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# The Effect of Porous Materials on Temperature Drop in a Standing Wave Thermoacoustic Cooler

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## ABSTRACT

*Thermoacoustics is a principle of sciences that offers an alternative solution for cooling system with a technology that is green and sustainable. The thermoacoustic energy conversion takes place mostly within the area of the porous structure that forms the core of the system. In this study, the effect of changing the material of the porous structure on the performance of the thermoacoustic refrigerating system is reported. Experiments were performed under standing wave environment with two different resonance frequencies with air at atmospheric pressure. The porous stack was chosen to be with three different materials of polycarbonate, ceramic and stainless steel. The results show that the use of ceramic celcor as the porous material provides the biggest temperature difference which means that thermoacoustic performance is better. The performance is even better when the system is working with higher resonance frequency. At atmospheric pressure condition with air as working medium, the thermoacoustic cooler with ceramic porous material is capable of producing temperature difference of 39.16 ℃ when operating at a frequency of 202.1 Hz.*

**Keywords:** Thermoacoustic cooler, porous media, standing wave thermoacoustics

## 1. INTRODUCTION

Environmental impacts are becoming increasingly relevant in the design and development of refrigerating systems. Research efforts are focusing more on the development of alternative refrigerants and alternative technologies to slowly eliminate the usage of environmentally harmful refrigerants [1]. In 1987, the Montreal Protocol required countries to minimise production and consumption of Chlorofluorocarbons (CFC) gas while encouraging the use of alternative technology [2]. Because of the limitations on utilizing gases that harm the ozone layer, researchers have been focusing on inventing new ability-based systems, such as the thermoacoustic system. The system does not use refrigerant gas but still provides refrigeration, it can be regarded a suitable replacement for the current refrigeration system [3].

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 [4]. An approach in category of alternative technologies is thermoacoustic refrigeration. Thermoacoustic refrigeration technology is based on the interaction of acoustic waves with a

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solid boundary creating thermoacoustic cooling effects. At high pressure with proper design, fabrication and operation, cooling effects that can be harnessed can be very significant [4]. The first prototype that utilizes thermoacoustic energy conversion was an ice cream cabinet that was invented through collaboration between The Penn State University, Unilever Engineering Excellent team, and Ben & Jerry's in 2004 with Sound Cool [5].

The basic equations and concepts for the thermoacoustic theory and the early history of thermoacoustic are documented by Swift [1,6]. Thermoacoustic refrigerant is a thermodynamic system that requires work input for the acoustic wave to expand and compress in order to function properly when the wave crosses the small channels of the porous structure. During the operation of a system, the employment of turbulent flow conditions with the presence of a barrier might result in an increase in heat transfer [7]. In thermoacoustics, the core component is the porous media known as a 'stack' or a 'regenerator' and most thermoacoustic effect happens there due to interactions between flow and solid surfaces. Although the porous structure imposes obstruction to the flow, it is still needed so that energy conversion for the thermoacoustic effect can happen effectively [8]. Hence, the compromise between the pressure drop and the energy creation needs to be met [8,9].

Thermoacoustic system operates at resonant frequency for efficient energy production. When the fluid particles at resonance frequency oscillate close to the solid wall, heat can be transferred from one end of the solid wall to the other, resulting in cooling effect [10]. 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. Most of the current investigations on thermoacoustic devices with standing wave are focussing on the stack, with concerns especially on the stack geometry [11], the position of the stack placement in the resonator [12] and the length of the porous structure of the stack [13]. The spiral and parallel plate types of stack geometry are the most often used, studied and analysed [10].

Tijani *et al.*, [14] performed an experimental research into the effect of the plate spacing in the stack on the thermoacoustic effect in the thermoacoustic refrigerator working with the operating frequency of 400 Hz and with helium as the working fluid that was operated under the pressure of 10 bar. The result show that the distance between the plates of about $2.5\delta_k$ was optimum for the cooling power. Similar results concerning temperature drop that can be obtained by the system with thermoacoustic principles, but for significantly different configuration of the refrigerator, which worked with air at atmospheric pressure and frequencies of 107 Hz and 86 Hz, were also observed by Setiawan *et al.*, [15]. The impact of the stack material on the temperature difference across the stack in other stack geometries like spiral, circular pore, and pin arrays was also studied experimentally by Wantha [16].

Nsofor and Ali [1] studied the performance of the thermoacoustic refrigerating system with respect to some critical operating parameters. The temperature different between the hot end and cold end of the stack ranged from 0°C to 15°C. It was also reported that the performance of the system may be impacted by the use of inert gaseous as working medium [10]. Zolpakar *et al.*, [10] also stated that air is still widely used as the working fluid because it is easily available for experiments related to investigation of relationship between design and operating parameters. To generate acoustic power, a resonance tube encloses the working fluid, stack, heat exchangers, and an acoustical source. To achieve significant cooling at the solid walls of the stack, the power delivered into the tube must be at the enclosure's natural frequency.

The most common resonance tubes are the half wavelength and the quarter wavelength resonators in order to generate a considerable temperature difference between the ends of the short stack that is positioned in the path of the oscillating working fluid particles [10]. Based on the previous research by Tijani *et al.*, [17], they build a simple design of thermoacoustic refrigerator by using specific materials such as POM-Ertacetal and also Poly-vinyl-chloride (PVC) for each component that was used. It aims to study the performance of thermoacoustic refrigerator for different operating conditions. In a different investigation, the thermal performance of random stack materials such as stainless-steel wool, copper scourers and also carbon foam were used for application in standing wave thermoacoustic refrigerators that is investigated experimentally by Yahya *et al.*, [18]. The materials used found to be affecting the performance of the thermoacoustic refrigerator and the result showed that stainless steel wool with ratio of hydraulic radius to the thermal penetration depth, $r_h/\delta_K$, of 2.0 and 1.1 achieved the maximum cooling power, the lowest cooling temperature and the highest COPR compared to the copper scourers and carbon foam.

Tijani *et al.*, [19] stated that the stack material must have a low thermal conductivity and the heat capacity should be larger than the heat capacity of the working gas. 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 [4, 6]. Then, Zolpakar *et al.*, [20] reported an experimental work on measurement of the performance of the stack in terms of the temperature difference that is achievable using a stack that was fabricated with a 3D printed material. The results showed that the 3D-printed stack has potential towards improvement of the temperature performance. The use of other stack materials such as copper [21] and stainless steel were also reported [22]. Both investigations showed that copper and stainless-steel stack produced a good effect on the performance of thermoacoustic refrigerator. Atiqah *et al.*, [23] showed that stack parameters can affect the temperature difference between the hot and cold heat exchangers. It has also been shown 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 [24].

Tasnim *et al.*, [25] compared the influence of stack properties with regular and random porous media on the performance of the thermoacoustic heat pump. Their device worked with the frequency of about 350 Hz and was filed with air at atmospheric pressure. The results showed that the temperature difference generated across the stack increased as the porosity increased. Then, Zolpakar *et al.*, [26] conducted a study to maximize the coefficient of performance (COP) of a thermoacoustic refrigerator by investigating the length of stack, $L_{sn}$, stack center position, $x_{sn}$, blockage ratio, $B$ and also drive ratio, $DR$. The result for their experimental work showed that a COP of up to 1.64 can be achieved which is great for future improvements in the current system.

Many analytical and numerical studies have been done on the porous structure of the stack as well. Ishikawa *et al.*, [27] numerically examined the energy fields in the stack and found it to be as the function of the drive ratio and the plate spacing. Marx *et al.*, [28] calculated numerically the temperature difference between the stack extremities and found that at higher Mach number some deviations between numerical results and the linear theory predictions occurred. Study of literature reveals that many researchers have worked on numerically as well as theoretically aspects to study the performance of thermoacoustic system with porous structure component known as the stack or the regenerator. On the contrary, limited amount of work has been carried out experimentally. Most of these experimental works were carried out by fabricating aluminum and other metallic type resonator for the system resulting to conduction heat losses. Hence, it is very important to conduct a detailed experimental work by constructing components of thermoacoustic refrigerator by different materials which are having less thermal conductivity thereby enhancement in the performance of thermoacoustic refrigerator can be achieved. In this paper, the measurement will be described regarding the effect of various materials of a stack on the performance of thermoacoustic refrigerator. The experimental work is done by using different types of material (i.e. stainless steel scourer, ceramic celcor and poly-carbonate foam) with the same length of stack.

## 2. METHODOLOGY

A thermoacoustic refrigerator comprises of a porous structure known as a stack, the body of the system known as the resonator and a loudspeaker/acoustic driver that drives the acoustic flow inside the system. This is as shown in Figure 1. The stack is the heart of the thermoacoustic refrigerator which transfers heat from one side to another by pumping action through inert gas environment inside the closed resonator tube. Nsofor and Ali [1] and Rahpeima and Ebrahimi [29] had created a simple thermoacoustic cooler by using cheap and easily available materials. The idea introduced by these researchers have been used as a benchmark for the current study. Figure 1 shows the schematic diagram of the experimental apparatus, while Figure 2 represents the actual laboratory build. The experimental system consists of the speaker as an acoustic driver, an acrylic tube as the resonator and a porous structure called stack as shown in Figure 3. The speaker used in the experiment is a D5 5 inch 2-way coaxial speaker that is capable of producing sound with power that is limited to 150 Watt. The speaker is put inside a box known as speaker box as shown in Figure 2. The speaker box is made of 30 cm x 30 cm x 10 cm acrylic box with a hole diameter of 3.1 cm at one surface of the speaker box that is connected to the resonator. The inner surfaces of the acrylic box are covered with a sponge to reduce the noise made by the speaker during the operation.

In the experiment, the resonator is designed with two different lengths in order to investigate the potential impact of resonance frequency on the temperature drop. The two lengths are shown in Figure 1 as $L_1$ = 0.65m and $L_2$ = 0.385m. The resonator is made from acrylic tube with 3.1 cm inner diameter and 3.5 cm outer diameter. Stack is the main component for thermoacoustic refrigeration. A good stack condition can give a good impact on the temperature drop. The investigation involves the use of different types of stack that is made of three different materials. The first stack is made from Polycarbonate (PCB) foam that 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 stack was all set to be at the same length of $L_s = 0.08$ m. The second stack is made from a scourer with stainless steel materials. The scourer was arranged to form porous structure with length that is almost similar to the other materials used. The third stack is made from ceramic celcor with honeycomb porous structure that was purchased from Corning and then was cut to fit the diameter of the resonator. For both the resonator lengths, the stack is placed at a location of $0.18\lambda$ from the location of the pressure sensor (pressure antinode). The wavelength, $\lambda$, depends on the resonance frequency of the flow and the speed of sound is 331.29 m/s.

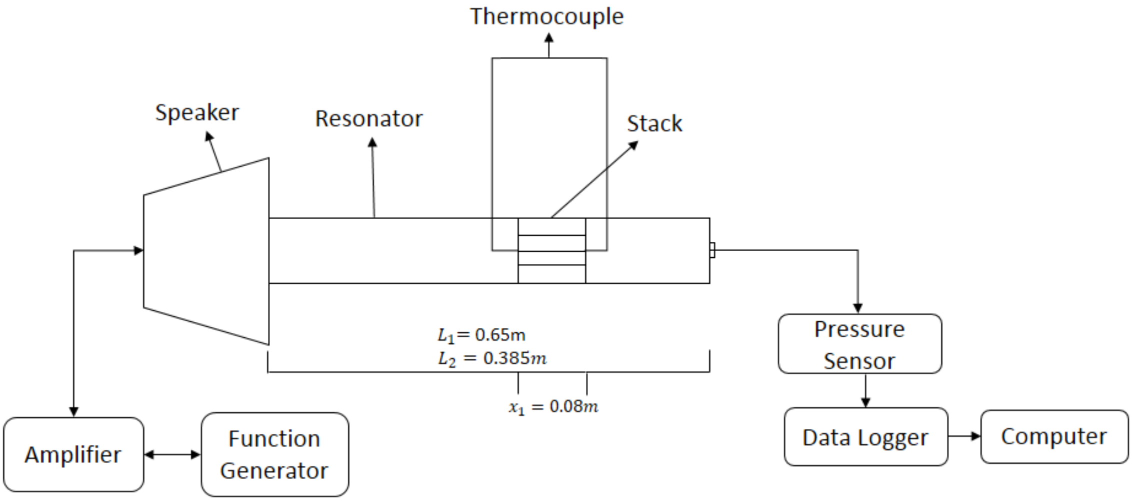


**Figure 1.** A schematic diagram of a simple standing wave thermoacoustic refrigerator with two different lengths of resonator.

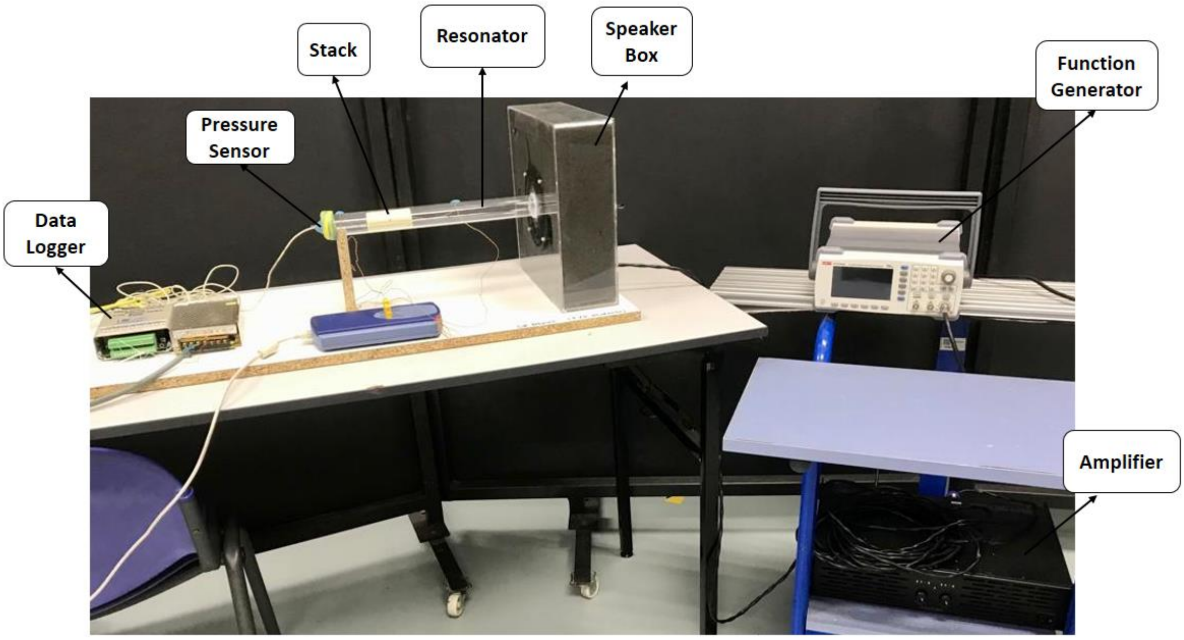


**Figure 2.** A laboratory rig for a simple standing wave thermoacoustic refrigerator with the porous structure placed inside the resonator.

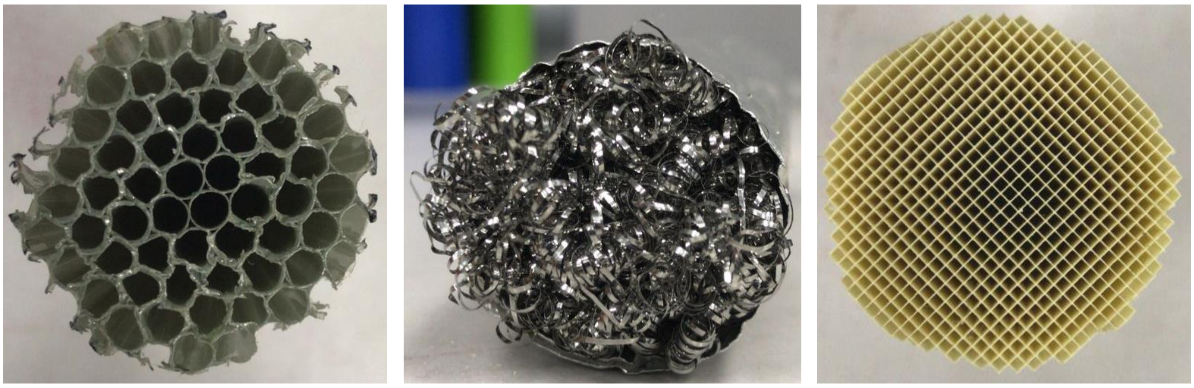

(a) (b) (c)

**Figure 3.** The porous structure of stack is made of (a) a polycarbonate foam (PCB), (b) a stainless steel scourer and (c) a ceramic celcor.

During the experiment, sensors and suitable instrumentation were used for measurements and data collection. For pressure analysis, a piezoresistive pressure sensor (Meggit model 8510B) was used and for temperature analysis, Picolog Data Logger TC08 with type-K thermocouples are used. The thermocouples are installed at two points which were labelled as $T_1$ (representing hot temperature value) and $T_2$ (representing cold temperature value), respectively. The locations of thermocouples are as shown in Figure 1 and also Figure 2. The experimental rig was first tested for resonance frequency and then data are collected at that resonance frequency setting.

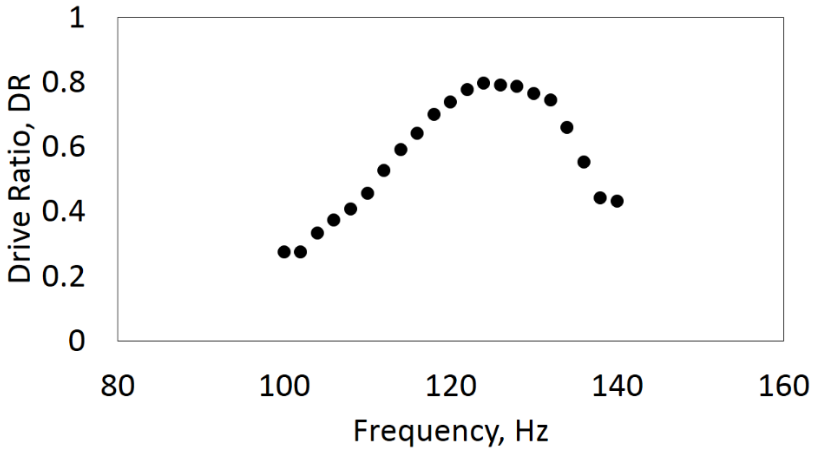
## 3. RESULTS AND DISCUSSION

Results are discussed based on experimental findings. The refrigerator performance is presented based on temperature difference that is recorded at two ends of the stack when different acoustic level and different stack materials are used. In the case of experimental study of thermoacoustic refrigerator, the oscillating flow condition is represented by a term known as a drive ratio, DR. The drive ratio, DR, is the ratio between the pressure amplitude at the location of the antinode, $P_a$, and the operating mean pressure of the system, $P_m$. For a quarter wavelength resonator, the location of pressure antinode is at the hard end of the resonator where pressure sensor was placed, as was shown in Figure 2. The experiment was conducted with air at an atmospheric pressure. Hence, the mean operating pressure is at 1 atmospheric. In general, the drive ratio also represents the amplitude of flow. As the voltage supply for the acoustic driver increases, the amplitude of flow inside the resonator increases too. As a result, the pressure amplitude at the location of antinode increases. Therefore, the increase of drive ratio also indicates the increase of flow amplitude inside the resonator.

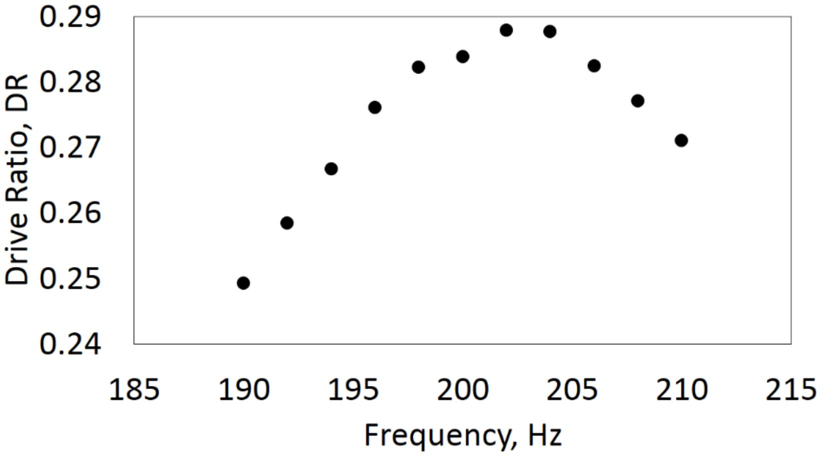
The experimental work starts with the determination of the resonance frequency of the experimental rig. The pressure amplitude data was monitored at the location of pressure antinode and was used to identify resonance frequency. This is done by fixing the input voltage of the speaker to a constant minimum value while varying the frequency until resonance is met. The frequency was tested within the range of 90 Hz to 150 Hz for the long resonator and 190 Hz to 220 Hz for the short resonator. Figure 4 shows the averaged data that are collected and then plotted as the drive ratio against frequency. Part (a) of Figure 4 shows the result for long resonator and part (b) is for short resonator. Resonance is achieved when maximum drive ratio is achieved in the resonator. The frequency at this maximum drive ratio is selected as the resonance frequency of the rig and will be used in the experiments. The findings show that the frequency of resonance is 123 Hz for long resonator and 202.1 Hz for short resonator.

After the resonance frequency is obtained, the experiment to determine temperature difference on the stack can be done. The first experiment is conducted for three different materials. Figure 5 shows the results obtained from the experimental works for long resonator with resonance frequency of 123 Hz. The stacks for experimental work are made from two non-metal materials (i.e. Polycarbonate foam (PCB) and Celcor Ceramic) and one metal material of stainless steel scourer. The experiments started with stacks of 8 cm made of stainless-steel scourer, polycarbonate foam and also ceramic celcor. The result, as shown in Figure 5, shows that the temperature drops between the two ends of the stack increases as the flow amplitude increases. Stack made of ceramic celcor offers the best temperature drop across the stacks with the highest temperature drop recorded at 22.15°C. The lowest temperature drop for ceramic celcor is 15.36°C which is still the best temperature drop compared to the temperature drop offered by the stack made of stainless-steel scourer and PCB.

Figure 5 also shows that the highest temperature drop for PCB stack material is 13.77 °C. Therefore, stack made of PCB is still offering the good performance in terms of temperature drop between two ends of the stack compared to the stainless-steel scourer. From observation, it was noticed that the solid wall of ceramic celcor is thinner compared to the PCB stack. The experimental results indicate that the thin wall is not only offering good heat transfer area between solid surface and the fluid but also the smooth flow of air with minimum blockage. This leads to effective thermodynamic process within the stack area. This wall thickness issue is related to the blockage ratio that may play a role in a heat transfer performance between the solid wall of the porous structure and the working fluid [9]. PCB material have thicker wall compared to ceramic celcor. In the experimentation work, non-metal material seems to offer good temperature difference between the two ends of the stack. This indicates that materials with higher heat capacity and lower thermal conductivity is favourable for thermoacoustic energy conversion.



(a)



(b)

**Figure 4.** Resonance frequency for (a) long resonator and (b) short resonator.

The experimental works are continued using shorter resonator with a length of 0.385 m. For this experiment, the resonance frequency was set at a frequency of 202.1 Hz. The results of temperature drop obtained using different stacks materials are shown in Figure 6. The figure shows the result for stack of 8 cm long placed at a similar location of $0.18\lambda$ from the pressure antinode. At this high resonance frequency, the highest temperature difference for thermoacoustic cooler with ceramic celcor as a stack was recorded as 39.16°C, whereas the highest temperature difference for PCB is 15.21°C. Again, ceramic celcor offers the best temperature drop compared to PCB stack. It is interesting to note that the results of temperature drop for stack made of stainless-steel scourer are almost similar to the PCB stack, only slightly lower for all amplitude of flow. This triggers the idea that the abundantly available scourer could be put to good use when being used as a stack in thermoacoustic system, provided that the system is operated at relatively high value of resonance frequency. It is also observed that shorter resonator provides better temperature drop compared to longer resonator. This means that the system with higher flow frequency offers better cooling performance compared to the system with lower flow frequency. This can be seen by comparing results of Figure 5 and Figure 6 for thermoacoustic cooler with ceramic celcor as a stack between both the resonator's length. The bigger impact of temperature drop is clearly seen when a shorter resonator is used. This is probably related to smaller losses related to blockage enforced by the porous material of the stack.

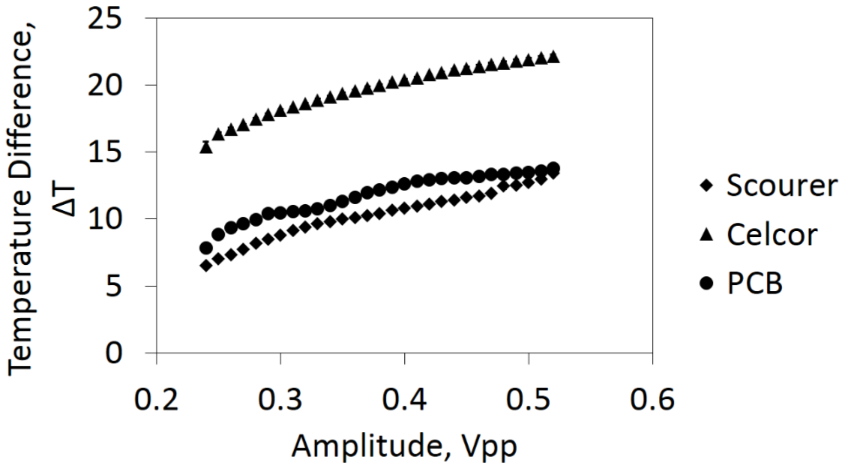


**Figure 5.** Temperature difference between two ends of stack with an increase of input peak-to-peak voltage, Vpp for a resonator of 0.65 m long.

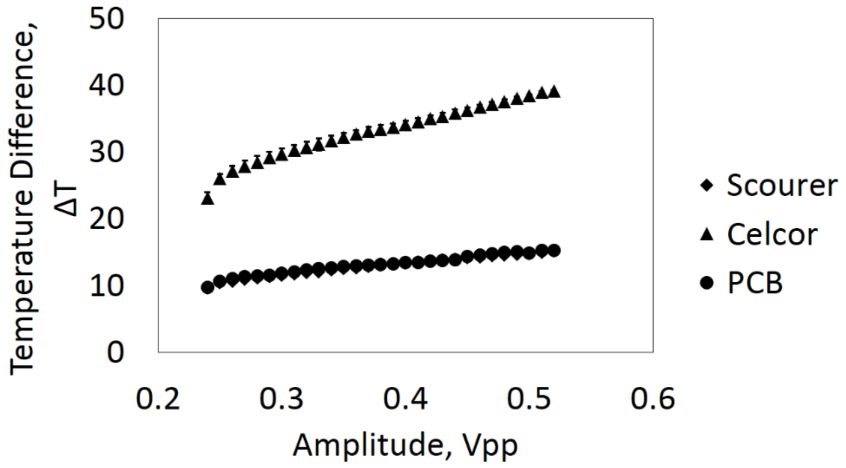


**Figure 6.** Temperature difference between two ends of stack with an increase of input peak-to-peak voltage, Vpp for a resonator of 0.385 m long.

In general, the similar trends of temperature drop results are obtained from the experimental works for long and short resonators. 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 experimental works were tested using metal and non-metal stacks. The results clearly show that the non-metal stack offers better temperature drop compared to that of the metal material. Similar observation was also reported by another numerical investigation reported by Achmadin *et al.* [30]. On another note, the experiments also show that the shorter resonator (with higher resonance frequency) offers better temperature difference compared to longer resonator (with lower resonance frequency). Interestingly, similar observations were also reported by the experimental works of Zolpakar *et al.*, [10] where the experimental work showed that short resonator are better than the long resonator. The temperature difference between hot and cold ends of the stack rises with the increase in drive ratio for all stack geometries at constant cooling load and mean pressure as shown in the results of Figure 5 and Figure 6. Evidently, the drive ratio also plays a very important role in enhancing thermoacoustic effect, leading to better heat transfer and hence temperature difference.

## 4. CONCLUSION

The accuracy of the selection of stack materials and resonator dimensions will have huge impact of the results of temperature drop. As expected, the higher the acoustic amplitude, the higher the thermoacoustic effect, as shown by the increase of the value for temperature different when the value of peak-to-peak voltage is increased. Based on the results obtained from experiment, the types of stack which is ceramic celcor give the best temperature difference compare to the polycarbonate foam and stainless steel scourer. The length of the resonator also gives an impact on the temperature difference for the thermoacoustic system. Among the three investigated parameters, the choice of stack's material (i.e. ceramic celcor) seems to be giving the most significant impact on temperature drop. For the resonator, the length of 0.385 m gives good temperature drop especially when the ceramic celcor stack material is used. The study also suggested that non-metal material of structured thin wall porous media is the best option for stack of a standing wave thermoacoustics cooler.

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