Design and Analysis of A Thermo-Acoustic Refrigerator

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Abstract—The design and functionality of thermo-acoustic refrigerator have been the focus of considerable attention from the research community since 1980. This environmental friendly technology has the potential to replace conventional refrigerator once the improvements in design and technology are realized. Thermo-acoustic is a term used to describe the effect arising from sound waves creating a heat gradient, and vice versa. In this paper, a typical modified thermo-acoustic refrigerator (TAR) consisting of acoustic driver (loudspeaker), resonator tube, thermocouple, stack, and a heat exchanger is designed. The effects of some design parameters such as wave patterns, frequency, and heat exchanger of thermo-acoustic refrigerator system were studied. It was found that a sine wave pattern lead to superior cooling effects compared to other wave patterns tested. Also adding the heat exchanger contributes significantly in increasing the temperature drop achieved by the modified TAR.

Keywords—Thermo-Acoustic refrigerator, Sound wave, Cooling system, Wave pattern, Frequency, Stack

1. Introduction

From creating comfortable home environments to manufacturing fast and efficient electronic devices, air conditioning and refrigeration still expensive, yet essential, services for both homes and industries. However, in an age of energy and environmental development, conventional cooling devices continue to generate greenhouse gases with high energy costs [1]. As the technology and knowledge improve year by year, a new innovative method has come to minimize the effect of global warming and at the same time has a low cost and long life usage. This innovation is the thermo-acoustic refrigerator (TAR). TAR was first discovered by European glass blowers 200 years ago when it was noticed sound generated when a cold glass tube was placed next to a hot glass stem. TAR uses the sound effect to convert temperature differential into mechanical energy or mechanical energy into temperature differential. The advantages of using TAR are simple and clean mechanical system which doesn’t use pistons, cranks and lubricants as the conventional refrigerator or air conditioning cooling systems. Moreover, thermo-acoustic refrigerators consider environment friendly and clean products since they don’t produce harmful gases that cause global warming or stratospheric ozone depletion.

2. Theoretical Background

Thermo-acoustic refrigerator uses standing waves to generate pressure difference along the resonator tube. Normally, waves do not reflect uniformly, resulting in constantly shifting gradients. However, in TAR the sound waves are reflected in such a way that they become standing waves, or waves that are self-sustaining and steady. This behavior generates a pattern of points that have alternating pressure maxima and velocities.

One of the important fundamental sciences behind thermo-acoustic refrigerator is thermodynamics, in specific the study of heat transfer. The ideal gas law states that

\[ PV = \rho RT \]

where \( P \), \( \rho \), and \( T \) are the pressure, density, and temperature of the gas, respectively, and \( R \) is the gas constant (for air \( R = 287 \) J/kg·K). This law states that changes in gas pressure is directly proportional to changes in temperature, as the pressure of gas increases, the gas temperature also increases.

2.1. Frequency

Any sound wave has a specific number of oscillations per second, called the wave’s frequency, and it is measured by the unit Hertz. In thermo-acoustic refrigerator closed tube, the required resonant frequency needed to get the maximum heat transfer rate is defined by the formula shown below:

\[ F = \frac{a}{2L} \]

where \( a \) is the speed of sound and \( L \) is the resonator tube length. The temperature \( T_m \) is given by,

\[ a = \sqrt{\frac{2k}{\rho c_p \omega}} \]

2.2. Penetration depth

Thermal penetration depth is one of the critical variables in designing thermo-acoustic refrigerator – in particularly the stack design. Thermal penetration depth is the spacing between stack walls. This variable helps to design the space between stack walls in a way that the spaces are not too close or too far. According to G.W. Swift, the ideal spacing in a stack is 4 thermal penetration depths [2]. The Thermal penetration depth \( \delta_k \) is given by the formula shown below:

\[ \delta_k = \frac{2L}{\sqrt{\rho c_p \omega}} \]

where \( k, \rho, c_p \) are the thermal conductivity, density and constant-pressure (isobaric) of the working fluid within the pore, respectively, and \( \omega \) is the angular acoustic frequency.

3. Experimental Design

The thermo-acoustic refrigerator was constructed using the following materials (Fig.1):

1) Resonator tube 2) Stack 3) Rubber plug
4) Loudspeaker (1000watt) 5) Box
6) Thermo-couple 7) Multi-meter

![Fig. 1. Schematic of the thermo-acoustic refrigerator.](image-url)
4. Result and Discussion

Once the thermoacoustic refrigerator is constructed, it was tested using a frequency of 260 Hz. Based on this frequency, the position of the stack was adjusted to reach the maximum temperature difference. Figure 2 shows the different stack positions and its corresponding temperature. The maximum temperature difference occurs when the stack position at 55 mm from the end of stack to the closed end of the resonator tube.

The maximum temperature difference occurs when the frequency is 270 Hz for the three different wave patterns; however sine wave pattern generates the highest temperature difference compare to square and triangle wave patterns. It has a temperature difference of 16°C, followed by the triangle wave which has 15°C and lastly is the squared wave which has 14°C. Similar behavior and trend but with different temperature drop have been achieved by Abakr et al. [3].

A significant improvement has been achieved in the current work to obtain more temperature difference by adding some sort of heat exchanger to the stack. Heat exchanger is one of the important methods that used to improve the performance of TAR. This method was used in Hofler’s thermo-acoustic refrigerator. Hofler used rectangular copper strips as a heat exchanger [4]. The idea of heat exchanger is that the cold heat exchanger removes heat from a cold temperature reservoir and supplies it to the cold side of the stack. Figure 4 shows the new modification of the stack.

Using the new stack modification, a result was conducted to analyze the effect of the heat exchanger on the thermo-acoustic refrigerator. Figure 5 shows the result of temperature difference corresponding to three different wave patterns and the new modification of the stack.

The heat exchanger improved the performance of the TAR, as the temperature difference increases compare with the old design (no heat exchanger). At 270 Hz sine wave pattern achieved the highest temperature difference of 25°C, followed by is the triangle wave which has 24°C and lastly is the squared wave which has 18°C.

5. Conclusion and recommendation

In conclusion, the influence of parameters such as stack position, stack heat exchanger, frequency and wave patterns were studied. It was found that sine wave gives the highest temperature difference; also adding heat exchanger improves the total performance of TAR. The current study is just one part of an ongoing overall study and analysis of the effect of other parameters such as geometry of resonator tube and stack.

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References