SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Thermoacoustic Cooler with Different Waveform Excitations and the Noise Control Test

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ARTICLE INFO

Article history:
Received 23 October 2023
Received in revised form 5 March 2024
Accepted 18 March 2024
Available online 15 April 2024

Keywords:
Thermoacoustics; wave forms; resonance; noise control

ABSTRACT

Many researchers have been devoted into improving the operation of thermoacoustic cooling system as it offers a promising alternative to traditional cooling methods. This study reported potential system's improvements that can be obtained when it is operated with different excitation of waveforms and resonator's material. Resonant test was first carried out to identify the frequency for the operation. Temperature drop that can be obtained by the system was then tested for sine wave, square wave and triangle wave excitations. It was found that a change in resonator material alters the resonance frequency for the operation. Resonance was recorded at 186.6 Hz when acrylic resonator was used while a resonance frequency of 170.5 Hz was found when polyvinyl-chloride's resonator was used. In term of temperature effects, the square wave excitation resulted to the maximum temperature difference of 45.64˚°C in the acrylic resonator, followed by sine wave at 43.46°C and triangle wave came in last at 40.11°C. Then, as the polyvinyl-chloride's resonator was used, smaller values of maximum temperature was observed with 38.07°C, 35.94°C and 30.05°C for square wave, sine wave and triangle wave, respectively.

1. Introduction

Heating and cooling systems have become essential in this modern society. In hot and humid climates, it contributes to massive usage of energy from depleted sources and operations are also contributing to high level of carbon emission [1]. In fact, the convenience of most cooling technology has unfortunately involved technology that is detrimental to the environment hence efforts were continuously done to bring this harm effect to a minimum level [2-6]. Refrigerant found in the conventional heating and cooling systems is found to be one of the main contributors to global

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https://doi.org/10.37934/arfmts.116.1.1726

warming and the depletion of ozone layer [7]. Consequently, sustainable alternatives must be developed and thermoacoustic cooling technology is one of the worthy considerations as there is no refrigerant to be found in thermoacoustic system [8].

Second The fundamental operation of thermoacoustic devices is like any other conventional thermodynamic devices where it involves the expansion, compression, and heat exchange of the working fluid [8]. For instance, a Carnot cycle is completed when heat is applied into the system so that an acoustic wave can be created particularly when a sufficient temperature gradient is sustained between the two ends of a porous structure inside the system. The gas particles expand and compress following the acoustic wave and they carry energy that can be converted into electricity by using suitable energy converting device. On the contrary, the work energy from an acoustic wave in the thermoacoustic device will complete a reverse Carnot cycle, producing heating or cooling with little to no moving parts involvements. In short, a thermoacoustic device can either be a heat engine [9] or a refrigerator depending on the configuration of the setup [10].

The thermoacoustic technologies of heat engine and refrigerator can be used for many applications that involve power generation and cooling activities. It could be designed to utilize waste-heat from industries [11], cold storage for keeping medicines and food [12], integrated with solar technology to convert solar energy into electricity [13] and also for electronics cooling [14]. The ability of to utilize waste heat from industry could offer solutions for the greenhouse gas emission that was recently reported to be produced by many industrial sectors [15]. Thermoaocustic technology relies heavily on the heat transfer, expansion and compression processes of the working fluid that travels with the acoustic wave. Hence the involvement of moving mechanism such as compressors and turbine can be avoided making the system simple, easy to maintain and attractive for miniature technology [14].

Thermoacoustic devices can be operated with either travelling wave, standing wave or both the waves [16]. It was reported that travelling wave provides a more efficient operation, but it involves complex design and control mechanisms. The standing wave device is also an attractive option as it is simpler and easier to operate [17]. The system can be operated with many types of working fluid and the noble gaseous are commonly used to maintain the environmental safety feature of the technology [18]. The thermoacoustic’s cooler’s and heat engine’s energy conversion effects can be achieved even by using the abundantly available air at atmospheric pressure [19-20]. Of course, changing the working fluid and working conditions can lead to a better performance to suit bigger demand [21].

Since the operation depends on the travel of gas medium particles following the wave, the performance of the system is affected by many factors such as the resonator’s tube length, the flow frequency, the stack’s material, and the amplitude of the flow [19,22,23]. In fact, studies reported that the type of wave that was generated inside the system gave effect to the performance of the system too. In some cases, the square wave was reported to perform better and in other cases, the triangular wave was shown to beat the performance of other types of waves [24]. The waveform tests were conducted for resonator with diameter between 50 mm and 100 mm and it was reported that the waveform performs differently in tubes with different diameter. Record of tests for resonator with tube diameter smaller than 44 mm was not found. Smaller diameter tube investigation is also needed to feed information for small and miniature technology. Hence, the performance of smaller diameter resonator tube is presented in this paper. Polyvinyl-chloride (PVC) [20,25] and acrylic [26,27] are two different materials commonly used for the resonator in many published works related to thermoacoustics but comparison of performance between the two materials was not yet reported. This paper intends to fill in this gap too.

Another concern related to thermoacoustic operation is that the device operated with loud noise that may be detrimental to users. The smaller the device, the higher the resonance frequency and therefore a noisier operation. Wasted materials can also be used as soundproof materials [28]. Therefore, this study offered additional information on method for dealing with the excessive noise by creating soundproof containers for the sound issue. Soundproof materials were tested to handle the loud noise.

2. Methodology

The experimental rig is as shown in Figure 1. Experimental investigations were carried out for the impact of soundwave's forms on temperature drops across the porous structure of thermoacoustics. Different waveforms (square wave, sine wave and triangular wave) were induced by using a function generator (RS Pro AFG 21005) that was attached to a 4" mid bass 400 W Calibre loudspeaker. An amplifier (Behringer KM750) was used to amplify and protect the signal that is supplied to the loudspeaker. The porous structure that is made of a ceramic celcor (Corning 600/3), as shown in Figure 2, with a length of 0.072 m was used as a stack in the system and its properties are provided in Table 1. The stack is placed at a location of 0.18λ from the driver where the term λ is the wavelength that is related to the speed of sound, c and the flow frequency, f, and is defined as $\lambda = c/f$.

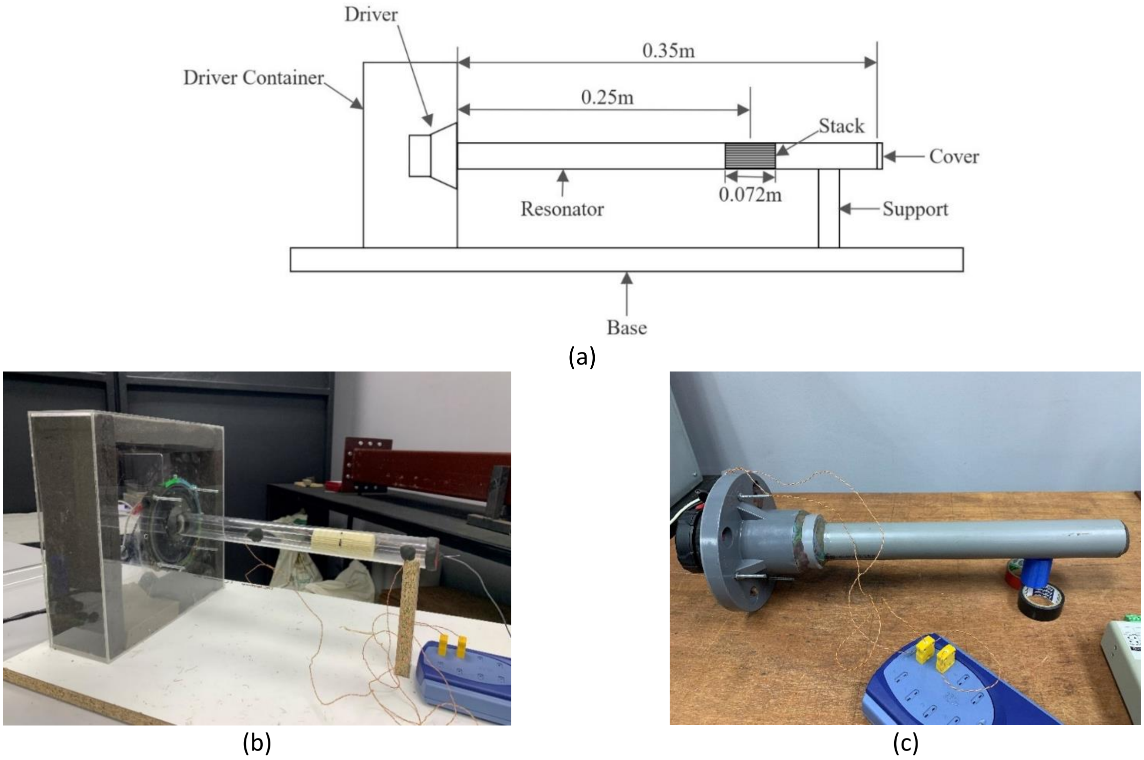


Fig. 1. (a) The schematic diagram of the thermoacoustic cooler test rig, (b) the acrylic test rig, and (c) the PVC test rig

Table 1
Product attributes

Product (cpsi/web)	Bulk Density (g/L)	Open Frontal Area (m^2)	Geometric Surface Area (cm^2/cm^3)	Heat Capacity at 200˚C ($JK^{-1}L^{-1}$)	Hydraulic Diameter (mm)
600/3	267	0.836	35.3	159	0.95

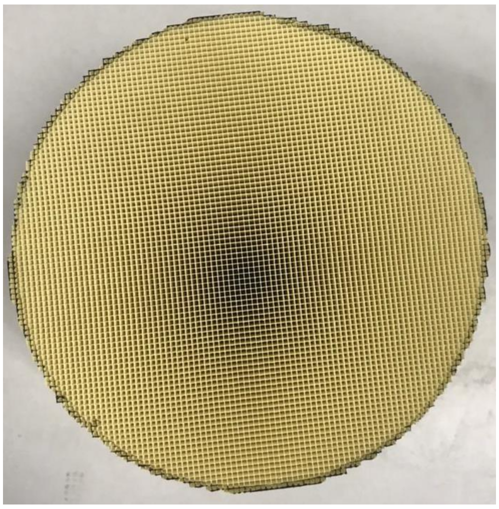


Fig. 2. Cross sectional view of the Corning 600/3 ceramic celcor for the stack

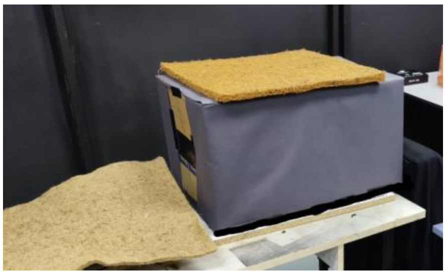
The resonator was tested with two different materials: acrylic and a polyvinyl chloride (PVC). The inner diameter and the length of the resonator are 32 mm and 350 mm, respectively. The thermal properties of the selected materials are tabulated in Table 2. An off the shelf polyvinyl-chloride (PVC) cap was used to seal the end of the resonator that was opposite the loudspeaker position.

Table 2
Properties of the resonators

Material	Specific Heat Capacity ($Jg^{-1}°C^{-1}$)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Density (g/cm^3)
Acrylic	1.46 – 2.16	0.187 – 0.209	1.17 – 1.25
PVC	0.57 – 1.75	0.128 – 0.099	1.44

The loudspeaker was driven with three different forms of wave: square wave, sine wave and triangular wave. The amplitude of the wave in the resonator was varied by varying the peak-to-peak voltage, Vpp, supply from the function generator to the speaker. The generated wave travels through the resonator as a standing wave. The resonance frequency of the flow was first identified by setting the peak-to-peak voltage supply to a minimum value of 0.1 V and the frequency was varied until a maximum value of pressure that was measured at the end of the resonator is detected. The pressure value was measured by using a piezoresistive pressure sensor (8507C-2 Meggitt). The theoretical resonance frequency for the setups was calculated to be 245 Hz given the length of 350 mm. Hence the resonance test was carried out by varying the frequency from 165 Hz to 255 Hz. The experiment was then carried out by fixing the frequency at the resonance value and then the peak-to-peak voltage supply is varied between 0.1 V and 0.5 V, considering the limit of operation for the loudspeaker. The resulting temperature drop was observed by measuring temperature at both the ends of the stack by using type-K thermocouple that was attached to a Picolog TC-08 signal conditioner and a computer.

The alarming sound during the operation of the device (measured to be at approximately 85 dB) triggers the need to identify a suitable sound reduction box for safety feature of the experimentation. Two different soundboxes were tested. Figure 3 shows the soundbox that was used in the experiment. One soundbox was made of a 35 cm X 40 cm X 90 cm wooden box with 1 cm thick coconut fibre foam attached to all the inner sides of the wooden wall. Another soundbox was customordered and was manufactured by Istiq Noise Control Sdn. Bhd. following the specification of the sound data (i.e., sound of approximately 250 Hz) that was recorded during the experiment. The box was a 35 cm x 45 cm x 100 cm aluminium box with 5 cm thick insulation foam attached to all the inner sides of the aluminium wall. A sound meter level (RION NL-29) was used to measure the intensity of the sound during the operation before the test rig was inserted into the soundbox. Another measurement was carried out for operation when the test rig was placed inside the soundboxes. The difference in the results due to the usage of the soundboxes are presented and discussed.


(a)


(b)

Fig. 3. (a) A wooden soundbox with coconut fibre foam and (b) an aluminium box with insulation foam to suppress the noise from the thermoacoustic test rig

3. Results
3.1 Resonance frequency

The resonance frequency must be identified first as thermoacoustic cooler operates the best at resonance flow amplitude. The theoretical resonance frequency for the setup was calculated to be 245 Hz given the resonator's length of 350 mm. The experimental result showed a lower resonance value as is shown in Figure 4. Theoretically, the resonance frequency for both the materials is the same because they are of the same length. However, the experimental results showed that the resonance frequency was altered when the material of the resonator changed. Figure 4 shows the graph of drive ratio, DR, plotted against frequency for the acrylic and PVC resonator. The drive ratio is the ratio between pressure that was recorded at the end of the resonator to the mean pressure of the operation. The mean pressure of the operation is the atmospheric pressure which was defined as a constant value of 0.1 MPa. At the same operating condition, the resonance frequency for the acrylic setup was found to be 186.6 Hz with a maximum drive ratio of 1.5231 while it was 170.5 Hz for the PVC setup with a maximum drive ratio of 1.3690. The higher range of drive ratio for wave inside acrylic indicates the possibility of higher acoustic energy that is presence inside the resonator.

The difference in resonance frequency value between two different resonator's material could be a result from the distinct acoustic properties of Acrylic and PVC. The sound waves propagation through the materials is highly affected by these acoustic properties such as density, elasticity, and internal friction. The speed of wave propagating through a material is determined by its density and elasticity [29]. From Table 2, the acrylic resonator presented a lower density compared to the PVC's. Thus, the acrylic material is less elastic, allowing more compression and deformation when wave passes through them. This results in a higher wave propagating speed in acrylic and a higher speed of wave leads to a higher resonance frequency. The structural differences in design or geometry such as minor discrepancies in shape or length may influence the resonance frequency too [30]. Variations in resonance frequency may also be due to boundary conditions including the attachment points, sealing mechanisms, or any additional component. Moreover, the difference in drive ratio within the

PVC setup may be attributed to losses from internal friction between the resonator's surface and the fluid flow, due to the use of different materials for the resonator [31].

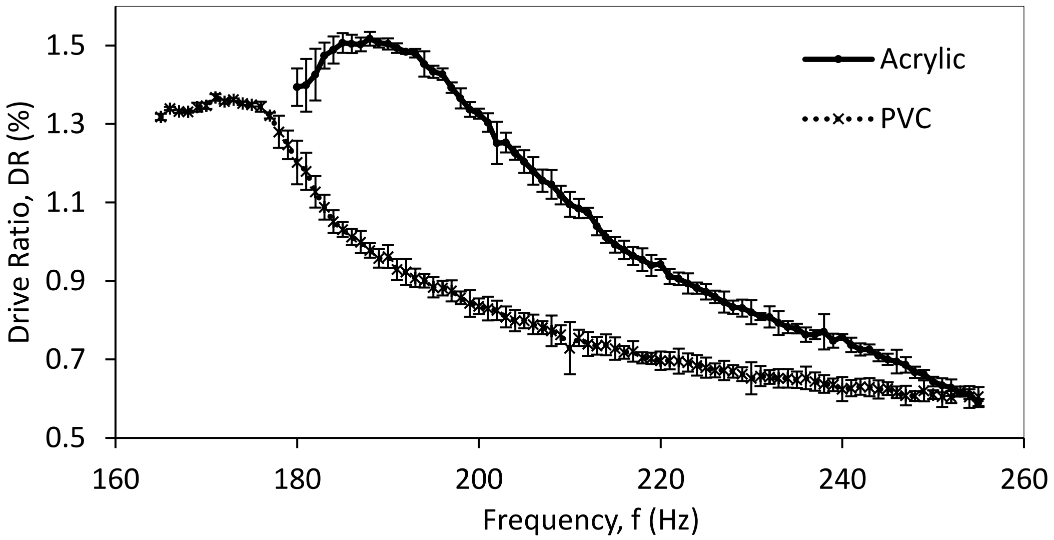


Fig. 4. Resonance frequency test for thermoacoustic rest rig with two different materials

3.2 Temperature Drops Across the Stack

Once resonance frequency was identified, the experiment was conducted with three waveforms, namely the sine wave, the square wave and the triangle wave. As predicted from the drive ratio result, the acrylic setup indeed performed better that the PVC setup. Figure 5 shows the temperature difference that was achieved for each of the waveforms under different amplitudes for both the setups.

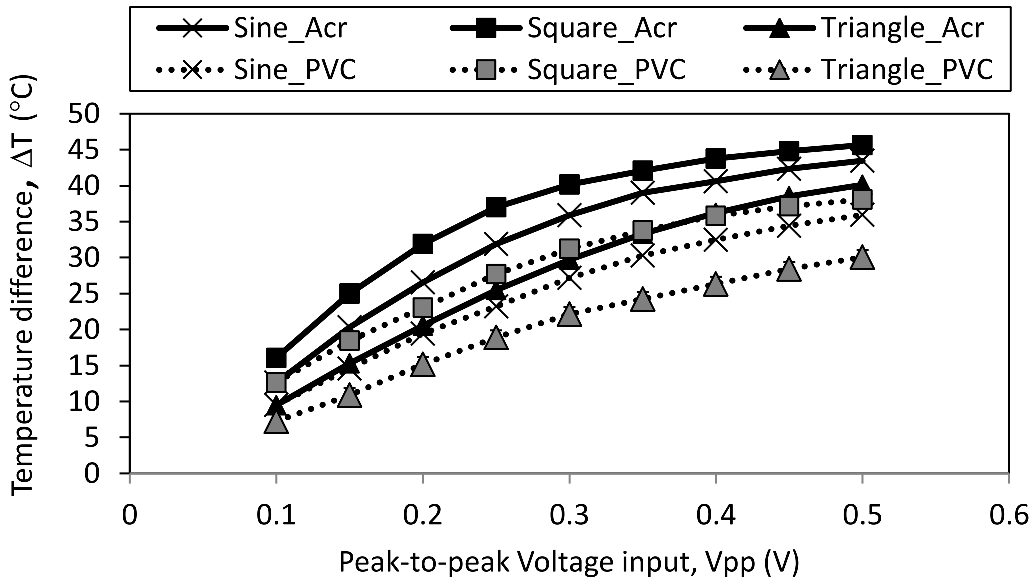


Fig. 5. Temperature difference between the two ends of the stack when different waveforms were tested at various peak-to-peak voltage, Vpp input

As the amplitude increases, the temperature difference increases as well. Other than that, the results show that each type of waveform had different cooling performance, with square wave being the best and triangle wave performed the worst, regardless of the material of the resonator. The maximum temperature difference achieved were 45.6°C and 38.07°C when excited by square wave at 0.50 V_{p-p} for the acrylic and PVC setup, respectively.

This phenomenon may be caused by the different energy content in these waveforms. Firstly, the results showed that the waveform that performed the best was the square wave. A square wave is made up of infinite sine waves of decreasing amplitude [29][32]. It contains only odd harmonics and its amplitudes of harmonics decay as $\frac{1}{k}$, with k being the harmonic number [33]. The high harmonics content in square wave is energy dense and contributes to the sharp transitions in the waveform. This results in rapid changes in amplitude and in turn, a relatively high energy content.

Sine wave is a smooth waveform that varies sinusoidally over time as the name suggests. It does not have any harmonics and has its energy concentrated solely in the fundamental frequency as it is a pure waveform. However, with large amplitude, it can still contain a significant amount of energy.

Lastly, the wave that increases and decreases linearly with time is the triangle wave. Like the square wave, its amplitude spectrum contains only odd harmonics. However, when compared to the square wave, its amplitudes of the harmonics decay much faster than square wave, as $\frac{1}{k^2}$, with k being the harmonic number [33]. Thus, the lower energy content of the triangle wave when compared to both the square wave and the sine wave.

This is also apparent in the perspective of the root-mean-square (RMS) values of the waves as reported in [34]. The RMS amplitude of sinusoidal, square, and triangular waves are $\frac{A}{\sqrt{2}}$, A and $\frac{A}{\sqrt{3}}$ respectively, where A is the peak amplitude of the waveform. In other words, the RMS value of sine wave is approximately 0.707 times the square wave while tringle wave is even lower at approximately 0.577 times the square wave [34]. Hence, the ranking in terms of energy content. However, the maximum temperature values are different for those two resonator materials when excited by square wave at 0.50 Vpp, which are 45.6°C and 38.07°C for the acrylic and PVC setup, respectively. This indicates that the material of the resonator is also important, as it is affecting the temperature drops across the stack due to their variations in thermal conductivity.

3.3 Noise Control Investigation

During experimentation, it was noticed that the sound level during the operation of the thermoacoustic cooler test rig was pretty high (approximately 85 dB). This high intensity sound is hazardous for the operator and others in the near vicinity of the operation [35]. Figure 6 shows the sound intensity level of the operation before and after the use of the soundbox. Without the soundbox, the sound intensity level increases with the increase of flow frequency. Long exposure to high sound intensity level can give bad effect on health. Hence, it is important to reduce the sound level during the operation. The sound level reduces a bit when the in-house build soundbox with coconut-fibre wall is used. However, the reduction is small presumably due to the porous nature of the fibre and the wooden wall of the box. Interestingly, when the custom-made Istiq soundbox was used, which the material was aluminium, the sound level was reduced to the level of sound that was commonly detected in the laboratory (i.e., 40 dB). While, the wooden box is expected to have better sound insulation compared to the aluminium, this unexpected result could be due to the use of different dampen material inside the box. The foam insulation in the Istiq's soundbox seems to show better ability to absorb the sound compared to the coconut fibre. Moreover, the sound of the operation did not penetrate through the soundbox even when the frequency of the operation is increased. The result shows that the noise levels recorded at three different frequencies—100 Hz, 150 Hz, and 200 Hz—have almost comparable values. This conclusion implies that the Istiq's custom-designed soundbox is a flexible and dependable noise management method capable of attenuating noise efficiently over a broad frequency range. This helps the thermoacoustic cooler to offer cooling capacity at high operating frequency and the operation can be made silent when it is designed appropriately by using a suitable soundbox.

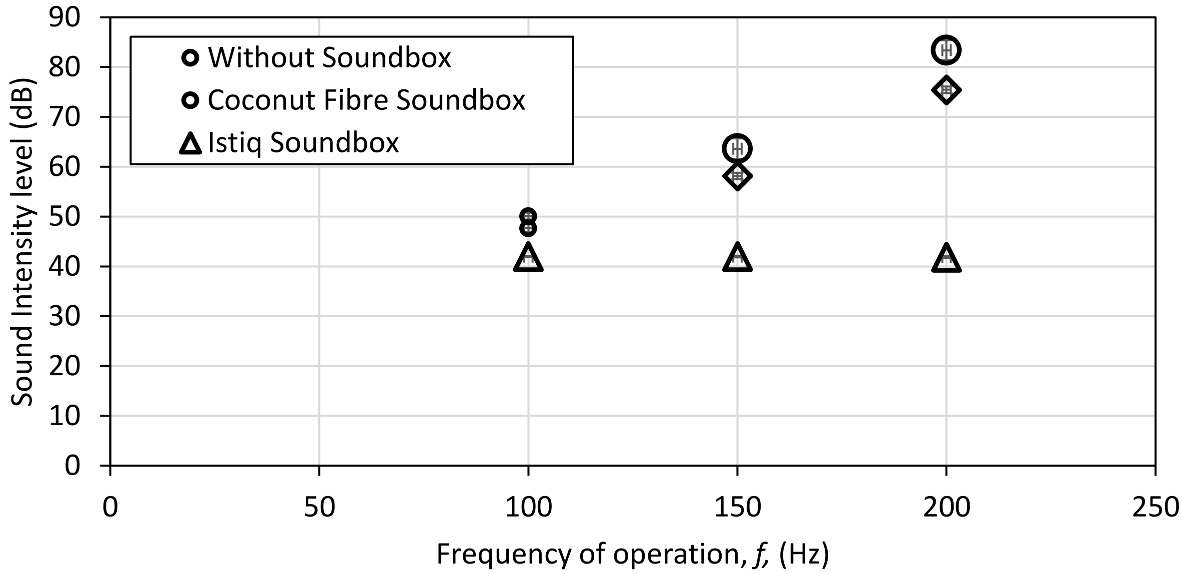


Fig. 6. The sound intensity level when thermoacoustic test rig was operated with and without a soundbox

4. Conclusion

The study showed that thermoacoustic flow conditions and performances are affected by the type of materials used for the resonator and the waveforms excitations. For the current study, the resonance frequency for acrylic resonator was 186.6 Hz while for PVC it was found to be at 170.5 Hz. Square wave was shown to provide the best temperature drops for the thermoacoustic cooler due to the high energy content in it. The study also showed that the noise level of the thermoacoustic cooler operation is reduced by 78% when the Istiq's noise control soundbox was used.

Acknowledgement

This research work was initially accepted and presented at the ICE-SEAM 2023. The research was further extended as part of the works funded by the Ministry of Higher Education Malaysia (FRGS/1/2023/TK08/UTEM/02/1). The work was conducted using facilities at Universiti Teknikal Malaysia Melaka.

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