

INVESTIGATION OF AN ATMOSPHERIC PRESSURE THERMOACOUSTIC COOLING SYSTEM BY VARYING ITS OPERATING FREQUENCY

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Abstract

This paper deals with the construction and performance of a thermoacoustic cooling system. The design of each component of the apparatus is described along with the reasons of using specific materials. The thermoacoustic cooling system consists of acoustic driver (loudspeaker), resonator, stack and the electronic apparatus for measurements and data acquisition. The system was assembled and the study was on the performance of the thermoacoustic refrigeration system operating in an atmospheric pressure with respect to the change of operating frequency, the optimum frequency range was also defined and the maximum temperature difference is illustrated throughout this paper.

Keywords: Atmospheric pressure, Cooling system, Optimum frequency,
Thermoacoustic.

1. Introduction

Thermoacoustic refrigeration is explored as a new cooling technology and it has been well developed during the last two decades because of its simple and robust architecture and its use of environmentally safe gases [1-3]. However, for a primary stage of this specialist field of thermoacoustic, a large-scale, helium-pressurised working gas thermoacoustic device [4, 5] required complicated and expensive measurement and data acquisition for the experimental setup. This paper effectively introduces the design and construction of an inexpensive thermoacoustic cooling system which is operating in a one bar air pressure [6]. The system consists of a loudspeaker, attached to one end of an acoustic resonator

Nomenclatures	
c_p	Isobaric specific heat per unit mass, kJ/kg.°C
f	Frequency, Hz
L	Length, m
v	Velocity of wave, 349 m/s
<i>Greek Symbols</i>	
$\delta\kappa$	Thermal penetration depth
κ	Thermal conductivity of gas, W/m.K
ρ	Density of gas, kg/m ³

tube, which is closed at the other end. The loudspeaker sustains an acoustic standing wave in the resonator tube.

The manufacturing process is well described and the performances measurements are presented throughout this paper.

2. Thermoacoustic Cooling System

A schematic illustration of the thermoacoustic cooling system is shown in Fig. 1. It consists of a loudspeaker placed in an acrylic plastic housing, a 2-inch acrylic resonator tube, stack and the electronic apparatus necessary for the measurements and data acquisition. The system is made out of separate components so that specific parts can be exchanged flexibly. In the following the design and construction of the different parts will be described in detail.

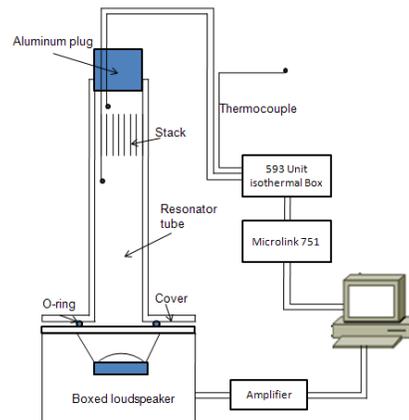


Fig. 1. Schematic Diagram of Experimental Set up of the Thermoacoustic Refrigeration System.

2.1. Acoustic driver

The acoustic driver consists of a commercial moving-coil loudspeaker. It sustains an acoustic standing wave to the resonator tube in a specific frequency range.

This frequency is defined as the sound waves oscillate a specific amount of times per second, the optimal resonant frequency is supposed to be at the first harmonic. In this study, the maximum heat transfer rate for the frequency of a wave travelling through a closed tube is given from the following equation [7]

$$f = \frac{v}{4L} \quad (1)$$

Here, the velocity of the wave in the room temperatures is roughly 349m/s. The length of the acrylic tube is assumed to be 250 mm. By substituting these values into Eq. (1); hence the frequency of 349 Hz is defined as the optimal frequency for this system.

In addition to that, the choice of the loudspeaker is based on requirements such as low losses, lightweight and the most important issue is to produce an operating frequency of the system which is the fundamental acoustic resonance frequency of the system. The calculation to define the resonance frequency of the system will be discussed later on this paper.

The 10-inch capable of handling 300W loudspeaker with the frequency range from 40 Hz to 4000 Hz is used of the system. This loudspeaker is placed in the acrylic plastic housing cube with 350 mm in length.

2.2. Resonator

The resonator is a 250 mm long and 2-inch diameter acrylic transparent tube. One end is mounted to the centre of the loudspeaker cover plate vertically and the other end is milled by an aluminium plug to form a closed end. Two 5 mm diameter holes were drilled into the tube at 8.20 mm and 22 mm from one end of the tube (the end milled by aluminium plug). A stack is located in between the two holes and two thermocouples are fitted into the holes in order to measure the temperatures at the two ends of the stack.

2.3. The stack

The stack is the most important part of an acoustic cooling system. It consists of many number of closely spaced surfaces aligned parallel to the length of the resonator tube. The function of the stack is to provide a medium for heat transfer as the sound wave oscillates through the resonator tube. Most stacks consist of different cross section of channel like honeycombed plastic spacers that do not conduct heat throughout the stack but rather absorb heat locally [7]. With this property, the stack can temporarily absorb the heat transferred by the sound waves. The spacing of these designs is crucial, according to Swift [1], the optimum spacing separation is four times of the thermal penetration depths. This can be calculated from the equation

$$\delta_{\kappa} = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \quad (2)$$

where the thermal conductivity of the gas, κ , is 0.025 W/m.K, frequency of the standing wave, f , is 385 Hz, density of the gas, ρ , is 1.3 kg/m³ and the isobaric

specific heat per unit mass of the gas, c_p , is 1.0049 kJ/kg.°C. By substituting the values into Eq. (2), the thermal penetration depths of about 0.13 mm are calculated.

Therefore, the optimum spacing separation is four times of the thermal penetration depth which is about 0.5 mm.

Base on this, the stack is made of 1 mm of diameter strand from broom and a roll of 38 mm ribbon. The strands to be placed in 5 mm separations. To construct this stack, a roll of 38 mm ribbon was unrolled. Lengths of strand from broom were glued across the width of the ribbon at equal intervals using a spray adhesive. This process was repeated until the 1.5 m length of ribbon was covered with strands. The ribbon then finally rolled around a small diameter rod and layers were gradually peeled off until the ribbon fit perfectly into the tube.

2.4. Electronic apparatus and data acquisition

The loudspeaker is driven by an 180W audio amplifier. Microlink 751 and 593 Unit Isothermal Box is used to measure the temperatures at the two ends of stack and room temperature during the experiment.

Three thermocouples were connected to the 593 Unit Isothermal Box and then connecting to Microlink 751. All the measurement temperatures are displayed on the computer screen, computer is used to control the system and analyse the temperature changes of the system.

3. Experimental Methodology

The experiment was conducted under a constant room temperature was adjusted to about 24°C, whereas, the tolerance of room temperature was found to be $\pm 2^\circ\text{C}$. The experiment was undergone at constant time duration which is 300 seconds. To define the reasonable time duration, many different time durations have been tested; results show that the temperatures were changing significantly in the first 180 seconds, however, no significant change of temperature after 300 seconds. Besides, the system was at room temperature initially. Temperature at both ends of the stack must be very close and found to be 1°C of tolerance initially.

Finally, the testing of frequency range was found between 365 Hz and 425 Hz with the increment of 10 Hz. To determine the proper frequency needed to achieve a standing wave, this is supposed to be at the first harmonic, or, when the wavelength is four times the length of the tube. Previous calculation result shows that the optimal resonant frequency for the system is 349 Hz. However, the primarily experiment did not show significant result for using frequency of 349 Hz until the operating frequency has been tuned up to 365 Hz.

4. Results and Discussion

Figure 2 shows the typical results for the temperature above the stack (maximum temperature) and below the stack (minimum temperature) as the operating frequency changes from a range between 365 Hz and 425 Hz as compared to the room temperature. The maximum temperature is about 27°C at the frequency of 365 Hz which is approximately 3°C above the room temperature. However, it

starts to increase rapidly as the operating frequency is tuned up, and it eventually reaches the highest temperature of about 46°C at around the frequency of 410 Hz. As the operating frequency continues to increase above 410 Hz, significant temperature drops leading toward room temperature is observed. Referring back to Fig. 2, there was no significant behaviour as compared to the maximum temperature at the lower part of the stack. Contrary, it became colder as the frequency increases and reaches the lowest temperature about 18°C at around 405 Hz. Finally it approaches the room temperature slowly.

The length of the resonator tube and the frequency range to be used for the experiments are based on Eq. (1). From the calculation result, frequency of 349 Hz was found to be the optimal resonant frequency of the system. Nevertheless, experimental results did not indicate that the highest temperature difference occurs at the optimal frequency. As the matter of fact, the maximum temperature difference occurs at about 405 Hz which is 50 Hz above the optimal frequency. The differences away to the optimal frequency may due to the location of the stack; the stack might not locate at the optimum position. Also the actual distance from loudspeaker to the aluminium plug is longer than the length of the tube which is 250 mm because of the cone distance of loudspeaker may be taking into account. Other than this, the stack layer separation to an optimal four thermal penetration depths must take consideration to the design. This rule is very important as has discussed before with the calculations.

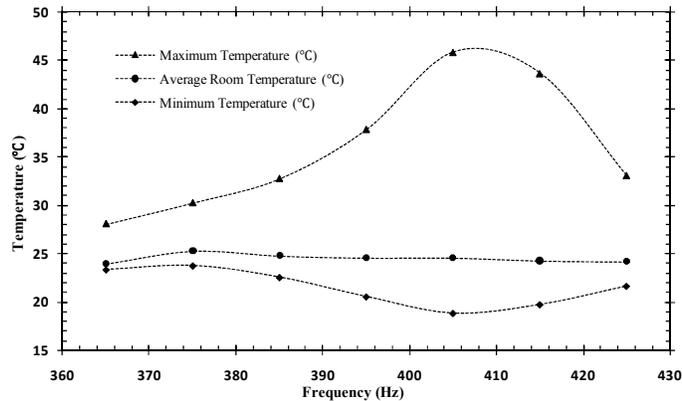


Fig. 2. Temperature Differences with Operating Frequency Range from 365 Hz to 425 Hz.

The temperature difference could be observed by measuring a vertical distance of two lines which are the maximum temperature and the minimum temperature at Fig. 2. The longer distance indicates the higher temperature difference is. However, Fig. 3 shows more intuitionistic of the temperature differences are. Temperature difference of about 5°C is obtained at the frequency of around 365 Hz. As the operating frequency keep increasing, the temperature difference enhances dramatically until it attains the maximum temperature difference of about 27 at around 405 Hz. At and above the frequency of 410 Hz, the plot is showing that the temperature difference starts decreasing considerably and inclining to the 0°C eventually.

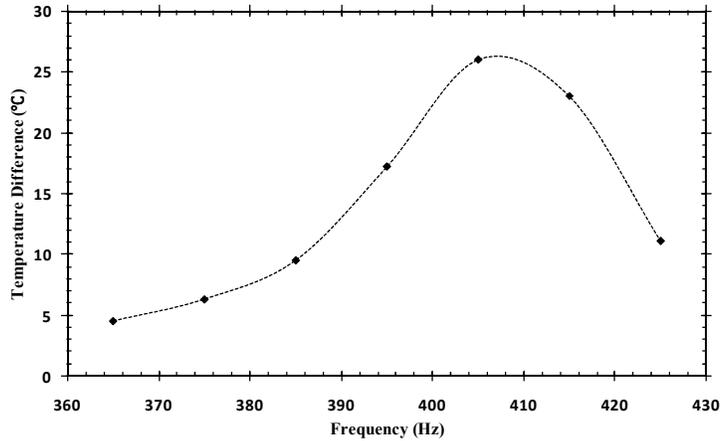


Fig. 3. Temperature Difference with Operating Frequency Range from 365 Hz to 425 Hz.

A typical result which is the highest temperature difference among all the experiments is illustrated in Fig. 4. This temperature difference was found at the operating frequency of 405 Hz. Referring to this figure, the temperature difference between the hot end and cold end of the stack increased rapidly for the first 150 seconds and reached the final value after 300 seconds of operation. The plot exhibited temperature difference of 23.8°C after 150 seconds with final temperature difference of 26°C. The hot end of the stack creates a high temperature gradient above room temperature, whereas there was no significant behaviour as hot end does at the cold end of the stack. Additionally, the cold end of the stack became colder during the initial rapid rate of temperature change; however, the temperature increase slightly after about 150 seconds of running time and eventually reached of incensement by 1.0°C.

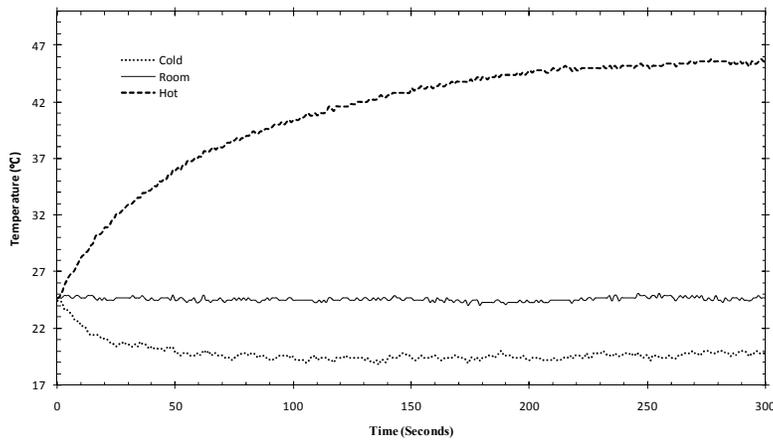


Fig. 4. Temperature Variation above (Hot) and below (Cold) the Stack as a Function of Time at Frequency of 405 Hz.

Based on this result, the system is able to generate a large temperature gradient. The maximum of about 21.3°C above the room temperature have been found at the hot side of the stack. The temperature is large enough to be detected by touching the acrylic tube surface by finger. The heat can be taken out through a heat exchangers, these heat can be used for other useful applications such as computer microprocessor cooling system or other electronics. Other than that, once the heat is brought out from the system by heat exchangers, this will decrease the temperature difference between the hot end and the cold end, allowing the cold end to become colder than with much heat accumulated at the hot end of the stack. This could be exhibited at cold end of the stack of the figure. The temperature of cold end increase after 110 seconds because of the accumulation of too much heat at the hot end, the aluminium plug could not dissipate enough heat out to the surroundings, and then the hotter end started transferring heat back to the cooler end. Thus, the temperature of the cold end of the stack increases.

5. Conclusions

In this paper, the construction of a thermoacoustic cooling system is discussed and it was constructed successfully, the maximum temperature difference generated by the system was obtained and its optimum operating frequency range was observed. It worked as a proof of concept device showing that a thermoacoustic device is possible and is able to cool air. In additional, the performance of the thermoacoustic cooling system can be improved if introduced heat exchanges to both ends of the stack, therefore coupling the stack to a heat source or heat sink, the transfer of heat would be more efficient. This cooling system can be used to study the effect of some important thermoacoustic parameters in the future, such as stack spacing, changing of wave patterns.

Acknowledgement

The support of EPSRC for this work under the “SCORE” project and the support of MOSTI from Malaysia are gratefully acknowledged, as are the contributions of the other partners in the project.

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