THE IMPACT OF STACK PARAMETERS ON THE TEMPERATURE DIFFERENCE OF A THERMOACOUSTIC COOLER

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Thermoacoustics offer alternative solution for cooling needs where a method that is safer to environment is used. The thermodynamic process that needs to be completed by using interaction between inert gaseous and porous material must be made efficient so that the system works properly. This paper reports numerical and experimental investigations of the use of several porous material in air at atmospheric pressure to provide cooling effect. Experimental investigation was also conducted by using cheap and abundant materials as the porous media. Results were collected at two different frequencies and with two different stack lengths. The study showed that thin-walled honeycomb porous structure made of polycarbonate offers the best temperature for thermoacoustic cooler with air at atmospheric pressure. The best coefficient of performance of 4.73 was recorded. Disparity between numerical and experimental results is expected to be the result of losses that need to be carefully addressed in the future especially when long stack is used in the system.

Key words*: thermoacoustic cooler, DeltaEC, porous media, standing wave thermoacoustic*

1. Introduction

The rising needs for cooling system and the awareness about global warming issues have led to the search of technologies such as thermoacoutics [1-2]. Even though the performance is yet to match that of the conventional vapor compression system but the technology has its own promising feature that should not be ignored as it has potential to be miniaturized or used in specific application such as in rural areas [3]. In 1987, the Montreal Protocol required countries to reduce production and consumption of chlorofluorocarbon, CFC, gas while encouraging the use of alternative technology [4]. Thermoacoustics can be considered a viable alternative since the system does not use refrigerant. The elimination of refrigerants and compressors in thermoacoustic refrigerators makes them an option for future investigation in our goals for a more environmentally friendly refrigeration system [6].

The thermal and acoustic interactions within thermoacoustic system leads to heat pumping effect that creates cooling ability. The presence of turbulent flow conditions with the addition of obstacles during an operation of a system can cause an enhancement of heat transfer [6]. In thermoacoustics, the obstacle is the porous media known as stack but most thermoacoustic effect happens there due to interactions between flow and solid surfaces. Thermoacoustic system works at resonant frequency so that good energy production can be generated. At that frequency, when the fluid particles oscillate next to the solid wall, a cooling effect can be produced due to heat being transferred from one end of the solid wall to the other [7]. That energy transfer happens due to change of pressure and velocity within the resonator that leads towards heat pumping effect from one end to another.

It was reported that the performance of the system may be impacted by the use of inert gaseous as working medium [7]. Air is still widely used as the working fluid because it is easily available and did not bring harm to environment. The system usually operates at resonance frequency so that the best cooling performance can be offered [7]. Simple design of thermoacoustic refrigerator by using common materials such as POM-Ertacetal and also Poly-vinyl-chloride (PVC) was reported to be able to provide cooling effect [8]. The materials used for the structure known as stack was found to be affecting the performance of the thermoacoustic refrigerator. Investigations showed that stainless steel wool with ratio of hydraulic radius to the thermal penetration depth, r_h/δ_K, of 2.0 and 1.1 achieved the maximum cooling power, the lowest cooling temperature and the highest coefficient of performance, COPR, compared to the copper scourers and carbon foam [9]. It was also suggested that the stack material must have low thermal conductivity and the heat capacity should be larger than the heat capacity of the working gas [10]. To date, even with an optimized stack design, the stack has been either hand-fabricated as parallel or spiral geometry using Mylar material or hand-cut of Corning Celcor ceramic [6]. Investigation on the use of 3D-printed stack shows that it has potential towards improvement of the temperature performance [11]. The use of other stack materials such as copper [12] and stainless steel were also reported [13]. Both investigations showed that copper and stainless-steel stack produced a good cooling effect for thermoacoustic refrigerator. Stacks length and position are two most common variables that need to be considered when designing thermoacoustic system [14]. It was also reported that stack positioned near to pressure antinodes can result in maximum performance of thermoacoustic refrigerator. In addition, the blockage ratio for the stack also plays a role in producing good heat transfer. The blockage ratio slightly reduces local heat transfer around the downstream stack [15].

DeltaEC is the design software commonly used in conjunction with thermoacoustics [16]. The software uses shooting methods when solving linear thermoacoustic theory for the designated system [17]. It was reported that higher harmonics are less desirable for thermoacoustic phenomena as they lower the temperature difference across the stack. Published work also suggested that the mean operating pressure has direct effect on the performance in terms of creating cooling capacity and temperature difference [18]. Optimization of thermoacoustic refrigeration was usually investigated prior to fabrication to obtain design parameters that can improve the coefficient of performance (COP) for thermoacoustic refrigeration system [19]. This paper reports the results of modelling works related to a standing wave thermoacoustic system with a quarter wavelength resonator using DeltaEC. The heat transfer performance of the system is represented by the temperature different at both the ends of stack inside a standing wave thermoacoustic cooler. Comparison of the coefficient of performance, COP, for different cases is also presented.

2. Methodology

The investigation was done using two methods. First, a DeltaEC model was solved to gain some understanding about potential cooling effect that can be offered by a standing wave thermoacoustic resonator with the use of defined stacks materials. Then, experimental investigations were tested, and the results are reported based on the impact of materials, stack length as well as the resonators length.

2.1. DeltaEC modelling

In DeltaEC, users are allowed to design thermoacoustic system by defining parts and segments to be used in the design. Figure 1 shows a simple schematic diagram for the thermoacoustic model with defined segments to represent parts of the system. The segments can be generally defined as two categories; the components used in developing the system and the additional instructions to complete the calculations for the model. For this model, thermoacoustic parts are designed by using components such as VSPEAKER, DUCT, SURFACE and HARDEND. The segments of BEGIN, ANCHOR and INSULATE are the additional instructions that are used to complete the calculation for the models. BEGIN allows the setting up of the initial values and operating conditions for numerical modelling. Air at atmospheric pressure was selected as the working fluid. The BEGIN segment is connected to a VSPEAKER which represents a speaker. The speaker is connected to another segment known as DUCT. The speaker will generate the acoustic waves needed in the thermoacoustic system. DUCT represents the resonator which is the body of the rig with air inside it. The air inside this segment accepts the sound input from the speaker. A porous media is placed at a certain location inside the resonator and the location and placement of this porous media is represented by STKCIRC. This segment represents the use of porous media with circular pores.

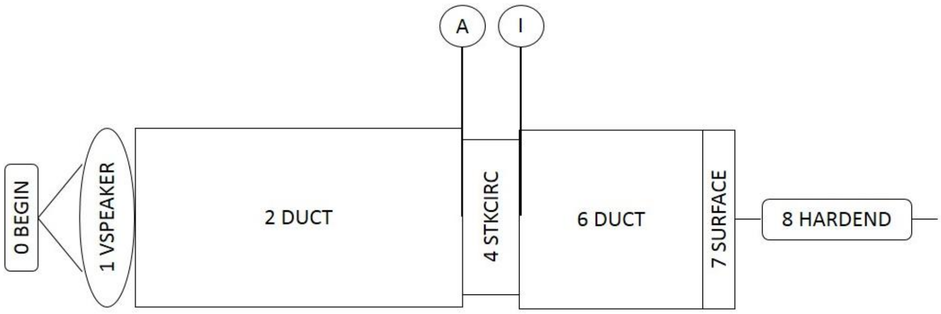


Figure 1. Schematic diagram of segments as defined in DeltaEC software

There is an ANCHOR segment (labelled as 'A' in fig. 1) which is located between the DUCT and the STKCIRC. ANCHOR does not represent real components but is needed to represent the potential of loss in the system. This lost is usually related to the imperfect insulation or connection between parts. Then, a porous structure known as 'stack' is located between the two DUCTS and is labelled in fig. 1 as STKCIRC. The porous structure is sandwiched between two ducts. This means that the stack is positioned inside the duct. The porous media is usually offering huge surface contact area with the fluid. For thermoacoustic effects to take place [20]. Thermoacoustic effects occur within a very small layer next to the plate known as the thermal boundary layer. It is defined as $\delta_k =$

$\sqrt{(2K/\rho_m c_p \omega)}$ with K as thermal conductivity, ρ_m, the mean density, c_p, the constant pressure specific heat, and ω, the angular frequency of the working fluid. There is also another layer that usually overlaps with the thermal layer (often with different thickness) and it is known as the viscous boundary layer, $\delta_v = \sqrt{(2\mu/\rho_m \omega)}$, where μ represents the viscosity of the fluid [5]. In DeltaEC simulation, the materials that can be selected for STKCIRC are fixed and the materials can be set either as stainless steel, tungsten, copper, mylar or ceramic celcor. These materials are used for the simulation works and they are categorized based on the metal and non-metal groups of materials. Tab. 1 shows the values for specific heat, c_p , and thermal conductivity, k_s, of all the materials. DeltaEC treats fluid properties as temperature dependent. However, for ease of discussions, the values shown in Tab. 1 are shown for a constant temperature of 300 K. The stacks are tested for two different lengths: a 4 cm long stack and an 8 cm long stack. After the stack segment, there is the INSULATE segment that is labelled as ‘I’ in fig. 1. This segment is used to recreate the default thermal insulation condition and stop the ANCHOR instruction that represents losses. It means that the INSULATE instruction restores the ideal condition into the model once calculation at the ‘STKCIRC’ is completed. In this model, the instructions of ‘ANCHOR’ and ‘INSULATE’ were used to represent losses in the flow within the area of porous structure. Elsewhere, the models are assumed perfectly insulated and ideal. In this thermoacoustic system, it is assumed that the thermoacoustic refrigerator system is operating in quarter wavelength environment where HARDEND is applied at the end of the resonator. This HARDEND represents the rigid wall at the end of the duct (the quarter wavelength resonator) that is filled with air at an atmospheric pressure.

Table 1. The value of properties for selected materials at a reference temperature of 300 K

Material	Specific heat, Cp $[Jkg^{-1}K^{-1}]$	Thermal conductivity, Ks $[Wm^{-1}K^{-1}]$
Mylar [5]	1100	0.16
Ceramic celcor [5]	1000	1.46
Acrylonitrile Butadine Styrene (ABS) [22]	1000	0.22
Poly-carbonate foam (PCB) [22]	1200	0.20
Lollipop Stick [22]	1800	0.22

DeltaEC solves the model based on Thermoacoustic Linear Equation [16,17]. The oscillating wave behaviors are represented by harmonic oscillations of density, ρ, pressure, p, and velocity, u. The oscillatory flow motion is 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 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. In general, the linear thermoacoustic theory used in DeltaEC can be represented by eq. (1) to (3). 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. The second order thermoacoustic effect is defined in eq. (4) and it is representing the energy that is carried in the axial direction of flow.

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

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

$$\frac{dT_m}{dx} = \frac{H_{2,k} - \frac{1}{2}\mathrm{Re}\left[p_1 U_1\left(1-\frac{T_m\beta(f_k-f_v)}{(1+\epsilon_s)(1+\sigma)(1-f_v)}\right)\right]}{\frac{\rho_m c_p|U_1|^2}{2\omega A(1-\sigma)|1-f_v|^2}\mathrm{Im}\left[f_v+\frac{(f_k-f_v)(1+\epsilon_s f_v/f_k)}{(1+\epsilon_s)(1+\sigma)}\right] - Ak - A_s k_s} \tag{3}$$

$$\begin{aligned} H_{2,k} = {} & \frac{1}{2}\mathrm{Re}\left[p_1 U_1\left(1-\frac{f_k-f_v}{(1+\varepsilon_s)(1+\sigma)(1-f_v)}\right)\right] \\ & + \frac{\rho_m c_p|U_1|^2}{2A\omega(1-\sigma)|1-f_v|^2}\frac{dT_m}{dx}Im\left[f_v+\frac{(f_k-f_v)(1+\epsilon_s f_v/f_k)}{(1+\epsilon_s)(1+\sigma)}\right] \\ & -(Ak+A_s k_s)\frac{dT_m}{dx} \end{aligned} \tag{4}$$

Ideally, the temperature gradient along the direction of flow, $\partial T/\partial x$, are treated as zero in all components except for the STKCIRC where temperature is expected to change in axial direction due to the transfer of heat between the working medium and the solid surface of the stack. This phenomenon is commonly referred to as the 'thermoacoustic effect'. The axial temperature gradient, as represented by eq. (3), involves the impact of the presence of porous structure that are represented by the shape factor, $f_{k,v}$, the thermal conductivity ratio, ϵ_s, the surface area of the solid, A_s, and the thermal conductivity of the solid material, k_s. For a porous structure with circular pore, the shape factors, $f_{k,v}$ and thermal conductivity ratio, ϵ_s, are defined as;

$$f_k = \frac{2J_1[(i-1)\,r_0/\delta_k]}{(i-1)(r_0/\delta_k)J_o[(i-1)\,r_0/\delta_k]} \tag{5}$$

$$f_v = \frac{2J_1[(i-1)\,r_0/\delta_v]}{(i-1)(r_0/\delta_v)J_o[(i-1)\,r_0/\delta_v]} \tag{6}$$

$$\epsilon_s = \left(\frac{k\rho_m c_p}{k_s\rho_s c_s}\right)^{1/2}\frac{f_k(1+i)\,r_0/2\delta_k}{\tanh[(1+i)\,l/\delta_s]} \tag{7}$$

The term r_0 is the radius of the circular pore in the porous structure, β represents the thermal expansion coefficient for an ideal gas, δ_k and δ_v are thermal and viscous penetration depth respectively, J_0 and J_1 are representing the zeroth and first order of Bessel function, k is the thermal conductivity of the fluid and k_s is thermal conductivity of the solid, ρ_s is density for solid surface, c_p and c_s are specific heat of the gas and solid, respectively. The software iterates the calculations using fourth-order Runge-Kutta integration. A shooting method was utilized 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.

In thermoacoustic system, the performance of the system is very much depending on the stack performance. This in turn depends on its length, L_s, stack centre position, x, plates spacing, y_0, and the thermal boundary layer within the channel of the stack, δ_k[11]. The stack's performance is defined by its coefficient of performance (COP) which is the ratio of the cooling power to the acoustic work supplied to the stack. The normalized cooling power, Q_{cn}, is defined as:

$$Q_{cn} = -\frac{\delta_{kn} D^2 \sin 2x_n}{8\gamma(1+\sigma)\Lambda} \times \left(\frac{\Delta T_{mn} \tan(x_n)}{(\gamma-1)BL_{sn}} \frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}} - (1+\sqrt{\sigma}-\sqrt{\sigma}\delta_{kn}) \right) \tag{8}$$

The normalized acoustic work, W_n, is:

$$W_n = \frac{\delta_{kn} L_{sn} D^2}{4\gamma} (\gamma-1) B \cos {x_n}^2 \times \left(\frac{\Delta T_{mn} \tan(x_n)}{BL_{sn}(\gamma-1)(1+\sqrt{\sigma})\Lambda} - 1 \right) - \frac{\delta_{kn} L_{sn} D^2}{4\gamma} \frac{\sqrt{\sigma} \sin {x_n}^2}{B\Lambda} \tag{9}$$

Where Λ is defined as:

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2}\sigma {\delta_{kn}}^2$$

The term L_{sn} is the normalized stack length and x_n is the normalized stack position. The porosity of the stack is sometimes called a blockage ratio and is defined as $B = y_0/(y_0 + 1)$, a dimensionless parameter for the geometry of the stack. The fluid properties are presented by γ for the specific heat ratio, σ for the Prandtl number, and δ_{kn} is the normalized thermal boundary layer of the stack. The dimensionless operating temperature drop, ΔT_{mn}, is the normalized temperature difference that is obtained across the stack, and the ratio p_0/p_m is known as the drive ratio, D. The performance of the stack is expressed in terms of the coefficient of performance, COP, which can be calculated as, COP = Q_{cn}/W_n . In this paper, the software is used to help gaining general idea of potential performance of a simple laboratory prototype of a standing wave thermoacoustic cooler. In order to gain more understanding, experimental investigations are also conducted. Comparison of results are made whenever possible between the results of the DeltaEC models and the experimental findings. The performance is defined by the temperature different generated across the stack, and the evaluation of coefficient of performance, COP. The experimental rig is built with dimensions that follows the DeltaEC models and the setup is discussed in the following section.

2.2. Experimental setup

The experimental setup was built using cheap and abundant materials following inspiration from published works [20]. Fig. 2 shows the experimental apparatus of the thermoacoustic cooler. The experimental system consists of the speaker (D5 5 inch 2-way coaxial speaker) as an acoustic driver, an acrylic tube as the resonator and a porous structure called stack. The types of stack used in the experiment is shown in fig. 3. The speaker is put inside a 30 cm x 30 cm x 10 cm acrylic box that is connected to the 3.1 cm diameter resonator.

In the experiment, the resonator is designed with two different lengths of L_1 = 0.65 m and L_2 = 0.385 m in order to investigate the potential impact of resonators length on the temperature drop. The investigation also involves two different lengths of stack ($L_s = 0.04$ m and $L_s = 0.08$ m) that is made of three different materials. The first stack is made from Acrylonitrile Butadiene Styrene (ABS) and is printed using a 3D printer. A Computer Aided Drawing (CAD) software known as Catia was used to designed honeycomb shaped pore with radius of hexagon of 5 mm. The second stack is made from Polycarbonate (PCB) foam that also offers honeycomb type of porous media. The material was purchased and then cut to size so that it fits into cylindrical shape of the resonator. The third stack is made from abundant material of lollipop stick that was arranged to form porous structure that is almost similar to the other two materials.

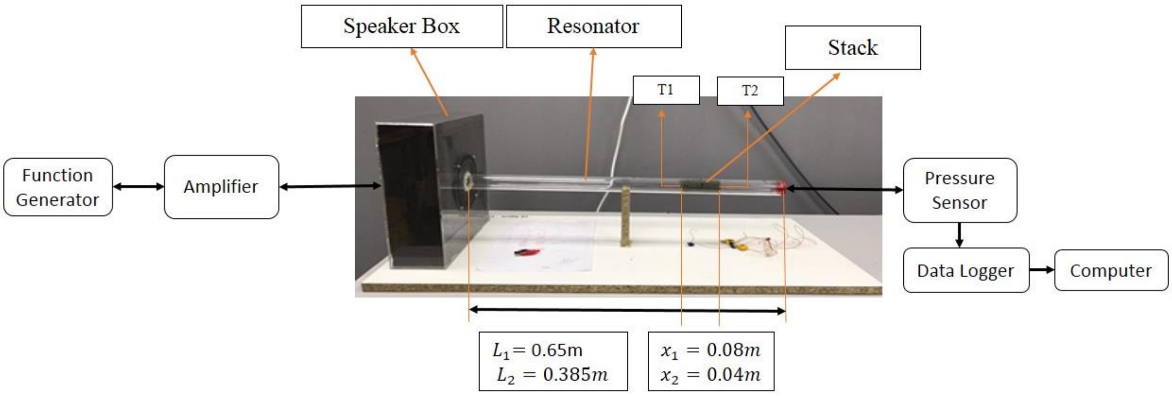
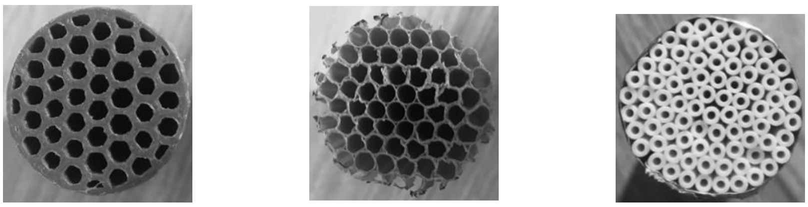


Figure 2. The experimental apparatus of the thermoacoustic cooler



(a) **(b)** **(c)**

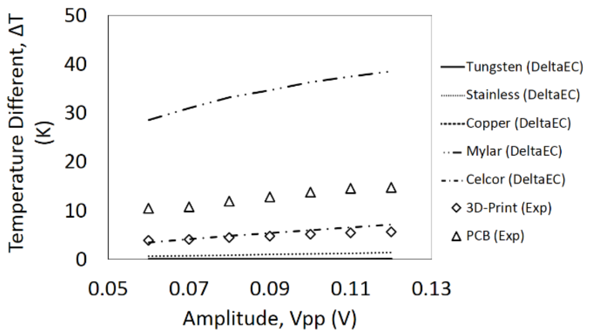
Figure 3. The porous structure is made of (a) Acrylonitrile Butadiene Styrene (ABS), (b) Poly-carbonate foam (PCB), and (c) Lollipop stick

During the experiment, sensors and suitable instrumentation were used for measurements and data collection. For pressure analysis, a piezoresistive sensor (Meggit model 8510B) was used and the sensor is connected to the data logger (Dataq DI-718B) that is fitted with signal conditioner (Model DI-8B41-01). For temperature analysis, Picolog Data Logger (TC08) with type-K thermocouples are used and is connected to the laptop for data acquisition. Picolog Data Logging Software is used to record the temperature reading for every data collection during experimental work. The thermocouples are installed at two points which are labelled in fig. 2 as T_1 (representing hot temperature value) and T_2 (representing cold temperature value), respectively. The locations of thermocouple were as shown in fig. 2. The experimental rig was first tested for resonance frequency and then data are collected at that resonance frequency setting.

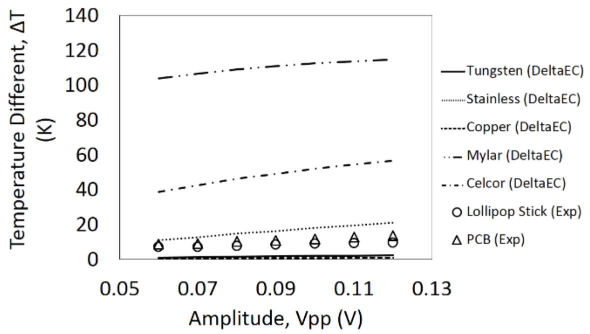
3. Results and discussions

3.1. Temperature Different

Results are discussed based on DeltaEC models and experimental findings. The refrigerator performance is presented based on temperature different across the stack when different acoustic level and different stack materials and lengths are used. Fig. 4 shows the results obtained from the DeltaEC simulation and experimental works that were investigated according to the desired parameter as described earlier. As was mentioned earlier, due to limited choice in model settings, the materials designed in DeltaEC are not the same as the one used in experiment. Discussions will be made based on the general category of metal versus non-metal materials. Hence, comparison is qualitatively made based on pattern and not the quantitative values. The results were collected using resonator that is 0.65 m long with resonance frequency of 123 Hz. The stack was tested at two different lengths of 4 cm and 8 cm.



(a) Stack 4 cm long



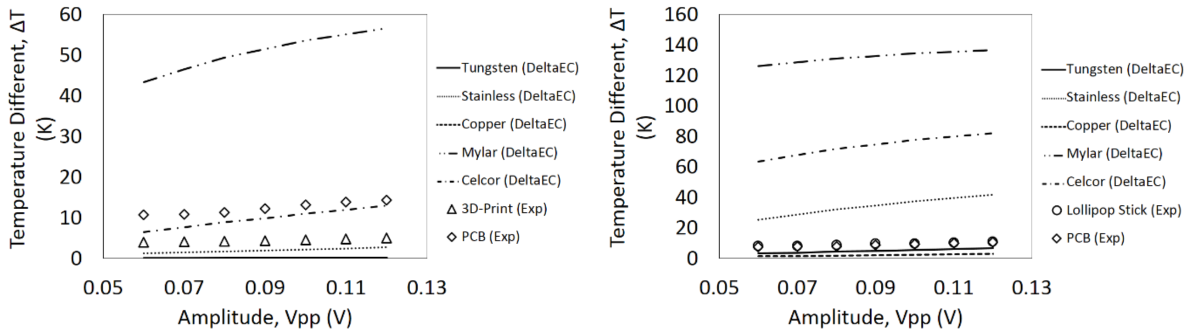
(b) Stack 8 cm long

Figure 4. The impact of stack's material on temperature drops across stack length of (a) 4 cm and (b) is 8 cm long inside resonator of 0.65 m long

The resonance frequency was first estimated using theoretical equation where the wavelength can be calculated as $\lambda = c/f$ with c as the speed of sound and f is the frequency. The length of the resonator is a quarter of the wavelength. The results are to be discussed based on the length of the stack. Parts (a) and (b) of fig. 4 show the results of temperature drops across the stack that is made of 4 cm and 8 cm length, respectively. In DeltaEC, the material is fixed to five tested materials which can be classified into two different groups (i.e., metal and non-metal). The results in fig. 4 (a) and (b) show that copper stack with 8 cm long provides better temperature drop between two ends of the stack compared to that of the 4 cm long. The 8 cm long stack produces a maximum temperature drop of 21.02 K between the two ends of the stack. This happens because increasing the stack length will increases the power density since more thermoacoustic interactions occur. DeltaEC model also predicts that copper performs poorer compared to other materials. The high thermal conductivity of copper leads to fast travel of heat between two ends of the stack. Hence, temperature different becomes very small. Non-metal materials such as mylar and celcor, provide better temperature drops. Based on the results in fig. 4 (a) and (b), mylar provides bigger temperature difference compared to celcor and it is probably related to the balance between thermal conductivity and specific heat capacity offered by the material, as was illustrated in tab. 1. Again, the 8 cm long stack is better than the 4 cm long stack. The highest temperature change for 8 cm stack made of non-metal is 114.82 K while for 4 cm stack the highest temperature drop is only 38.59 K.

DeltaEC is based on one-dimensional nonlinear thermoacoustic models. Real experimental values may be different especially if losses and nonlinearity of flow take place. In order to tests the theory, series of experimental works are conducted by using different materials of stack. The experimental work starts with the determination of the resonance frequency of the experimental rig. The pressure amplitude data was monitored at the location of pressure antinode and was used to identify resonance frequency. The frequency was raised until resonance is achieved when maximum pressure is recorded for the rig. Experimentation shows that the resonance frequency is 123 ± 0.4 Hz for the long resonator. Experiments were done for 3 different stack materials. The results are shown as part of fig. 4. The stacks for experimental works are selected based on observation of DeltaEC results where non-metal based material offers a better temperature drop. For this reason, the stacks for experimental works are made from three non-metal materials of poly-carbonate honeycomb foam (PCB), 3D printed Acrylonitrile Butadiene Styrene (ABS) and porous structure of lollypop sticks. The experiments started with stacks of 4 cm made of PCB and ABS. The results, as shown in fig. 4 (a), show that PCB offers a better temperature drop across the stacks. The experimentation is then continued with PCB and lollypop stick type of stack with length of 8 cm. The ABS stack was not tested in this longer resonator setting as it was shown to be ineffective compared to PCB. Fig. 4 (b) shows that the stack made of PCB is still offering the best performance in terms of temperature drop between the two ends of the stack. It is noteworthy that the solid wall of PCB is thinner compared to the ABS. This leads to effective thermodynamic process within the stack area. Similar wall thickness issue is observed for experimentation using PCB and lollypop sticks. The lollypop sticks have thicker walls compared to PCB foam. The maximum temperature difference achieved by a PCB stack is 14.73 ± 0.14 °C, while the largest temperature difference achieved by a 3D-print stack is 5.7 ± 0.05 °C. In all the experimental works, regardless of length of stack, PCB seems to offer good temperature different between the two ends of the stack. The temperature different offered by PCB stack is slightly better when a shorter stack is used.

The different materials of stack are tested again and this time the models are solved for a shorter resonator with a length of 0.385 m. The resonance frequency for this short rig is 202.1 ± 0.001 Hz. Fig. 5 shows the temperature different that can be obtained between the two ends of the stack when the input peak-to-peak voltage, Vpp, of the speaker increases.



(a) Stack 4 cm long **(b) Stack 8 cm long**

Figure 5. The impact of stack's material temperature drop across stack length of (a) 4 cm (b) is 8cm long inside resonator of 0.385 m long

For DeltaEC simulation, the lowest temperature at the cold end is recorded to be at 239.39 K for the short stack and 159.25 K for the long stack. The differences in values of temperature drop between the two ends of the stack is shown in fig. 5 (a) and (b). Again, mylar provides the best performance for temperature drops. This means that the stack's material properties of specific heat and thermal conductivity are important factors to be considered either when using long or short resonators. In fig. 5 (a) and (b), temperature drop across stack is shown for two different non-metal materials: mylar and celcor. The results show that celcor stack produced a lower temperature different. Similar observation was seen earlier for the results of long resonator as was presented in fig 4. It seems that non-metal stack with higher specific heat and lower thermal conductivity provides better temperature drop. Comparison between results in fig. 4 and fig. 5 shows that system with higher resonance frequency offers better temperature difference at the stack. DeltaEC results also show that stack made of non-metal material offers better thermoacoustic performance compared to the stack made of metal materials.

In the experimental work, the highest temperature difference of 14.3 ± 0.17 °C was recorded when PCB is used as a stack. Again, similar to the cases with long resonator, PCB offers a better temperature drop compared to ABS stack. It is interesting to note that the results of temperature drop for stack made of lollipop sticks are almost similar to the PCB stack. This triggers the idea that the abundantly available lollipop sticks could be put to good use in thermoacoustic system. It is also observed that, in contrary to the DeltaEC prediction, the experiment with shorter stack provides a slightly better temperature drop compared to that with a longer stack. This can be seen by careful observation especially for the results of PCB stack between both the short stack (i.e., part (a) of fig. 4) and the longer stack (i.e., part (b) of Figure 4). This is probably related to losses such as the blockage enforced by the porous material of the stack and streaming which were not adequately addressed by the linear model.

3.2. Stack's Performance

The overall performance of the system needs to be evaluated based on the evaluation of the ratio of the output to the input of the system which is defined through the coefficient of performance (COP) as presented in tab. 2.

Table 2. The coefficient of performance for the cooler based on experimental results

Materials (stack's length)	Coefficient of Performance, COP	
	Long resonator	Short resonator
Acrylonitrile Butadiene Styrene, ABS (4 cm)	3.89	2.71
Poly-Carbonate foam, PCB (4 cm)	4.73	3.60
Poly-Carbonate foam, PCB (8 cm)	3.05	1.99
Lollipop stick (8 cm)	3.56	2.48

From the results, the best COP value of 4.73 is found when PCB of 4 cm long is used as a stack. Long resonator rig offers better COP compared to short resonator. This means that a more efficient energy change happens when the resonator is longer. Evidently, temperature drops alone is not sufficient to represent performance. Although shorter stack was experimentally shown to offers more temperature drop, but it happens at a cost of more power input leading towards lower COP. The operation of long resonator rig at lower resonance frequency involves small losses. However, when the stack is made too long, energy transfer between the air and the solid surface is not any more effective due to the limitation of the gas travel distance.

4. Conclusion

In general, similar trend of temperature drops are obtained for the DeltaEC models and the experimentations. Both are showing that the temperature drop becomes bigger as the flow amplitude increases. In addition, both results are also showing that stack's material plays important role in the achievement of temperature drop in the system. The DeltaEC models were solved based on materials that are available in the models. Although direct comparison could not be done between numerical works and experiments, but the modelling practice helps in understanding that the non-metal stack is predicted to offer more temperature drops compared to metal stack. Quantitative disparity between DeltaEC and experimental results are expected to be due to the inability of the current DeltaEC models in capturing experimental losses. Small contributions of losses were already introduced through the use of instructions such as ANCHOR and INSULATE, but they seem to be insufficiently representing the real value. Nonetheless, DeltaEC predicts that temperature difference is bigger when longer stack is used. Similar observation was also reported by another numerical investigation reported by Achmadin et al. [21]. On a contrary, the experiments showed that the shorter stack offers better temperature difference compared to longer stack. Interestingly, similar observations were also reported by the experimental works of Zolpakar et al., [11] where the short stacks are better than the long stack. The increment of stack length may provide opportunity for better power density when more thermoacoustic interactions occur. However, increasing the stack length will also increase the acoustic impedance and the pressure drop especially for dense stack [11]. This is as reflected by the results of COP where rig with shorter stack seems to offer better COP than the longer one. In this paper, stack made from PCB material with 4 cm long and placed inside long resonator gives the best result for temperature drop and COP of thermoacoustic refrigerator system. The experimental results indicated that losses are sometimes inevitable especially as vibration becomes more prominent particularly at high flow amplitude and high resonance frequency. More experimentations are certainly needed to obtain better understanding on this matter. Nevertheless, the current findings show that DeltaEC models can be fairly used for designing thermoacoustic cooling system, but care should be exercised to count for potential losses especially when long stack is used in the system.

Acknowledgement

The authors would like to thank Universiti Teknikal Malaysia Melaka and Ministry of Higher Education Malaysia (FRGS/1/2020/FKM-CARE/F00434) for providing supports for this research.

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Submitted: 18.10.2021
Revised: 13.01.2022
Accepted: 27.03.2022.