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Investigation on Standing Wave Thermoacoustic Generator Using DeltaEC

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ABSTRACT

There is currently an urgent demand to reuse waste heat from industrial processes with approaches that require minimal investment and low cost of operation. Thermoacoustic generator (TAG) is a device that converts heat energy into useful work through the use of acoustic wave, porous media (honeycomb ceramic celcor) and heat exchangers that are all enclosed in a custom-defined resonator. This paper reports the basic design of thermoacoustic generator that is tested using a design software known as a Design Environmental for Low-amplitude Thermoacoustic Energy Conversion (DeltaEC). Many studies have highlighted the relationships between the geometry of the stack and the performance of the device. In this study, attention is given on the impact of the length of stack which was found to be the best at a length of 0.6 m when the frequency of the flow is at 127.4 Hz. Performance indicators like the acoustic power and the temperature difference across the stack have been used to analyse the results. The result shows that the highest acoustic power can be achieved when the generator that work with air at an atmospheric pressure is designed with a resonator of 2.14 m long and a stack with a length of 0.6 m. The maximum value for acoustic power is predicted to be as much as 24.01 kW.

1. Introduction

Recently, global warming and resulting climate change have become a major talking point in terms of mankind's future. To reduce it, alternative technologies need to be studied for the solutions to the problems encountered [1]. Application of cooling and heating system in thermal engineering are recognised and have been studied both theoretically and practically in building energy system, electronic devices, solar energy collectors and many more [2]. Conventional power generation systems usually need burning process of fossil fuels which have brought in serious environmental problems due to the incomplete combustion of the fuel that is used in the system [3]. In addition, fuel is to be considered non-renewable resources, or it takes too long a time to be resourced, and it

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is threatened by serious depletion. Hence, efficient use of energy and the development of green technology are the topics of interests in recent technological developments. Much of the world's energy comes from fossil fuels, owned by a few countries, at prices that fluctuate and damage the environment. To overcome energy dependence and reduce environmental damage, many countries turn to renewable energy [4] Heat recovery solutions for the reuse of waste heat from industrial processes, for an example, are attracting many interests due to the new legislation to minimize dependency on fossil fuels [5].

The mechanism involving heat transport is highly essential and is needed in the industry for final possessions of desired qualities [6]. Thermoacoustic energy conversion processes can be used to recover some of the waste heat to generate electricity. Thermoacoustic phenomenon is a phenomenon based on thermodynamic interactions of pressure, displacement and temperature oscillations of fluid when it is oscillated and interacted with solid boundaries. The heat transfer between the working gas and the solid material, subjected to an appropriate phase of pressure and velocity oscillations, enables the thermoacoustic effect to convert thermal energy into acoustic energy [7]. A thermoacoustic engine turns part of the heat supply into electricity when acoustic sound is generated by the onset temperature and drives the oscillatory flow motion with oscillating pressure that drives the moving mechanism of energy conversion device like a linear motor or a bi-directional turbine. The presence of a porous structure inside the resonator help amplifying the thermal impact of the flow. The work in these sound waves can be harnessed using a piston to drive a flywheel or a linear alternator [8]. Thermoacoustic technology is seen attractive because the devices use environmentally friendly working fluids, like noble gases, and they have no or very limited moving parts in the system during the energy conversion processes which reduces potential maintenance costs [9].

The thermoacoustic generator that is built for the purpose of investigation to be reported in this paper is a device that can convert heat from a source to an acoustic energy that will be used to generate electricity through the use of suitable electric converter devices. A simple design of a thermoacoustic generator is as shown in Figure 1. It consists of two heat exchangers that are placed at both ends of a porous structure, commonly referred to in thermoacoustic community as a 'stack', and all these structures are placed inside a host that is known as a resonator.

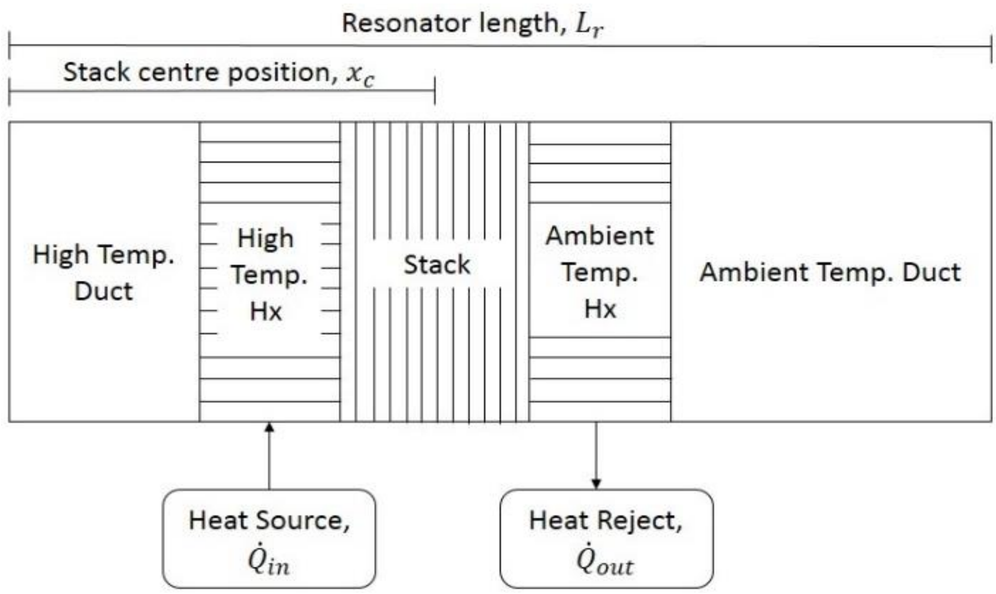

Fig. 1. The simple design of thermoacoustic generator for DeltaEC simulation

Based on a previous study done by Sashwin *et al.,* [10] it was stated that the use of a good heat exchanger design can provide good heat transfer performance with acceptable pressure drop in the system. Besides, Lukmon *et al.,* [11] stated that the use of noble fluid such as water as a medium for heat transfer in the operation of the system can reduce the greenhouse effect. Technology like thermoacoustics can be used to generate energy based on a somewhat clean and green operations. It is expected that a large acoustic power, and hence a larger electricity, can be generated if the geometrical configuration of the device is optimum. Usually, an inert gas such as helium is used as a working fluid for this system and Zolpakar *et al.,* [12] stated that air is still widely used as the working fluid because it is easily available for experimental works. An experimental investigation on the performance of simple thermoacoustic engine (TAE) was conducted by Hariharan *et al.,* [13]. This study found that the stack length and its position within the resonator affect significantly the thermal efficiency of TAE. Based on the previous research by Tartibu [14], the experimental results suggested that some of the geometrical parameters namely the stack length, its position and its porosity, are interdependent [14]. In an earlier work, Jin *et al.,* [15] focused the study on the impact of operating frequency and the onset temperature. This study pointed out that the resonator length is crucial in the operation of the TAE. In addition, the possibility to drop the onset temperature below 100^{o}C was also demonstrated. According to Cahyadi *et al.,* [16], an extension of the resonator length resulted in a drop of the resonant frequency. This study emphasized the importance of selecting the resonator length carefully for TAE to work optimally and produce higher acoustic power.

Clearly, thermoacoustic energy system needs to be designed properly at the early stage of investigation to avoid spending too much money on a design that could be incorrect. Traditionally, differential equations have been employed to model physical assumptions adopted for real world problem [17]. Normally in thermoacoustic system, the design of the system is usually done through a thermoacoustic design software known as Design environment for low amplitude Thermoacoustic Energy, or DeltaE in short (later known as DeltaEC) [18-20]. The software helps researcher to assemble parts of the system into a model and then solved the linear thermoacoustic equations related to the model so that flow distribution inside the system is in accordance to the thermoacoustic principles. Clark *et al.,* [21] of the Los Alamos group invented the DeltaEC program, which is a computer software that calculates thermoacoustic device performance and helps in the design of the desired equipment. The program numerically integrates the respective one-dimensional (1D) linear acoustic wave equation using Runge-Kutta integration method to solve for the fundamental acoustic variables. The DeltaEC model relies on Rott's linear theory and uses a quasi-one-dimensional analysis of the dynamic equations [22]. DeltaEC can be used as verification method for design and optimization procedures of thermoacoustic system [20]. Many research groups had carried out geometrical optimization based on either experimental work or numerical solution of linear thermoacoustic theory using software such as DeltaEC [22]. Tijani *et al.,* [23] successfully optimized the stack unit using manual calculation of linear thermoacoustic theory as well as the numerical prediction from DeltaEC model in order to meet the requirement of cooling power at various discrete values of stack parameters including the normalized stack length and stack's center position.

In Malaysia, the study of thermoacoustic systems is scarce. DeltaEC is a software that was used by many researchers in the past in order to design a functional thermoacoustic system. In this paper, the design stage of a thermoacoustic system that is to be tested in a laboratory in Malaysia is reported and potential performance from the designated thermoacoustic generator system is predicted by using DeltaEC software design. Due to the issues of controlling the harmful effects on the environment, it is necessary to choose the good design for part that is used in the system [24]. Various range of geometry parameters of the generator are considered during the design process in order to not only meet the performance of the generator but also to utilize as much as possible the targeted value of the supplied waste heat. The variation trends of the output performances are further analyze in the perspective of acoustic power and temperature difference. Distributions of various parameters in the TAG is analyzed to give a clear evaluation of the performance of the tested system. Results from the proposed rig assist in determining the optimum design of the performance for the development of a standing wave thermoacoustic generator.

2. Methodology

The Thermoacoustic Linear Equation is used by the DeltaEC software to solve the thermoacoustic flow in the model of the thermoacoustic generator. The linear thermoacoustic equation represents the linear model of the oscillatory flow condition that can be expressed by using the simplified mass, momentum and energy equations of the flow [13]. Harmonic oscillations of density, ρ, pressure, p, and velocity, u are used to simulate oscillating wave behaviour. In thermoacoustics, the oscillating flow is changing with time. The oscillatory flow motion is also influenced by the angular velocity defined as $\omega = 2\pi f$ where f is the frequency of the flow. The continuity, momentum and energy equations for thermoacoustic environments can be defined by inserting the oscillating terms into the standard Navier-Stokes Equation. The speed of sound is related to pressure and density through the relationship of $c = \sqrt{(\partial p/\partial \rho)_s}$ where p is the pressure, ρ is the density and the subscript s represents the isentropic process of the sound propagation. This relationship is applicable for the simple harmonic of the ordinary sound wave that is distributed across the channel. An isentropic process can be used to approximate the fast travel of a sound wave. DeltaEC generally solves the linear thermoacoustic theory that can be represented by Eq. (1) to (4) [19, 20]. The terms P, ω, ρ_m, x, A, U_1, ρ, c, γ, σ, β, T_m, $H_{2,k}$ represent the pressure, angular velocity, mean density of air, axial location, area, first order harmonic of the volume flow rate, density, speed of sound, the ratio of isobaric to isochoric specific heats, Prandtl number, thermal expansion coefficient, mean temperature and the second order thermoacoustic effect, respectively. Eq. (4) defines the second order thermoacoustic effect, which represents the energy that is carried in the axial direction of the flow.

$$\frac{\partial P_1}{\partial x} = -\frac{i\omega\rho_m}{A(1-f_v)}U_1 \tag{1}$$

$$\frac{\partial U_1}{\partial x} = -\frac{i\omega A}{\rho c^2}\left(1 + \frac{(\gamma-1)f_k}{1+\epsilon_s}\right)P_1 + \frac{(f_k-f_v)}{(1-\sigma)(1-f_v)(1+\epsilon_s)}\beta\frac{\partial T_m}{\partial x}U_1 \tag{2}$$

$$\frac{dT_m}{dx} = \frac{H_{2,k}-\frac{1}{2}\mathrm{Re}\left[p_1U_1\left(1-\frac{T_m\beta(f_k-f_v)}{(1+\epsilon_s)(1+\sigma)(1-f_v)}\right)\right]}{\frac{\rho_m c_p|U_1|^2}{2\omega A(1-\sigma)|1-f_v|^2}\mathrm{Im}\left[f_v+\frac{(f_k-f_v)(1+\epsilon_s f_v/f_k)}{(1+\epsilon_s)(1+\sigma)}\right]-Ak-A_sk_s} \tag{3}$$

$$H_{2,k} = \frac{1}{2}\mathrm{Re}\left[p_1U_1\left(1-\frac{f_k-f_v}{(1+\varepsilon_s)(1+\sigma)(1-f_v)}\right)\right] + \frac{\rho_m c_p|U_1|^2}{2A\omega(1-\sigma)|1-f_v|^2}\frac{dT_m}{dx}Im\left[f_v+\frac{(f_k-f_v)(1+\epsilon_s f_v/f_k)}{(1+\epsilon_s)(1+\sigma)}\right] - (Ak + A_sk_s)\frac{dT_m}{dx} \tag{4}$$

Eq. (1) to (4) are used by DeltaEC to solve for the thermoacoustic flow inside the system that is designed by the user. As mentioned earlier, the software iterates the calculations based on fourth-order Runge-Kutta integration. The system is designed using defined segments and DeltaEC solve the equations for all the segments. A shooting method was utilised where guess values are defined using known or predictable values and then DeltaEC will solve the equations that suit the target of the designs and come up with solution for the model. Generally, DeltaEC is a design software that can be used to obtain general idea of the potential cooling capability or power generation that can be offered by the designated thermoacoustic devices. In this study, it will be used to design a thermoacoustic generator where heat source is to be converted into acoustic power using the thermoacoustic principles.

There are two important parameters in thermoacoustic generator which are the total thermal power that is available for conversion in the thermoacoustic generator (TAG), labelled in Eq. (5) as H and the acoustic power, E. The thermal efficiency of the thermoacoustic generator is the ratio of normalized acoustic power developed by the engine to the total power supplied to the engine through the hot heat exchanger and it is given as [25]:

$$\eta_{th} = \frac{\Delta E}{H} \tag{5}$$

The resonant frequency is proportional to the sound speed (c) and inversely proportional to the resonator length (L). This is demonstrated by Eq. (6) which is pointing out the relationship between these parameters when a quarter wavelength rig is involved [26]:

$$f = \frac{c}{4L} \tag{6}$$

The longer the length of the duct, the smaller the resonant frequency. This has been demonstrated experimentally by Cahyadi *et al.,* [16]. However, length is not the only parameter that is affecting the resonance frequency. The presence of structures such as heat exchangers and stack need to be considered too. The current study emphasized on the importance of selecting the length of duct and also the length of stack carefully for thermoacoustic generator to work optimally and produce higher acoustic power. Based on all these considerations, the analysis was performed numerically using DeltaEC software. The impact of the length of the duct and the stack are the focus of this study.

In DeltaEC, there are some parameters that can be determined based on the system's design. In this study, the frequency is fixed to a resonance value of 124.7 Hz with air set at an atmospheric pressure. There is a total of nine segments that have been used in defining the parts of the designed system in DeltaEC, as shown in Figure 2. The segments involve the use of six different functions, which are BEGIN, SURFACE, DUCT, HX, STKCIRC and HARDEND. BEGIN is the segment/function that contains initial conditions for the numerical calculations to be conducted using DeltaEC. The segment was labelled in Figure 2 as '0 BEGIN' and the supplied data as shown in Table 1 shows that the calculation is initialized based on initial conditions of an atmospheric pressure and also a room temperature. A segment known as SURFACE is used to represent the presence of a surface with thermal-hysteresis or also known as viscous dissipation. It always absorbs acoustic power and therefore used at both ends of the DUCT. DUCT is located next to the SURFACE and this is representing a hollow cylinder that forms part of the resonator. Heat exchanger is labelled as HX. There are two heat exchangers placed at different locations. A hot heat exchanger supplied heat to the system and it is located in segment 3. In segment 5, there is another heat exchanger but this one absorbs some of the heat (i.e. cold heat exchanger) so that enough temperature gradient can be sustained at the two ends of the porous media label as STKCIRC. There is an ANCHOR segment which is labelled as 'A' in Figure 2. The segment is placed between HX in segment 5 and DUCT in segment 7. It is representing the potential loss that happens in the system. In this thermoacoustic system, it is assumed that the thermoacoustic generator system is operating in a quarter wavelength environment and for this reason a segment known as HARDEND is applied at the right end of the duct. This HARDEND represents the rigid wall at the end of the duct. In addition, there is an RPN segment used at the end of the system. This RPN segment is a mathematical segment that allows the user to obtain parameters for the analysis. It depends on the instruction defined by the user and in cases where values are not declared in RPN, the presence of it will not interfere with the modelling results. This is a useful function as it lets the user to easily calculate any quantity of interest by instructing the software to do the calculation when there is a need for it.

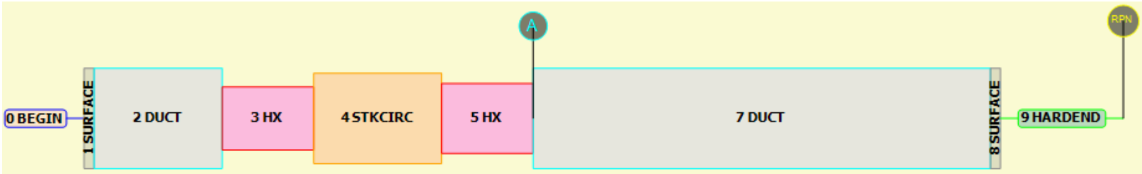

Fig. 2. Schematic diagram of the design of thermoacoustic generator in DeltaEC

Table 1 shows the parameters that were defined in each segments. The investigation focuses on the impact of the length of the duct and also the length of the stack which, in Table 1, is described as DUCT (ambient) and STKCIRC, respectively.

The length of the stack in STKCIRC has been adjusted to be in the range of 0.02 m to 0.7 m while the flow frequency value was set to be at a constant value of 127.4 Hz. For the length of duct/resonator analysis, the duct of segment 7 (i.e. DUCT (*Ambient*) in Table 1) has been adjusted to be with length in the range of 0.2 m to 3.4 m. There are some segments that require value for GasA/A such as HX and also STKCIRC. GasA/A is the volumetric porosity which is the fraction of the total area that is available to gas. It represents the porosity of the structure for gas medium to flow. In addition, the segment HX (i.e. hot area and cold area) required additional information known as the plate spacing, y_0 which represents the size of the gap between solid walls that is available for the gas to flow. For the STKCIRC segment, as in Table 1, there is a requirement for the Lplate value. Lplate value is half the thickness of the solid sheet between pores which is also known as the plate or wall thickness.

In order to verify the model that was developed for this study, the result of pressure that occur within each segment in DeltaEC simulation is compared with the theoretical prediction of pressure value that can be expected in the segments by using Eq. (8). The general solution for p_1 for sinusoidal periodic flow in the channel can be represented as $C\cos k(x - x_0)$. This is the form of solution shown in Eq. (7). The term k is the wave number defined as $k = \omega/c$ with $\omega = 2\pi f$ as the angular velocity that is a function of flow frequency, f, and c is the speed of sound. For a special case of a standing wave situation, a hard end is applied at the one end of the test rig $(x = l)$ which is known as the pressure antinode location if the rig is having a length equal to a quarter of the wavelength of air. At the location of the hardend, the velocity is zero. Hence the solution can be shown as [27]

$$P_1 = C\cos k(x - l) \tag{7}$$

Table 1
The parameters defined for all segments in DeltaEC software

Parameter	Value
BEGIN	
Mean Pressure, Pa	1.0133×10^5
Frequency, Hz	127.40
Temperature Begin, K	296
Pressure, Pa	7.3549×10^4
DUCT (Hot)	
Material	Stainless
Area, m^2	9.5033×10^{-3}
Perimeter, m	0.34558
Length, m	0.14
HX (Hot area)	
Material	Copper
Area, m^2	9.5033×10^{-3}
GasA/A	0.3930
Length, m	0.1
y_0, m	4.83×10^{-4}
HeatIn, W	2210
STKCIRC	
Material	Celcor
Area, m^2	9.5033×10^{-3}
GasA/A	0.81
Length, m	Vary as in Table 2
Radius, m	5×10^{-4}
Lplate, m	5×10^{-5}
HX (Cold area)	
Material	Copper
Area, m^2	9.5033×10^{-3}
GasA/A	0.486
Length, m	0.1
y_0, m	4.06×10^{-4}
HeatIn, W	-2125.1
DUCT (Ambient)	
Material	Stainless
Area, m^2	9.5033×10^{-3}
Perimeter, m	0.34558
Length, m	Vary as in Table 2

The amplitude of the constant *C* depends on the applied force on the flow at the other end of the rig (i.e., the location of the acoustic driver). The amplitude of pressure at the location of pressure antinode is denoted as P_a. By applying Eq. (8) with $C = P_a$ to calculate for the oscillating pressure amplitude, an oscillatory pressure value at locations along the resonator can be estimated as

$$P_1 = P_a \cos k(x - l) \tag{8}$$

The terms k, P_a , x and l represent the wave number, pressure amplitude at antinode, the location from the antinode and the length of resonator from pressure node to antinode. Measurement is done for pressure at a location near the end of the resonator. The location is defined as shown in the block diagram of Figure 3. The total length of the model is 2.14 m, as modelled in the

DeltaEC. The values form the model are compared to the values predicted by the one-dimensional non-linear thermoacoustic theory to verify the model.

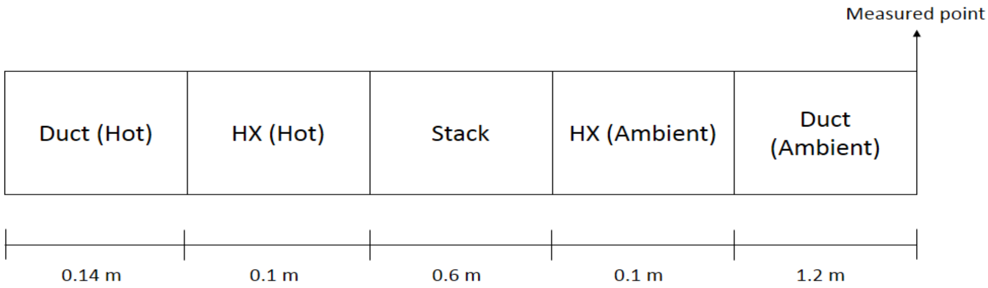

Fig. 3. The block diagram of thermoacoustic generator in DeltaEC software

3. Results

A total of fifty three cases have been tested in order to study the influence of the resonator's length, and also the stack's length on the performance of the thermoacoustic generator. The resonator's length was varied by changing the length of segment 7 which was shown as '7 DUCT' in Figure 1 and this segment was defined as 'DUCT (ambient)' in Table 1. Table 2 shows the value for parameters that were used during the simulation of thermoacoustic generator in order to test the performance of the system. The results are observed based on parameters like the generated acoustic power than can be achieved in each case, and also the temperature difference that is recorded between the two ends of the stack that was used in the system. The results are observed for all the parameters as listed in Table 2. The simulation of the length of the stack is done first and then followed by the simulation for the cases with variation of the length of the duct. Then, a study of the acoustic power generated from the optimized parameters was obtained from the simulation with the use of the optimised lengths of stack and resonator. All the simulations were tested at the resonance frequency of 127.4 Hz.

Table 2
The parameters defined for cases as investigated in DeltaEC software

Simulation	Parameters		
	Frequency, Hz	DUCT (ambient) 's length, m	Stack's length, m
Cases 1 to 35	127.40	0.48	0.02 to 0.7 (for every 0.02 m increment)
Cases 36 to 52		0.2 to 3.4 (for every 0.2 m increment)	0.6 (optimised)
Case 53		1.2 (optimised)	0.6 (optimised)

Figure 4 shows the predicted temperature difference that were recorded at the two ends of the porous media. The temperature changes according to the change of the length of the porous stack. The frequency and the length of the 'DUCT (Ambient)' are set constant during this simulation and the values are 127.40 Hz and 0.48 m, respectively. The length of stack was varied from 0.02 m to 0.7 m. The results show that the temperature difference is increasing as the stack length increases.

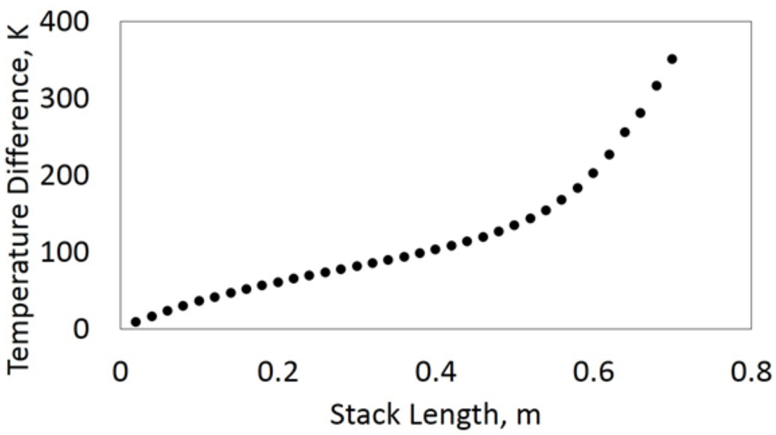

Fig. 4. The result of temperature difference when stack with different length is tested with flow at a frequency of 127.40 Hz

Amongst the tested length of stack, the results in Figure 4 show that the stack length of 0.7 m produces the highest temperature difference compared to the other lengths of stack that were used. For this part of the simulation, the total length of the designed rig did not change and only the length of stack is different. The highest temperature difference is achieved when the stack is the longest. There is a change of trend for temperature increase that can be seen from the results of Figure 4. At first, the temperature increases slowly with the increase of stack length. After the length of approximately 0.45 m, drastic increase of temperature with the increase of stack length is observed. It seems that the axial conduction reduces as the length of stack increases. When the stack is longer than 0.45 m, the travel of heat from the hot to cold ends becomes difficult and therefore higher temperature difference is recorded between the two ends.

In Figure 5, the result of acoustic power that can be generated in the system is shown when stack with different length is tested. Stack lengths in the range of 0.02 m to 0.70 m are used in this simulation and flow frequency was set to the calculated resonance value of 127.40 Hz. The 'DUCT (Ambient)' was fixed to a length of 0.48 m. The result shows that acoustic power generation increases with the increase of stack's length. A maximum value of 23.86 kW acoustic generation is reached when the stack length is 0.6 m. A long stack means that there will be more blockage on the flow inside the system. The decision on the length of the stack should be made based on the evaluation of power that can be expected from the system when the stack is used.

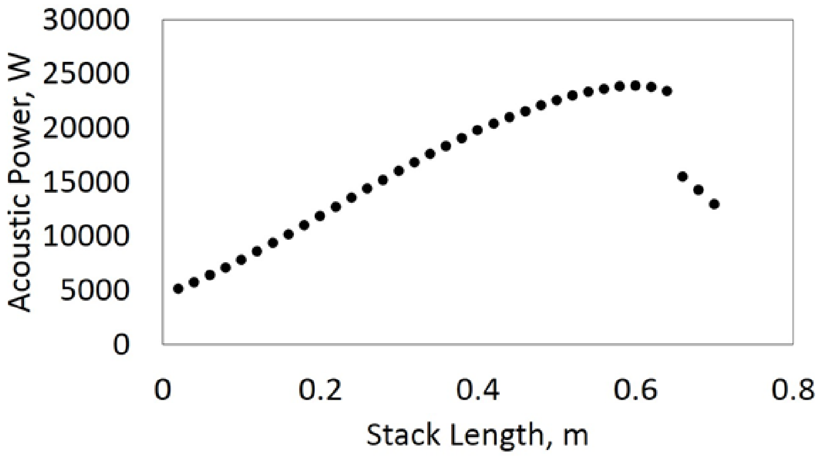

Fig. 5. The result of acoustic power generation for thermoacoustic generator that uses different lengths of stack

Figure 6 shows the changes of acoustic power of the system when the length of ‘DUCT (Ambient)’ changes. The acoustic power is generated by the temperature difference between the two ends of the stack and it was estimated from the calculation of the converged model of the DeltaEC software according to the investigated parameters. For this simulation, the frequency was set to be at a resonance value of 127.4 Hz and the stack was set to an optimum length of 0.6 m. Based on the results, it can be seen that the acoustic power stays constant when the resonator’s lengths increases with the increase of ‘DUCT (Ambient)’ until the ‘DUCT (Ambient)’ is approximately 2 m long. After that, the acoustic power reduces when the length of the resonator increases. This means that the change in the pattern for acoustic power is affected by the change of the length of resonator. The maximum acoustic power of 24 kW is generated when the ‘DUCT (Ambient)’ is less than 2 m long. This corresponds to a resonator length of 2.14 m. Further increment of resonator length will only lead to reduction of power production. DeltaEC prediction shows that the length of duct higher than 2 m is not suitable for this thermoacoustic generator design since it will reduce the value for acoustic power of the system. For the purpose of further investigation, a resonator that is with length of less than 2 m is selected to be used with optimised stack length of 0.6 m. A closer view on the acoustic power results reveal that the maximum acoustic power was achieved when the ‘DUCT (Ambient) is 1.2 m long. Therefore, this value is used for further investigation.

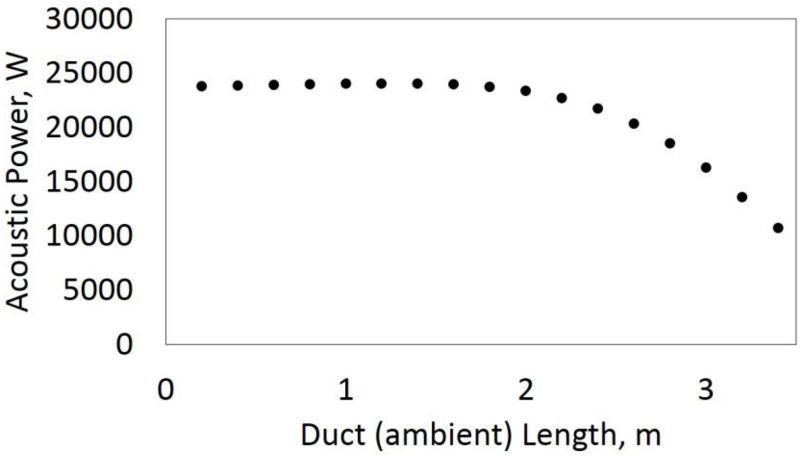

Fig. 6. The result of acoustic power generation and flow frequency across the thermoacoustic generator rig when the resonator is at different lengths

Figure 7 shows the acoustic power distribution along the thermoacoustic generator when it is operated with optimised condition. The frequency of the flow is 127.4 Hz. A stack of 0.6 m is placed between the hot and cold heat exchangers that are situated inside a resonator with a ‘DUCT (Ambient)’ of 1.2 m long. Acoustic power is found maximum at the area of the stack. The results indicate that the design of thermoacoustic generator with the identified optimised parameter is able to produce acoustic power inside the system. The generated power will need to be harnessed or converted into electricity using a suitable converter or device. The results of Figure 6 suggested that the converter is best placed at the right side of the resonator, in the area of duct after the cold heat exchanger, where acoustic power values are still high.

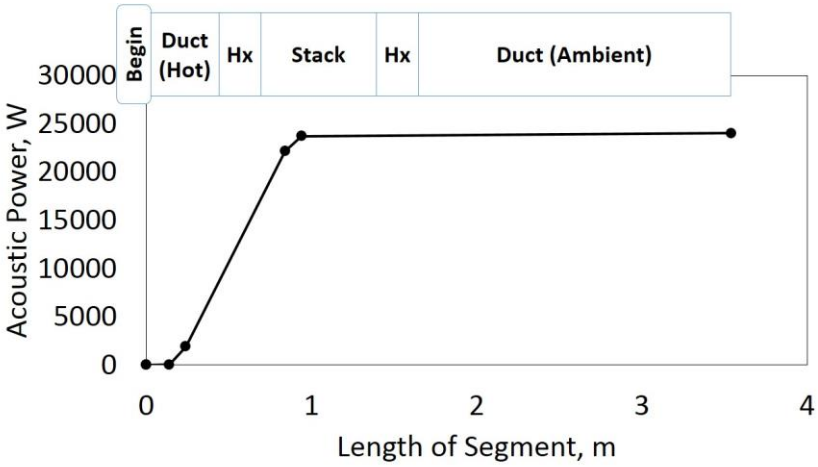

Fig. 7. The result of acoustic power generation across the thermoacoustic generator rig when the optimized lengths of stack and 'DUCT (Ambient)' are used.

The investigation as reported in this paper shows that the adjustment of the length of resonator and the length of stack will affect the acoustic power value that can be generated within the thermoacoustic generator system. Longer stack resulted in higher temperature difference to occur between the two ends of the stack and as a result a better acoustic power can be achieved. Then, the investigation of the effect of length of res onator shows that the 'DUCT (Ambient)' with length of less than 2 m will create good acoustic power for the designed thermoacoustic generator system.

For the verification of the model that was developed in DeltaEC, the pressure values from the simulation work are compared to the theoretical calculations. Figure 8 shows the change of pressure amplitude that was recorded at the end of the resonator as the heat input to the system increases. The results are based on the model with optimized duct and stack lengths of 1.2 m and 0.6 m, respectively. The results show that the trend of pressure changes with the change of heat input that were obtained from the models in DeltaEC are consistent with the trend predicted by the theory. However, the theory predicted higher value of pressure for each heat input compared to the pressure value that is generated from DeltaEC software. This is probably related to the use of instruction like ANCHOR in DeltaEC models that represents potential losses in real system. The theory did not take into consideration any losses or nonlinearity effects. This led to differences in amplitude between the pressure value from the model and the theoretical value. Nevertheless, the trend is the same. The trend shows that when the heat input supply to the system is higher, the value of the pressure produced at the end of the test rig is also higher. Similar observations were also reported by Sarode *et al.,* [25] and Agarwal *et al.,* [28] in which the value for pressure amplitude is increased when the heat input used is increased.

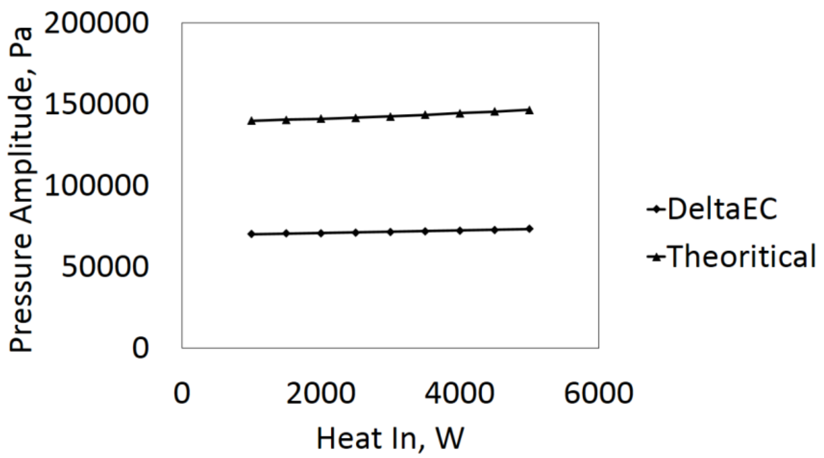

Fig. 8. The result of pressure amplitude at the end of test rig thermoacoustic generator

4. Conclusions

In this paper, a numerical model describing the parametric investigations on thermoacoustic generator have been solved using a software known as DeltaEC. The length of stack has been investigated to study the effect of it on the performance of the thermoacoustic generator. The result shows that the longer the length of stack, the better the temperature drop that can be achieved. Since the generator is driven by the temperature difference, the high temperature difference is favourable. However, it was also found that an optimised length of stack for the designated quarter wavelength standing wave design was at 0.6 m where acoustic power is the highest. The length of resonator is also shown to influence the system's performance. The results suggested that the resonator with 'DUCT (Ambient)' that is less than 2 m long provides the highest acoustic power. Similar observation on the trend of the result was also reported by Balonji *et al.,* [29], which strengthen the findings of the current numerical design of the system. Considering the total length of the resonator (i.e. including all the parts), a resonator with a total length of 2.14 m is found the most efficient. The findings serve as the design guideline for the future experimental rig that will be developed for investigations of thermoacoustic generator.

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