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Design and Optimization of a Standing Wave Thermoacoustic Refrigerator Using DELTAEC

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ABSTRACT

Thermoacoustic refrigeration is among the best alternatives to conventional refrigeration systems because of the use of inert gases for instance helium or air. On the contrary, refrigerants used in some conventional refrigeration systems are very harmful to the ozone layer and can contribute to global warming problems. In addition, in the event of their leakage, they cause harm to humans. Thermoacoustic technology can be described as a clean, renewable technology. The thermoacoustic refrigerator's main function is to utilize sound waves to create a cooling effect. The aim of this research is to design a standing wave thermoacoustic refrigerator driven by an acoustic driver using the simulation program DELTAEC to achieve high cooling capacity and improve the coefficient of performance. In addition, it discusses the design process. Besides that, the influence of significant stack and resonator parameters (inertance and compliance) is discussed in order to assist thermoacoustic researchers in better understanding and designing the thermoacoustic refrigerator. According to the results obtained, the designed thermoacoustc refrigerator performed best. It has achieved a cooling load (cooling capacity) of 312W and a COP of 1.9275 at a difference in temperature of 25K between the AHX and CHX.

1. Introduction

Most recently, the world has witnessed climatic change and environmental damage due to several causes. One of the causes is conventional refrigeration systems. Conventional refrigeration systems (e.g., vapor compression systems) use refrigerants that contain CFCs (chlorofluorocarbons) and HCFCs (hydrochloroflorocarbons), which seriously damages the ozone layer and can cause global warming issues. In addition, in the event of their leakage, they cause harm to humans. Because of this, researchers are trying to find new alternatives to conventional refrigeration systems. [1-2].

Thermoacoustic refrigeration systems are one of the better options, which is a relatively new green technology. This technology has many advantages if compared to conventional systems, such as not moving mechanical parts (no need for lubricants), which makes it highly reliable constructional simplicity and the ease with which it can be manufactured and assembled using locally available materials at a low cost. In addition, it can reduce the amount of electricity consumed by using a proportional control system for loudspeaker operation based on the cooling load. Most importantly, a major advantage of the thermoacoustic systems is that they are environmentally friendly through the use of chemically inert gases (for instance,

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helium) and air as working gases, which are not harmful to the environment or humans [3-5].

Thermoacoustics is a branch of science that deals with the interactions of two fields: Thermodynamics and Acoustics. It focuses on the conversion of heat into sound energy and vice versa. In other words, there is interference between acoustic waves and a solid boundary of the stack. Therefore, this type of interference is known as the "thermoacoustic effect" [6]. Thermoacoustic researchers classify the thermoacoustic effect into two main categories: the engines category is devices that convert thermal energy into acoustic energy, which are called thermoacoustic engines. The second category is devices that convert acoustic energy into thermal energy, which transfers heat from a low-temperature reservoir to a high-temperature reservoir and it is called a thermoacoustc refrigerator.

A thermoacoustic refrigerator device absorbs heat from a low-temperature reservoir and rejects it to a high-temperature reservoir using acoustic energy (an acoustic wave). It is mainly composed of an ordinary loudspeaker coupled to a resonator that is filled with a working gas and contains AHX and CHX and a stack. The loudspeaker emits acoustic waves at the desired frequency. After that, the acoustic wave moves through the resonator, creating hot and cold temperature areas due to the distribution of high and low-pressure areas through the resonator [7].

Although the thermoacoustic phenomenon was discovered several centuries ago, it has not received much attention as an energy conversion method. In 1980, Rott [8] made a breakthrough in the study of thermoacoustic phenomena by developing a linear theory. Thermoacoustc technology has garnered increasing attention as a new research area for heat engines and refrigerators. In particular, at Los Elmore National Laboratories, Swift and others were involved in the development of thermoacoustic systems [4] [9]. Tijani [10] using his design algorithm, constructed a loudspeaker-driven refrigerator that could achieve a low temperature of -65 °C. The performance of thermoacoustic refrigerators is influenced by various of operational conditions, including working fluids, geometrical parameters, and voltage supplied, that have been studied extensively in previous studies [11–15]. The researchers also interested in numerical and experimental thermoacoustic refrigerator investigations to improve the stack's parameters [16–21]. Kajurek et al. [22] the procedure for designing a small thermos-acoustic refrigerator with a nominal cooling capacity of 10 W and a difference in temperature of 30 K between the AHX and CHX. Shivakumara and Bheemsha [23] conducted an experimental study on a standing-wave thermoacoustc refrigerator to study the performance of the thermoacoustic refrigerator at 2 and 10W. Based on the prior literature, It is apparent that the standing wave thermoacoustic refrigerator still has low cooling capacity and performance. The current paper aims to design and optimize a thermoacoustic refrigerator using the simulation program DELTAEC for a temperature difference of 25ºC and using helium as an oscillating gas. So, the reasons for choosing the standing-wave thermoacoustc refrigerator are increased cooling capacity and improved thermal performance, low cost, simple construction, and good qualities. Besides that, carried out a study of the effect of parameters in both the stack and the resonator (inertance and compliance) on cooling capacity (cooling power) and coeffcient of performance because those parameters have a significant impact on the performance of the refrigerator.

2. Basic principle of the thermoacoustic refrigerator

In this section, the working principle of a thermoacoustc refrigerator is explained. The thermoacoustic process (thermoacoustic effect) of the refrigeration cycle can be simplified into four steps. To clarify, the movement of one parcel of the gas can be tracked back and forth between stack’s plates based on conditions of increase and decrease in temperature and pressure (see Figure 1b) as follows [24]:

- **Adiabatic Compression**

  The gas parcel undergoes adiabatic compression causes acoustic wave and move to the left. As a result, its pressure increases, so the parcel's temperature increases accordingly.

- **Isothermal Compression**

  The gas will have a higher temperature than the adjacent walls. Therefore, it rejects heat to the surface of the stack, resulting in a decrease in the gas parcel's temperature and the volume of the gas parcel begins to shrink.

- **Adiabatic Expansion**

  When the wave continues its cycle, the gas parcel adiabatically expands and returns to its right direction. As a result, its pressure drops, leading to a reduction in the temperature of the gas and a larger volume.

- **Isothermal Expansion**

  In this stage, the gas parcel temperature is lower than the plate temperature of the stack, so heat flows from the wall to the gas parcel.

During this process, a small amount of heat is transferred. Thus, in order to transfer more heat, the process's cooling or heating power is increased by adding more parallel channels.

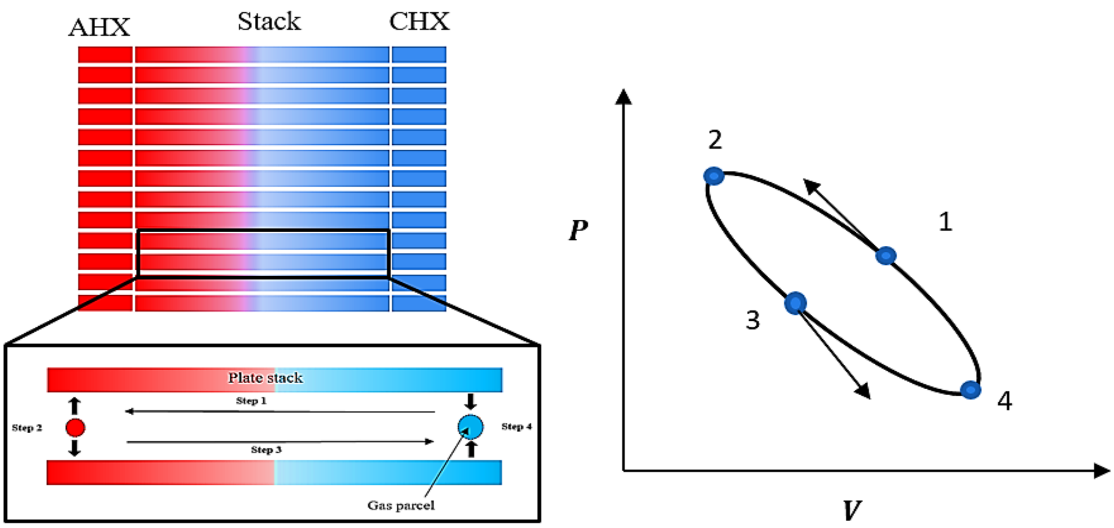

Figure 1. Heat transfer processes in the stack (thermoacoustic effect)

3. Design of the thermoacoustic refrigerator

The standing wave thermoacoustic refrigerator consists of the following: stack, heat exchangers, resonator and acoustic driver (ordinary loudspeaker), (See Figure 2).

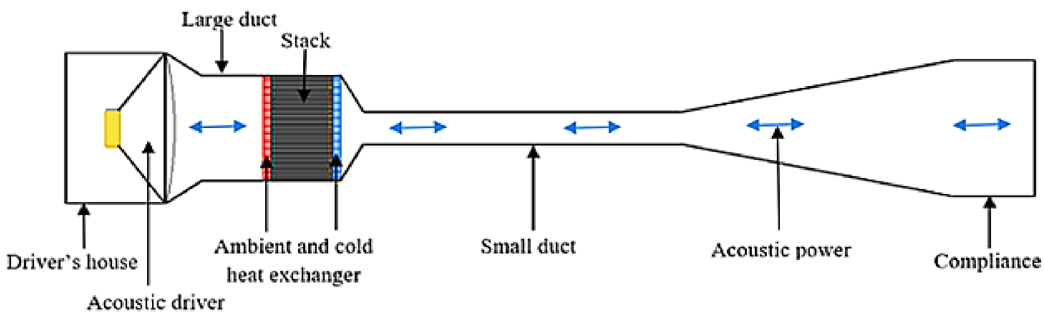

Figure 2. Diagram view of the standing wave thermos-acoustic refrigerator designed

1.1 Stack

The stack is the heart of the thermoacoustic refrigerator (where the thermoacoustic effect occurs). Thus, it is a significant component that determines the performance of a refrigerator. The stack material must have a heat capacity greater than the heat capacity of the gas (helium) and have low thermal conductivity to prevent significantly losing acoustic power (heat conduction along the temperature gradient) [25]. In the present research, Mylar was selected because it has these characteristics. The different geometries that might be used to build it include paralel plates, circular holes and pin arrays. Nonetheless, some of them could be challenging to build. Thus, the stack for the current design was chosen to have a parallel plate geometry [26]. In addition, there is another parameter to take into account while designing a stack is penetration depths. There are two types of penetration depths: thermal and viscous. The thermal penetration depth describes heat diffusion during a complete oscillation cycle of a gas parcel, while the viscous penetration depth gives an idea of momentum diffusion, where the viscosity effect is negative and causes sound power losses. Through this parameter, the spacing between the stack's plates can be determined and it is possible to assess the heat transfer and the impact of viscosity between the plate of the stack and the gas parcel. [19, 27], see Eq. (1 and 2). [19, 27], see Eq. (1 and 2).

$$\delta_k = \sqrt{\frac{2k}{\omega\rho C_p}} \qquad (1)$$

$$\delta_v = \sqrt{\frac{2\mu}{\omega\rho}} \qquad (2)$$

where k, μ, λ, and ω are thermal conductivity, dynamic viscosity, wavelength and angular frequency, respectively.

1.2 Heat exchangers

The thermoacoustic refrigerator's ambient and cold heat exchangers are also another important component for completing the thermoacoustic cooling process. AHX is used to reject heat from the refrigerator and is placed on the hot side of the stack, while CHX provides heat into the refrigerator and is placed on the cold side of the stack. to create a greater temperature gradient across the stack. However, the design of these heat exchangers for heat transfer is challenged as the working gas parcel is osciliating under the thermoacoustic-effect. [28]. Furthermore, the optimal heat exchanger length must be matched to the amplitude of the gas displacement. A detailed discussed of that is given by Swift [29]. The displacement of gas amplitude could be calculated from the following Eq. (3).

$$|\xi| = \frac{|U|}{\omega A} \qquad (3)$$

where U, ω and A are Volume flow rate, angular frequency and area, respectively.

1.3 Resonator

The resonator is one necessary component of the thermoacoustic refrigerator to maintain acoustic waves where the stack and ambient and cold heat exchangers are placed and is filled with working gas. The resonance frequency of the thermoacoustic refrigerator is used to estimate the resonator's length. [22]. Typically, the resonator length is a quarter or half wavelength for a standing wave thermoacoustic refrigerator.

$$\lambda = \frac{a}{f} \qquad (4)$$

where a and f are the speed of sound m/s and frequency Hz, respectively.

The resonator can have an impact on acoustic energy. The dissipation of acoustic energy is caused by both penetration depths (thermal and viscosity) in the boundary layer of the resonator wall. There are ways to minimize the dissipation of acoustic energy of a standing wave thermoacoustic refrigerator. The first is to utilize a resonator shape with a quarter wave-length, which dissipates half the energy when compared to a half wavelength resonator [29], while the The second method is to reduce the diameter of the resonator at the stack's cold side, as shown by Hofler and called a "Hofler resonator" [30]. The resonator is represented by the large duct (compliance) and the small duct (inertance), which both affect the performance of the refrigerator.

1.4 Acoustic diver (ordinary loudspeaker)

The acoustic driver is one of the important components in a thermoacoustic refrigerator, where electrical power is converted to acoustic power (excitation of the sound wave) in order to create a cooling effect [4]. There are two categories of acoustic drivers: a loudspeaker and an alternator motor. Ordinary loudspeakers are available and cheap, and their low power-producing capacity allows them to be employed for relatively low-power thermoacoustic applications. while linear alternators are costlier and have a higher mass because these alternators demand higher levels of manufacturing accuracy. Also, there is a lack of research. In addition, their high power-producing capacity. As a result, it is used in high-power thermoacoustic applications [31-32]. An ordinary loudspeaker (model: 12XL1200) was used in this current design. Its specifications are shown in Table 1.

Table 1: The primary specifications of the acoustic driver (loudspeaker) [33]

A (cm^2)	R_e (Ω)	R_m (N.s/m)	L (mH)	M (g)	BL (N/A)	Ҡ (N/m)	f (Hz)	$2\|\xi_1\|$(mm)
518	5	3.2	1.3	152	23.6	14285.714	50-2500	25

1.5 Working gas

The performance of a thermoacoustic refrigerator is significantly impacted by the working gas. There are many characteristics to consider in choosing a gas, such as a fast sound speed, a low Prandtl number and a high thermal conductivity [4, 34]. In addition, the working gas should be inert, life-safe, environmentally friendly, non-flammable, commercially available, and cheap. Therefore, inert gases are used in thermoacoustic refrigerators to meet these requirements. [35-36]. For the current design, helium is used as the working gas. because it has the highest sound velocity, thermal conductivity and low Prandtl number in comparison with the other noble gases [37].

1.6 DELTAEC simulation

DeltaEC is a computer software that can be used to estimate the thermoacoustic refrigerator's performance, which is an acronym for "Design for Low Amplitude Thermoacoustic Energy Conversion"[38]. It allows the user to design the refrigerator to achieve the desired results. The program DeltaEC numerically integrates each of the equations for continuity, momentum and energy for thermo-acoustic devices. It is designed to solve the one-dimensional wave equation. The DELTAEC program is free and available software [39]. In the design process of the current thermoacoustic refrigerator, the operation conditions were set at the mean pressure, frequency, working gas and difference in temperature AHX and CHX at 1bar, 145 Hz, helium and 25K, respectively.

In the simulation process, this refrigerator's current model utilized DeltaEC as its shooting method, where the pressure amplitude, pressure amplitude phase, mean temperature, heat extracted from the AHX and cooling power (cooling capacity) applied to the CHX was set as the guess parameters. Whereas target parameters were established at the real and imaginary parts of the inverse of the acoustic impedance and the total energy flow was calculated at the final segment of the apparatus with the temperatures of the hot and cold heat exchangers set at 300K and 275K, respectively.

In general, it can estimate the thermoacoustic refrigerator’s performance thermoacoustic refrigerator using the coefficient of performance (COP), which is obtained from the ratio of cooling load to acoustic power, see Eq. (5).

$$COP = \frac{\dot{Q}}{\dot{E_{AD}}} \quad (5)$$

where $\dot{Q}$ and $\dot{E_{AD}}$ are cooling capacity and sound power, respectively.

2. Results and discussion

2.1 The effect spacing plate of the stack

The stack's plate spacing has an important impact on the process of thermoacoustic cooling. The plate spacing and thermal penetration depth (δ_k) have a relationship in which the ratio of a plate's half-space to its thermal penetration depth (Y_o/δ_k) is important for heat transfer between stack walls and working gas parcels. Figure 3 illustrates the impact of the ratio (Y_o/δ_k) on the cooling power and COP of the designed thermoacoustic refrigerator. In Figure 3, it can be seen both cooling power and COP rise to their maxima before beginning to decrease. This means that increasing the spacing between the plates leads to decreased thermal contact between the stack pate and the working gas parcel, which reduces the thermoacoustic heat transfer while decreasing plate spacing causes an increasing viscosity effect. however, the cooling power and COP are best when the ratio (Yo/δk) is 1.45.

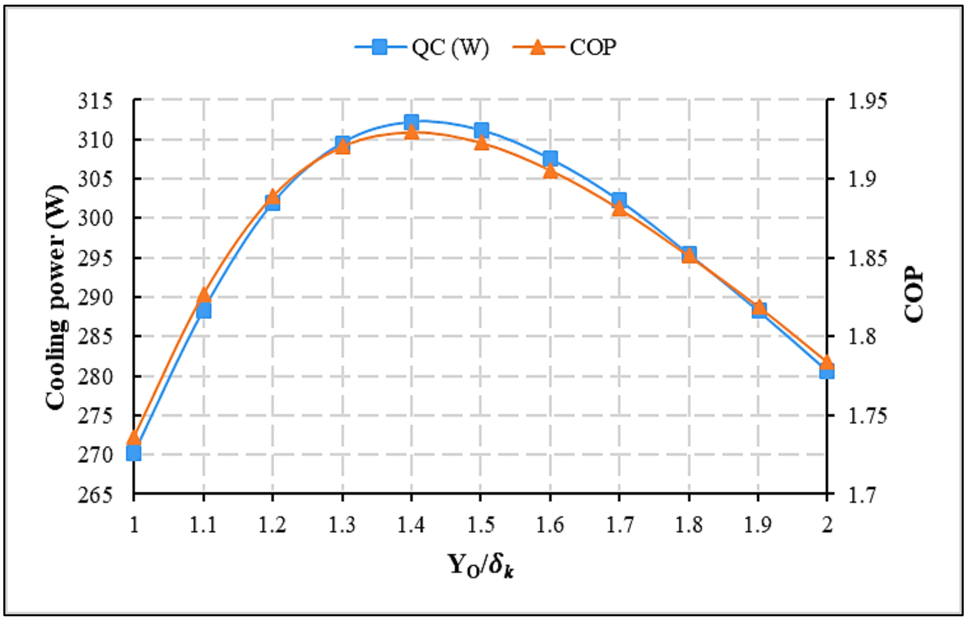

Figure 3. The effect of ($\frac{YO}{\delta_k}$) on cooling capacity and coefficient of performance

2.2 The effect length of the stack

Here, the impact of stack length on the thermoacoustic refrigerator's COP and cooling capacity was investigated. The length of the stack contributes mainly to the thermoacoustic cooling process. Through Figure 4, it is evident that both cooling power and COP began to increase and then decrease. The shorter stack will have low cooling power since there won't be enough surface area for interactions with gas parcels. In contrast, increasing the length of stack led to an increase in the acoustic impedance and pressure drop, which adversely affected the performance. Thus, the optimal length is tested when designing the thermo-acoustic refrigerator in order to get the best performance. The stack length chosen in the current design is 11 cm.

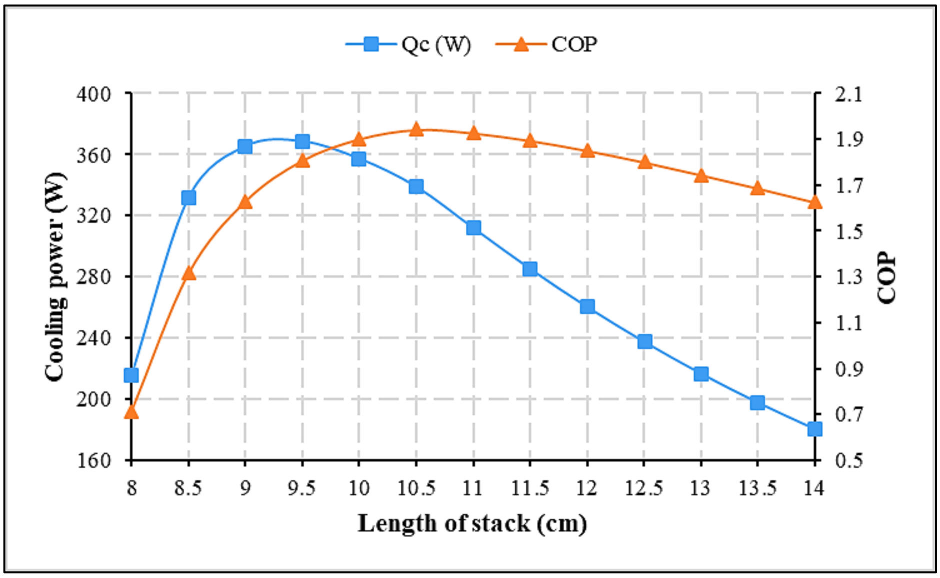

Figure 4. The effect of the length of the stack on the cooling capacity and coefficient of performance.

2.3 The effect stack's position

The stack's position in the resonator has a significant effect on the thermoacoustic refrigerator's performance. Figure 5 shows the effect of stack position (distance from the ordinary loudspeaker—acoustic source) on cooling capacity and COP. Figure 5 shows that the cooling capacity (cooling load) is maximum when the stack is close to the acoustic source and decreases as the stack moves away from the acoustic source. This can be explained as the position of the stack is nearly at the pressure antinode and the velocity node, where the best thermoacoustic effect and heat transfer occur, while moving away from the loudspeaker the pressure amplitude will decrease and lead to a decrease in the heat transfer. On the other hand, the value of COP is decreasing and reaches its lowest when the stack is near the loudspeaker. Based on the current results it was chosen position of the stack was to be between 31.5-32.5cm.

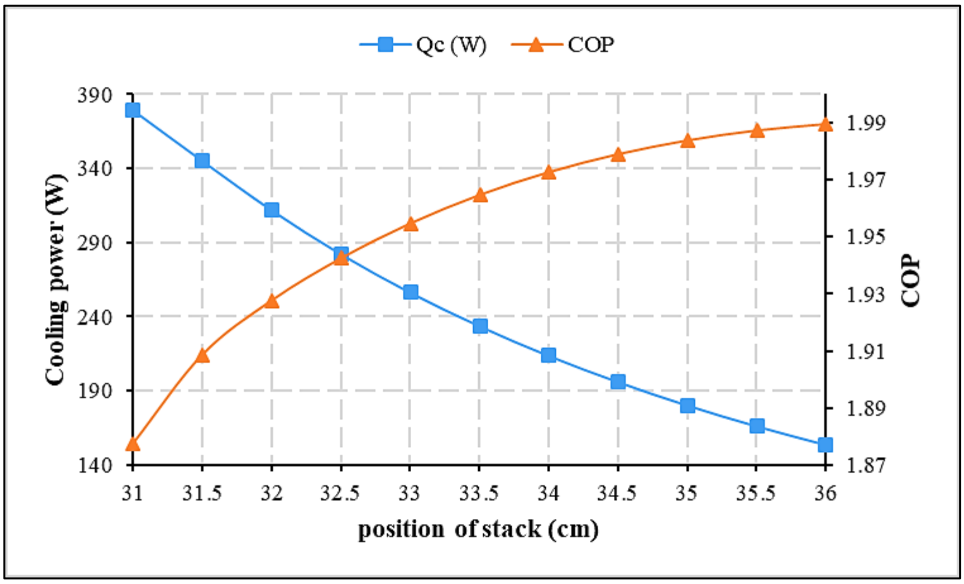

Figure 5. The effect of stack position on cooling capacity and coefficient of performance

2.4 The effect of the resonator

This time, the effect of the resonator on the thermoacoustic refrigerator current has been considered. Inertance and compliance have an important impact on the sound conditions, which in turn impact the thermoacoustic refrigerator's performance. This study was carried out on a simulation model by changing the dimensions (length and diameter) for both inertance and compliance, as shown in Figure 6. Consequently, the results shown in this study, the purpose of which was to find the optimum dimensions of the resonator from the viewpoint of the maximum cooling capacity achievable and improve the thermoacoustic refrigerator's performance. This means that changing dimensions (inertance and compliance) lead to a The thermoacoustic refrigerator's acoustic conditions are changing and its close to the acoustic conditions is required by a loudspeaker at its best. Thus, the diameter and length for inertance and compliance equal 9.5 cm, 40 cm, 27.64 cm, and 150 cm respectively.

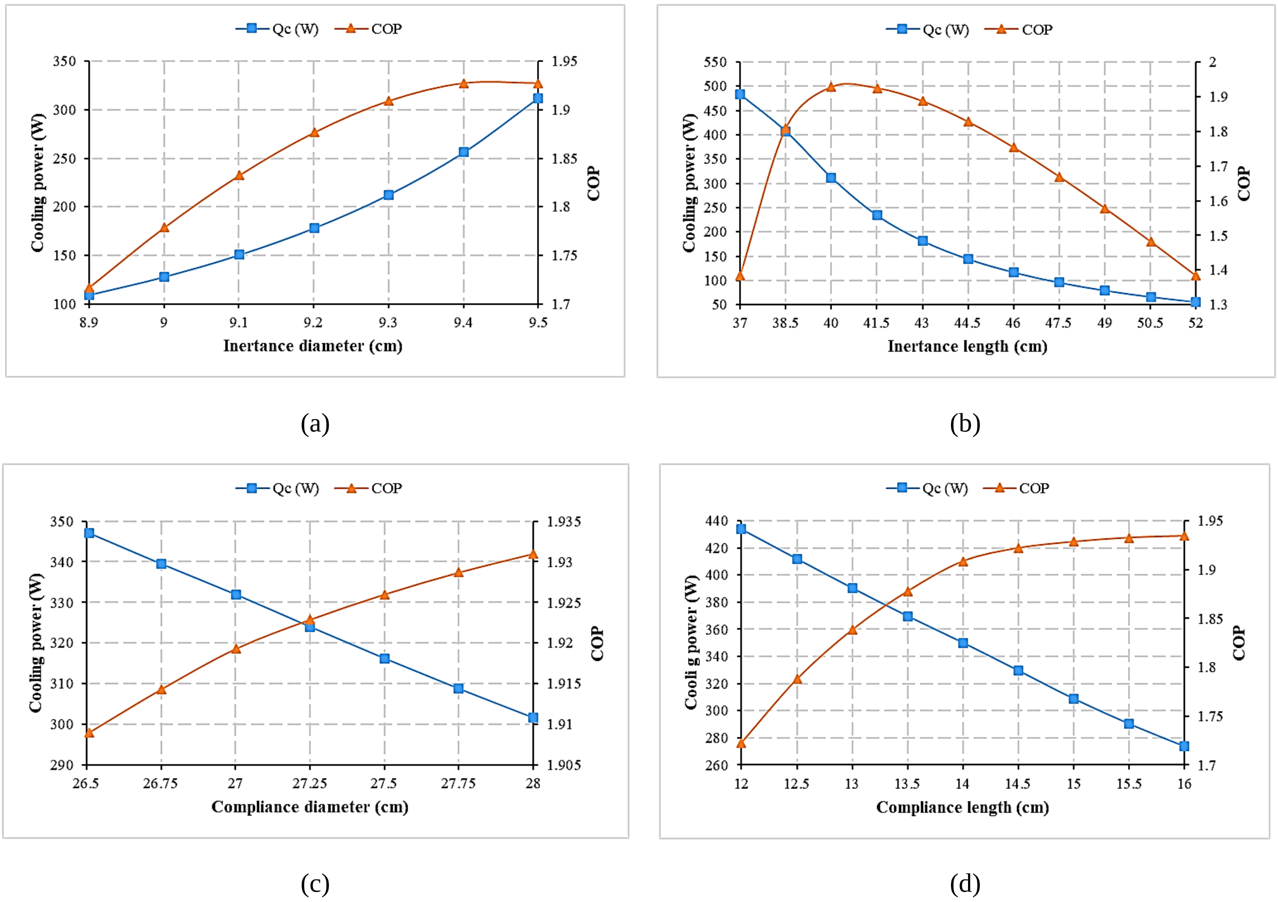

Figure 6. The effect of inertance diameter (a), inertance length (b), compliance diameter (c) and compliance length (d) on cooling capacity and coefficient of performance

The standing-wave thermoacoustic refrigerator's design was optimized using the simulation software DeltaEC, allowing us to predict the refrigerator's performance Table 2 displays the final optimum parameters, which were chosen based on the thermoacoustic refrigerator's maximum cooling load and COP.

Table 2: The final optimum dimensions and specifications for the standing-wave thermoa-coustic refrigerator.

Components	Diameter (mm)	Length (mm)	Porosity (%)	Hydraulic radius (mm)
Ambient heat exchanger (AHX)	282	30	50	2.5
Cold heat exchanger (CHX)	282	50	50	2.5
Stack	282	110	85	0.85
Inertance	95	400	------	23.75
Compliance	276.4	150	------	69.1

5. Conclusions

The standing-wave thermoacoustc refrigerator was created and optimized using the simulation software DeltaEC. In this paper present, we explain the thermoacoustic refrigerator's working principle, as well as the details of its components and the parameters required in the design process. However, the results obtained in the ratio of the stack's plate spacing, as well as establishing the stack's location and length and effect resonator (inertance and compliance) is important when using them for designing a standing-wave thermo-acoustic refrigerator. Hence, the improved thermoacoustic refrigerator is able to achieve a cooling capacity of 312W with a 25 K difference in temperature on both sides of the ambient heat exchanger and cold heat exchanger, and its coefficient of performance (COP) is 1.9275.

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Nomenclature

$\dot{E}$: Acoustic power (W)
$|U|$: Volume flow rate (m^3/s)
$|\xi|$: Displacement of gas (m)
δ_k: Thermal penetration depth (m)
δv: Viscous penetration depth (m)
k: Thermal conductivity W/m·K
µ: Dynamic viscosity kg/m. s
Yo: half plate spacing
a: Speed of sound m/s
f: Frequency Hz
Cp: Isobaric specific heat capacity, J/kg·K
AHX: Ambient heat exchanger
CHX: Cold heat exchanger
COP: Coefficient of performance
$\dot{Q}$: Cooling power (W)
λ: Wavelength (m)
ω: Angular frequency (s^{-1})
AD: acoustic driver
A: Area (m^2)
R_e: Coil resistance (Ω)
R_m: Mechanical resistance (N.s/m)
L: Coil inductance (mH)
$\boldsymbol{M}$: Moving mass (Kg)
Bl: Force factor (N/A)
Ƙ: Spring constant (N/m)