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Influence of stack plate thickness and voltage input on the performance of loudspeaker-driven thermoacoustic refrigerator

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Abstract. A loudspeaker-driven thermoacoustic refrigerator has been built and tested to gain understanding of its thermal performance and the cooling rate. The influence of plate thickness made of acrylic sheet was experimentally investigated by varying plate thickness of the stack, 0.15 mm, 0.5 mm and 1 mm, respectively. The experiments were conducted with various voltage input to the driver starting from setting 4 to 9 voltage peak-to-peak. The temperatures at both ends of the stack were acquired. For all variations, thermoacoustic cooling effect occurred in seconds and escalated rapidly in two minutes and became stable in ten-minute time. The experimental results showed that higher voltage input yielded higher thermal performance and faster cooling rate. For each set of experiment, the operating frequency and other parameters of the stack were kept unchanged. The experimental results show that the thermal performance and cooling rate increase with the decrease of plate thickness. The largest temperature difference, 14.8°C, was achieved with 0.1 mm plate thickness at voltage setting 9. However, the thermal performance gained for 0.5 mm plate thickness voltage setting of 9, was arguably the optimum thickness in terms of advantages in the ease of fabricating the stack and more consistent cooling.

1. Introduction

Refrigeration has been playing important role in almost every aspect of life to the level that living without it is impossible. It is even rated by the National Academy of Engineering as the 10th position in “*Greatest engineering achievement in the 20th century*” [1]. Despite the advantages, refrigeration’s high demand of energy and the use of harmful refrigerants have been some of major concerns in the obligatory need of greener technologies in the future. One of alternatives introduced is thermoacoustic technology devices which convert heat energy to sound energy and vice versa. The former is known as thermoacoustic engines or prime movers and the latter is called thermoacoustic heat pumps or refrigerators.

Over the last two decades various designs of thermoacoustic refrigerators [2] and engines [3] have been built and tested in order to increase their performance and reliability. A new spacecraft thermoacoustic cryocooler was developed and used in the space shuttle [4] and a temperature of – 65°C at cold side was achieved [5] by applying Rott’s theories [6] and the modification of the theory

by Hoffler and Swift [2,7]. These devices are attractive for harmless operation using air or inert gas and simplified manufacturing with much less moving parts in the system [8]. Since then, there are many studies in the existing literature that worked in an attempt to build and increase the performance of the refrigerator.

The operating condition, working fluid and the geometry of the refrigerator parts are main aspects to work with [9]. Experiments have been conducted to gain higher performance and efficiency by experimentally lowering the Prandtl number of the working fluid [10], increasing the ratio of acoustic pressure to mean pressure (drive ratio) numerically [11] and building an empirical equation for resonance frequency of the device [12]. The length of stack, the plate spacing and stack position in a resonator were analyzed [13] and the effects of blockage ratio, the ratio of plate thickness and plate spacing was simulated [14].

Stack is the heart of thermoacoustic refrigerator due to heat transfer occurs around it have great impact on the thermal performance of the device. Amplitude of sound wave input (in terms of acoustic energy) determines the efficiency of the refrigerator. Therefore, these two will be one of the first things to approach in constructing a thermoacoustic refrigerator. This paper will present the results of the experiments on this matters which emphasized on getting optimum plate thickness and input energy for a given resonator. The largest temperature difference across the stack, 14.7°C , which was realized in less than 10 minutes showed the feasibility of providing enough cooling for an environmentally friendly refrigeration system with a significant cooling rate. The potential application areas are commercial refrigerators and industrial air conditioning.

2. Design parameters of the thermoacoustic refrigerator

The schematic presentation of $\lambda/4$ wavelength thermoacoustic refrigerator is shown in figure 1. It operates by using high amplitude sound waves and inert gases to produce cooling. The frequency of the driver, such as loudspeaker, and the geometry of the resonator are calculated so as to get a standing sound wave in the resonator. A porous component called a stack is placed in the tube in such a way that a temperature difference due to thermoacoustic effect is created along the stack. One end of the stack starts to heat up while other end starts to cool down. By controlling temperature of hot side of stack (by means of a heat exchanger), the cold end of stack can provide lower temperature. There are five main components in a thermoacoustic refrigerator which are a resonator, a stack, a driver, working fluid and heat exchangers. In this experiment, there is no heat exchanger attached to device.

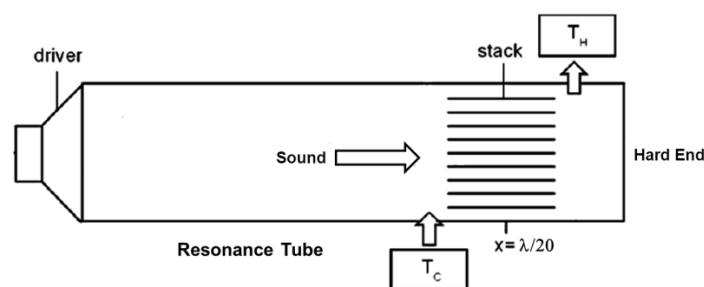


Figure 1. The schematic of $\lambda/4$ wavelength thermoacoustic refrigerator.

2.1. Resonator

A smooth, linear cylindrical resonator without steps, misalignments and abrupt transition should be used to avoid unwanted eddying or non-linear pressure variations that would greatly complicated the analysis [15]. The length and diameter of resonator are 40 cm and 5.3 cm, respectively. The resonance frequency of sound wave is mainly determined by the length and the diameter of resonator [16].

$$f_n = \frac{nv}{4\left(L + \frac{1+D}{2\pi}\right)} \quad (1)$$

However, these theories must meet the result of the frequency test of the thermoacoustic device which was performed by inserting a condenser microphone into the resonator and connected it to the oscilloscope to get a relation between the frequency and its connecting voltage. The one with the highest voltage result was the resonance frequency which is best operating frequency for the device.

The easiest way to decrease the acoustic power losses is to decrease the surface area of resonator wall; therefore the $\lambda/4$ wavelength resonator was chosen [2]. The material of resonator should be low in thermal conductivity and must endure vibration and pressure to the certain level. Acrylic tube was chosen because of these characteristics and its transparency help in order to arrange the stack and thermocouples and visualize them as well inside the resonator.

2.2. Stack

The dimension of the stack should be around 10% of the resonator volume and the spacing between the plates is determined by the thermal penetration depth of the stack which is 2 – 4 times the value of it [5]. In this experiment, acrylic sheet was cut into 6 cm length with the wide adjusted to the inside diameter of the resonator. The space between two plates ($2y_o$) is 0.55 mm ($3\delta_K$).

$$\delta_K = \sqrt{\frac{K}{\pi\rho f c_p}} \quad (2)$$

Low thermal conductivity and relatively large heat capacity is among the characteristics of the stack material to minimize heat transfer along the x-axis and maximize heat storing while phasing the sound wave in order to produce cooling effect [10]. Widely available acrylic sheet was chosen to meet these criterions. The variations of stack plate thickness ($2l_o$) are 0.15 mm, 0.5 mm and 1 mm. The stack was located at the distance of $\lambda/20$ from the closed end of the resonator [5] as this position will bring the optimum performance to the device because a well-balanced of pressure and velocity of the sound wave is achieved [3].

Figure 2(a) shows a cross sectional view of parallel plate stack, the blockage ratio is defined as the ratio of area available to gas in the stack to the total area of the stack. It is expressed as

$$BR = \frac{2y_o}{2y_o + 2l_o} \quad (3)$$

Figure 2(b) shows the gas parcels around the stack which experience displacement and temperature oscillation in association with the pressure variations. When the gas parcel compressed, it transfers heat to the plate so that temperature of the plate higher than that of the gas. Then the gas parcel expands and absorbs the heat of the plate. This phenomena which is induced by sound energy continues and generates temperature difference along the stack. Occurrence of the temperature difference will gradually end if the critical temperature gradient (∇T_{crit}) across the stack is equal to the local temperature gradient [17], where

$$\nabla T_{crit} = \frac{p}{\xi\rho c_p} \quad (4)$$

p is the acoustic pressure and ξ is the acoustic displacement amplitude. This temperature is important in determining the properties of a thermoacoustic device, since efficiency depends on a temperature differential caused by the sound waves that is larger than the critical temperature so that a large cooling effect is created [5].

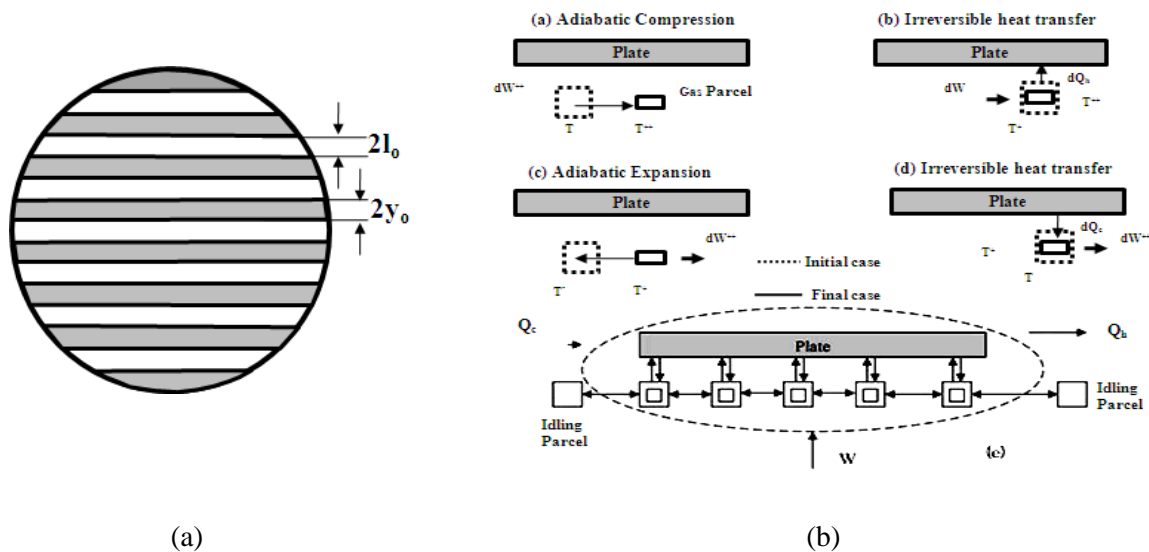


Figure 2. (a). A cross sectional view of the stack (b). Heat transfer between plate and gas parcels [18]

2.3. Working gas

The thermal penetration depth in designing stack also put into consideration the properties of working gas, which in this experiment was air. Air was chosen mainly because of its availability and its Prandtl number falls into the acceptable category of working gas for thermoacoustic device [10].

3. Fabrication and procedure of the experiments

Components of the refrigerator was fabricated or chosen based on the literatures. The resonator was built from a 40 cm straight acrylic tube. The internal diameter of the tube is 5.3 and the wall thickness is 3 mm. The length of the resonator was set equal to quarter of wavelength of the acoustic wave based on equation 2. Air at atmospheric pressure was used as a working fluid, as mentioned in section 2.

An 8Ω loudspeaker with the maximum power of 30 W was used as acoustic driver and installed at one end of the resonator. Another end was closed tightly using the same material as the resonator. After determining the operating frequency experimentally, the square wave at frequency 180 Hz was set in built-in function generator of a National Instrument Elvis II and the sound wave was amplified.

The length and the thickness of each stack plate were 6 cm and 0.1 mm, respectively. The stack was made of acrylic sheet and cut manually to fit into a cylindrical stack holder. The spacing between the plates was realized by gluing 0.55 mm fishing line on to the surface of each plate. Then the plates were arranged and glued in a stack holder made of the same material as the plates. The stack holder was inserted into the resonator. The fabrication of the stack was done in the same procedures for other sets of experiments with 0.5 mm and 0.15 mm plate thickness, respectively.

Five type K thermocouples with accuracy of 0.05 were used; one for ambient temperature and two of those were inserted at different position at each end area of the stack. The temperature data from all thermocouples were acquired simultaneously every second by using National Instrument data acquisition module 9211. Both thermocouples at hot side read the same temperature while those at the cold side showed difference in reading of 1 – 2°C. The lowest reading was featured on the graphs.

3.1. Experimental Set-Up

Figure 3 shows the experimental setup of the thermoacoustic refrigerator constructed at the Heat Transfer Laboratory, University of Indonesia. The stack was placed at 6 cm from the closed end. The

frequency and wave amplitudes were measured by a condenser microphone which was located at pressure antinode of the resonator. The microphone was connected to a built-in oscilloscope of National Instrument Elvis II via Labview software. The oscilloscope confirmed the form and frequency of the wave input.

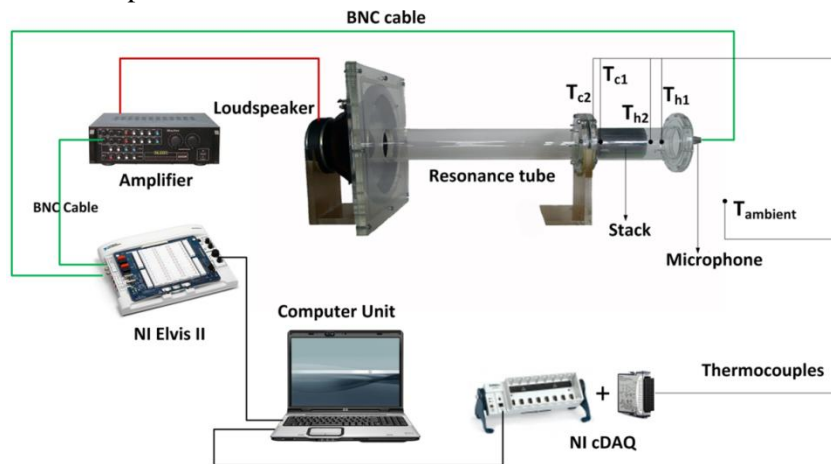


Figure 3. The experimental set-up of the experiment

The experiment was conducted with variations in voltage peak to peak setting from four to nine as the input voltage to the driver using a built in function generator in NI Elvis. The thickness of the plate stack was varied; 0.15 mm, 0.5 mm and 1 mm. Figure 4 is the capture of one of the experiment that shows (a) the function generator used to input the sound wave and input voltage to the driver and (b) the oscilloscope monitor.

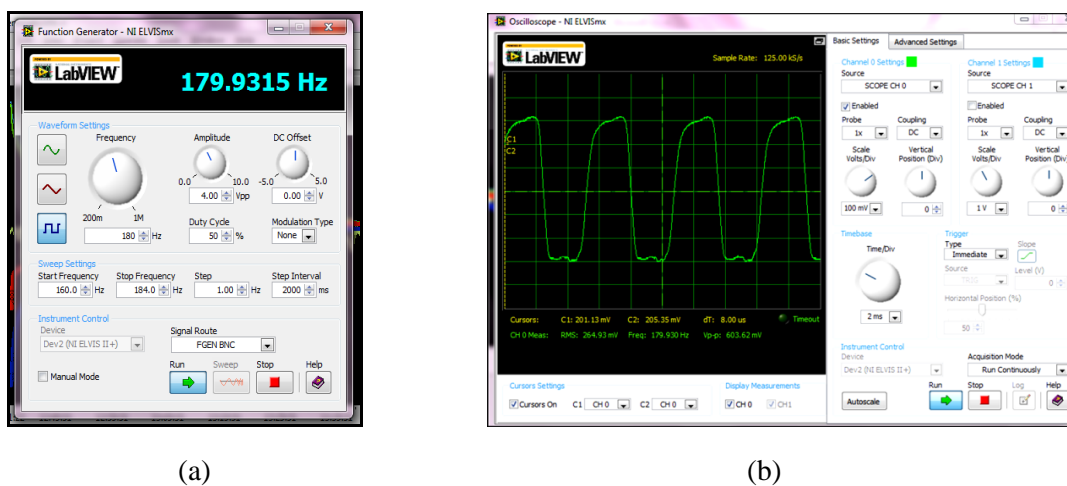


Figure 4. Wave and voltage setting using National instrument Elvis II Function Generator (a) and (b) waveform and wave amplitude reading using NI Elvis II Oscilloscope

4. Result and Discussion

The theoretical resonance frequency for the resonator based on Equation 2 is 209.6 Hz. The resonance frequency became around 180 Hz after installing the loudspeaker and placing the stack in the resonator. The existence of other structures and extra volume after the driver alter the resonance frequency [12]. 180 Hz is an approximation since the local temperature gradients established by the device alter the resonance frequency of the internal fluid [14].

Figure 5 shows the tested frequencies and their connecting voltage result at different positions; positions 1 to 6 which are near the edge of the tube, $\lambda/20$ from the driver, $\lambda/8$, at the middle of tube length, $\lambda/20$ from the tube end and the last one is the left end. The frequency that resulted higher voltage was considered as the resonance frequency which was consistently around 180 Hz.

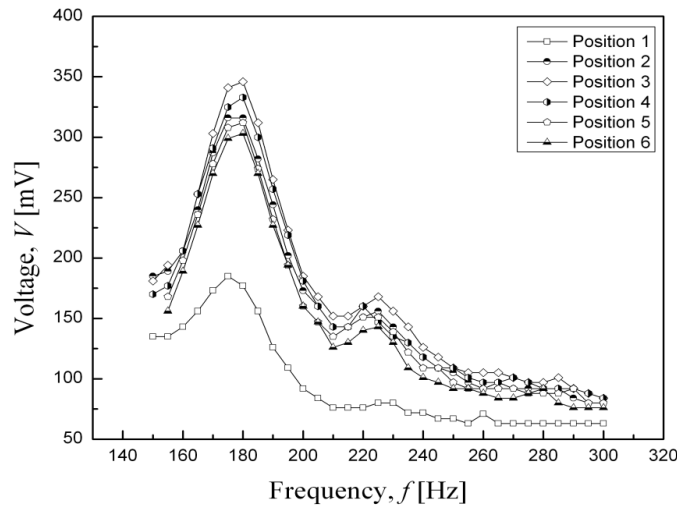


Figure 5. Frequencies and their connecting voltage output at different position in resonator

4.1. Effect of input voltage setting on thermal performance

To understand how sound wave amplitude affects the thermal performance of the resonator, sound wave amplitude was varied by setting the voltage peak to peak input from 4 to 9 with one increment for each experiment. The experiments were conducted for three different plate thicknesses; 1mm, 0.5 mm and 0.15 mm, respectively. Figure 6 shows the typical results for temperatures at the hot side of the stack (T_h) and the cold side of the stack (T_c) in a room with 26.5°C ambient temperature (T_a).

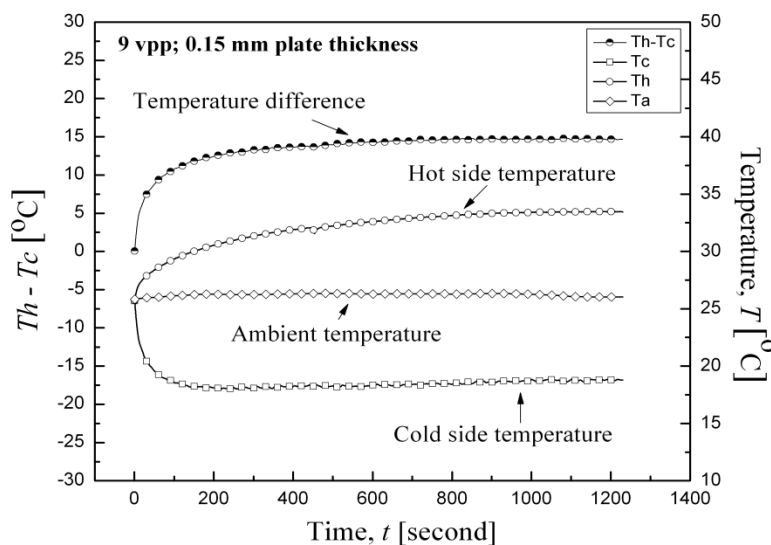


Figure 6. The largest temperature difference of hot side and cold side of stack

It is seen that the thermoacoustic phenomena inside the resonance tube yielded temperature difference between two extremities of the parallel plate stack. The result shown is the largest

temperature difference, 14.8°C achieved in 10 minute time that occurred by using 0.15 mm plate thickness at input setting 9 vpp. Temperature at the cold side of the stack decreased rapidly to the lowest point, 18.4°C, in two minutes. Temperature at the hot side increased to the highest point, 34.2°C, in 10 minutes while at the same time the temperature at the cold side started to increase slightly. The trend in Figure 6 is similar to that found in the literature [19].

Figure 7 presents the temperature difference across the stack yielded with various input voltage using 0.15 mm plate thickness. As expected the plot shows that higher input voltage will produce linearly higher temperature difference. The difference grows rapidly more than 50% in 30 seconds and continues to around 80% in 4 minutes and becomes generally constant in 10 minutes. These trends are in agreement to those shown in literature [15]. It is observed that starting from 10 minutes duration of experiment the local temperature gradient is relatively equal to the critical temperature gradient so that the acoustic energy have been fully used to overcome the heat dissipation[17].

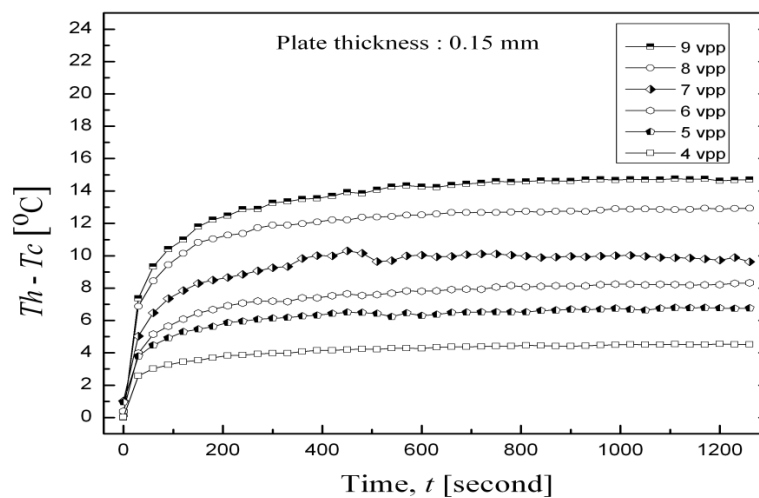


Figure 7. The thermal performance of the resonator from 4 to 9 vpp

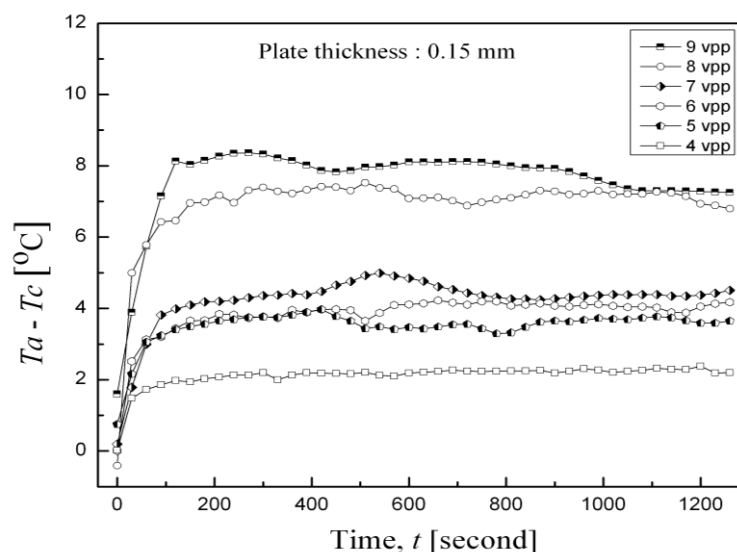


Figure 8. Cooling rate of cold side of the stack, plate thickness of 0.15 mm

The difference in temperature of the stack cold side (plate thickness of 0.15 mm) and the ambient temperature was plotted against time in figure 8. The data was recorded for 20 minutes with various

input voltage to the loudspeaker. The figure shows that at 9 vpp input to the driver the temperature of cold side decreased the most, 8.4°C, in 90 seconds. The temperature then began fluctuating on the cold side of the stack due to drifting of thermocouples but it stayed lower than others. The figure also indicates that the cooling rate with input voltage 8 and 9 were faster than other input voltages although the trends are similar for all variations. The data was also recorded for different plate thickness, 0.5 mm and 1 mm with various input voltage.

4.2. The effect of plate thickness on the thermal performance and cooling rate

Figure 9 depicts that using stack plate of 0.15 mm thickness produced the largest temperature difference across the stack and the fastest cooling rate compared to plate thickness of 0.15 mm and 1 mm. The input voltage to the driver remained constant during the experiment. At 9 vpp, the largest temperature difference (T_h-T_c) for plate thicknesses of 0.15 mm, 0.5 mm and 1 mm were 14.8°C, 13.1°C and 9.2°C respectively. It indicates that for the given resonator geometry, thinner plates means lower blockage ratio and produces higher thermal performance as found in literature [20].

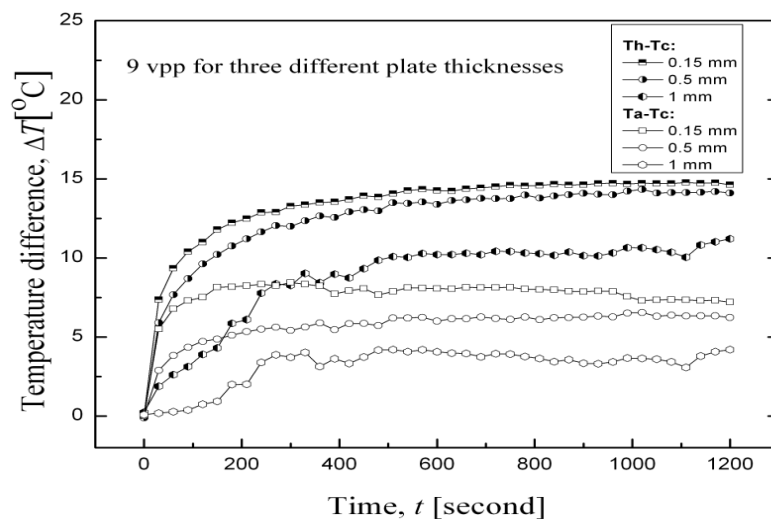


Figure 9. Thermal performance and cooling rate with variation in stack plate thickness at 9 Vpp

Figure 9 also shows that at the same condition of input voltage, decrease in temperature at cold side of the stack (T_c-T_a) were up to 8.1°C, 7°C and 4°C for plate thicknesses of 0.15 mm, 0.5 mm and 1 mm, respectively. It was observed that thinner stack plate shows faster cooling rate at the cost more effort in fabricating the stack plate and deterioration of the stack plate after several set of experiment due to less rigidity in material used for the stack.

5. Conclusions

In this study, experiments are conducted to observe the performance of the refrigerator in terms of temperature difference produced at the ends of the stack and the cooling rate. The results showed that higher amplitude of sound wave (ranging from 4 to 9 vpp setting) produce larger temperature difference, as expected. The experimental result showed that using plate thickness of 0.15 mm at 9 vpp yielded the largest temperature difference when compared to 0.5 mm and 1 mm plate for the given voltage input to the driver. Decrease in plate thickness leads to significant increase in cooling rate; which are for 0.15 mm plate thickness temperature dropped 8.5°C below the ambient temperature in two minutes. For 0.5 mm and 1 mm plate thicknesses, the temperature drops 5°C and 1°C, respectively, below ambient in the same amount of time. Thinner plates which provide more area for heat transfer relative to the given resonator ensure faster cooling rate. However, whether the thinnest is

the most optimum one still needs further study since by using plate of 0.5 mm thickness the cooling effect was more consistent and the stack structure was much more rigid compared to others.

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