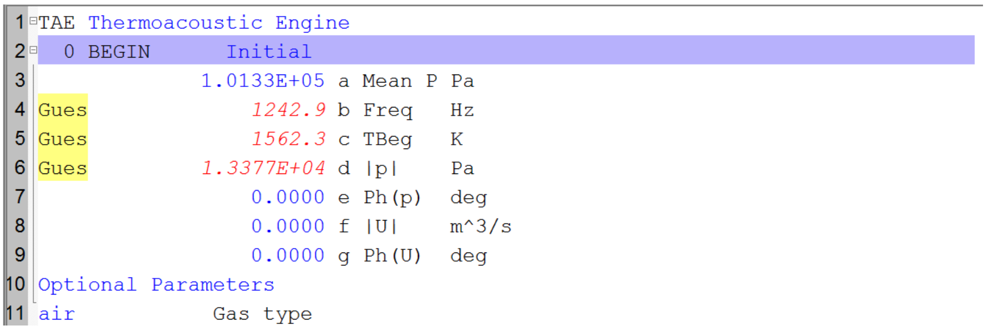
Figure 1: Modelling simplification [25]

Table 1: Geometrical of design

Segment	Diameter, D (mm)	Length, L (mm)
Hot Duct	30	27
Hot Heat Exchangers	24	1.0,1.5,2.0,2.5,3.0
Stack	24	20, 25
Ambient Heat Exchangers	24	10
Resonator Tube	24	120

3.1 Analysis Approach

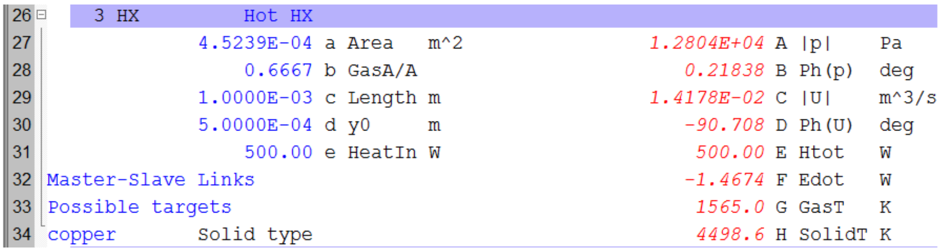
Standing wave Thermoacoustic Prime mover consist of 6 basic segments or parts and others minor segment that need to be defined in order for the program to solve the problems and thus display the result. Figure 2 shows the initial step to define the attributes inside the system. Line 3 represents the working pressure of the system and it indicates 101325 Pascal which is under atmospheric presssure. Line 4 represents the resonance frequency and line 6 for the pressure amplitude of the system. Line 7 to 9 was set to be zero and lastly air was chosen as the working fluid (line 11) in this system.



```
1  TAE Thermoacoustic Engine
2    0 BEGIN        Initial
3                 1.0133E+05 a Mean P  Pa
4  Gues               1242.9 b Freq    Hz
5  Gues               1562.3 c TBeg    K
6  Gues           1.3377E+04 d |p|     Pa
7                     0.0000 e Ph(p)   deg
8                     0.0000 f |U|     m^3/s
9                     0.0000 g Ph(U)   deg
10 Optional Parameters
11 air             Gas type
```

Figure 2: Initial step to define the attributes inside the system

The hot duct is like a vassel to store the hot gas that is heated by the hot heat exchanger. It need to be defined precisely for the system to run smoothly without any problems. Figure 3 shows the heat exchanger section. Perimeter is a crucial for Delta EC to identify what type of duct the particular section, is circular tube. This perimeter was chosen for the simulation. The lines on right side (red) are the value of other parameters on the particular section that will be calculated by the system itself.



```
26 ⊟  3 HX          Hot HX
27               4.5239E-04 a Area   m^2        1.2804E+04 A |p|    Pa
28                   0.6667 b GasA/A               0.21838 B Ph(p)  deg
29               1.0000E-03 c Length m          1.4178E-02 C |U|    m^3/s
30               5.0000E-04 d y0     m             -90.708 D Ph(U)  deg
31                   500.00 e HeatIn W              500.00 E Htot   W
32 Master-Slave Links                              -1.4674 F Edot   W
33 Possible targets                                 1565.0 G GasT   K
34 copper        Solid type                         4498.6 H SolidT K
```

Figure 3: Heat exchanger section

Two types of heat exchanger provided by the software such as parallel plates (HX) and cylindrical tubes (TX). Power supplied to hot heat exchanger, have been edited the value on the line 31 . The material for both heat exhchangers were cooper. Stack is the heart in every thermoacoustic heat engine system, in real condition there are too many types of stack that can be used and yet there are only 4 types of stack that are available in DeltaEC for instance STKSLAB, STKRECT, STKCIRC and STKPIN. Figure 1.4 shows the most common stack geometries, with the *x* axis perpendicular to the page. STKRECT was used in this simulation, by referring figure 4 below there are 4 unusual new parameters that need to be defined by the user.

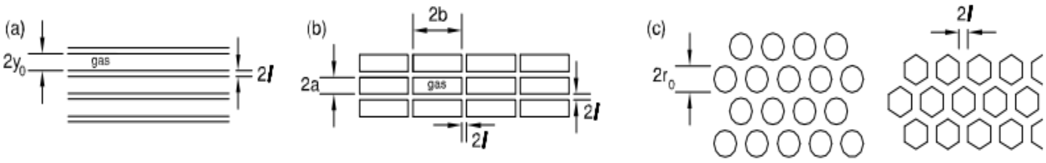
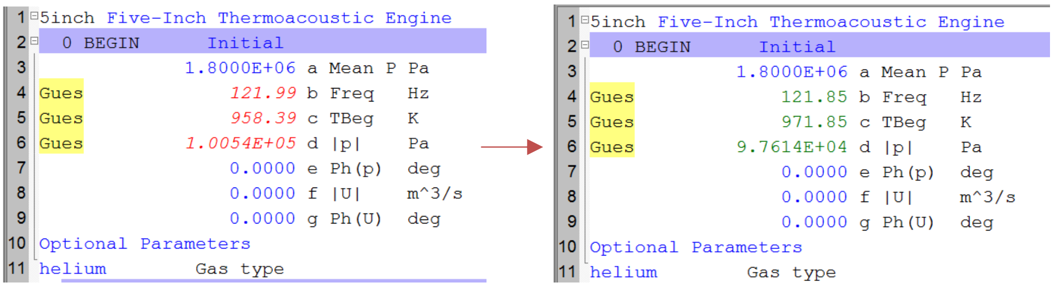


Figure 4: (a) STKSLAB. (b) STKRECT. (c) STKCIR.[29]

3.2 Simulation & post-processing



```
1 ⊟5inch Five-Inch Thermoacoustic Engine
2 ⊟  0 BEGIN       Initial
3                1.8000E+06 a Mean P Pa
4 Gues               121.99 b Freq   Hz
5 Gues               958.39 c TBeg   K
6 Gues           1.0054E+05 d |p|    Pa
7                    0.0000 e Ph(p)  deg
8                    0.0000 f |U|    m^3/s
9                    0.0000 g Ph(U)  deg
10 Optional Parameters
11 helium          Gas type
```

```
1 ⊟5inch Five-Inch Thermoacoustic Engine
2 ⊟  0 BEGIN       Initial
3                1.8000E+06 a Mean P Pa
4 Gues               121.85 b Freq   Hz
5 Gues               971.85 c TBeg   K
6 Gues           9.7614E+04 d |p|    Pa
7                    0.0000 e Ph(p)  deg
8                    0.0000 f |U|    m^3/s
9                    0.0000 g Ph(U)  deg
10 Optional Parameters
11 helium          Gas type
```

Figure 5: Shows before and after the system is simulated

Figure 5 above, the red value tells the user that the software is not yet simulated and green value will appears when the software complete the simulation. Gues mode tells us at what conditions the system will start to spontaneously oscillate when some values in the system are defined. Data on the line 4, 5, and 6 were taken as the result for this simulation. Onset temperature difference can be extracted by minus the value on the right TBeg and Tend. All data taken from the simulation then converted to Excel for futher analysis.

4. Results and discussion

DeltaEC requires low cost computer compare to other software and result taken are quite accurate due to the design of the software itself. Thermoacoustic prime mover with lowest onset temperature and highest maximum acoustic power is the most suitable system to be used in any applications such as energy converter, small power plant and many more.

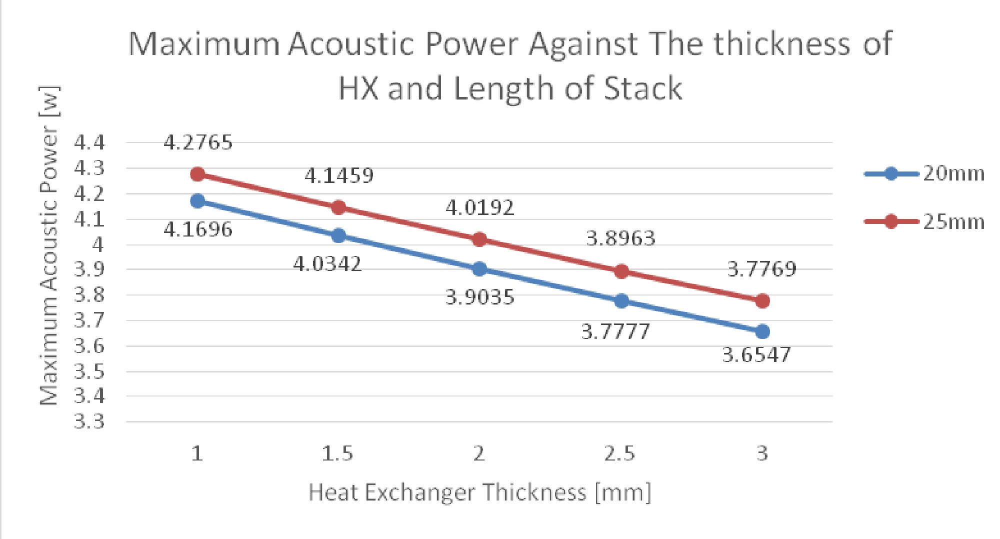


Figure 6: Maximum acoustic power.

By referring figure 6, it can be stated that 25mm stack produced higher maximum acoustic power compared to the 20 mm stack. The maximum acoustic power deviation between 25 mm stack and 20 mm was too small and approximately 2.9 %. Hot HX thickness affecting nearly 3.5% of the maximum acoustic power. Onset temperature difference for both parameter seems significantly higher, the onset temperature difference on stack with 25 mm length was roughly 19% higher compared to the 20 mm stack. The system started to oscillate on lower onset temperature difference for 20 mm stack and higher on the 25 mm stack system. In every heat engine system, the work generated is depending on the temperature difference between heat source and heat sink thus thermoacoustic prime mover system that indicates higher onset temperature will generate higher acoustic power. Heat exchanger thickness was proportional to the onset temperature difference for both stack length (20 mm and 25 mm). The increasing on hot heat exchanger thickness affected the maximum acoustic power generated on the prime mover system. Lowest thickness of heat exchanger (1 mm) will transfer heat efficiently and faster to the system and subsequently will supply more heat flux to the system. Heat is essential to generate acoustic power in thermoacoustic prime mover system, the more or fast heat is supplied (higher heat flux) to the stack the more acoustic power will be produced and the lower the onset temperature difference required for the system to oscillate.

Conclusion

The thickness of Hot HX plays the major role in affecting the maximum acoustic power generated, the level of onset temperature difference and maximum pressure amplitude followed by the stack length. Hot HX dimension (thickness) contributes nearly 3.3% changes in maximum acoustic power where the lowest thickness scores the highest maximum acoustic power generated. 2.9% of increment on maximum acoustic power generated by altering the length of the stack by 5 mm. Greater onset temperature difference doesn't means the system will perform better, higher onset temperature difference requires higher temperature difference between the stack to start oscillating. Altering the stack length by 5 mm might not be the suitable method to increase the maximum pressure amplitude because it only produce 4.1 % higher pressure amplitude and loss approximately 12.83% from the maximum pressure amplitude compare to the 20 mm stack which is score around 10.7 % losses. Choosing the 25 mm stack system instead of 20 mm will increase the onset temperature difference by 19% which is not truly efficient. 1 mm thickness of hot HX serves lower onset temperature difference compare to the others on both 25 mm and 20 mm stack length.

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