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An Experimental Study of Thermoacoustic Couples

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Abstract
In this study, a simple thermoacoustic refrigerator system experiment set was established by using the design parameters in accordance with the relevant literature. In the experimental setup, a loudspeaker was used as an acoustic power source, and a suitable frequency value was determined for the system. Three kinds of stack materials with different thermal conductivity coefficients, respectively, mylar, cotton, and glass wool, were placed in the resonance tube. The temperature values at both ends of the stack material were measured by placed temperature gauges. In the measurements made within the same time period, the temperature differences were measured as 5.2°C for mylar, 4.7°C for cotton, and 4.3°C for glass wool, respectively. It was determined that the highest temperature difference was in the mylar material.

1.Introduction

Refrigerators are used in almost all areas. Hydrofluorocarbons (HFC) and chlorofluorocarbons (CFC) found in refrigerants used in conventional refrigerators cause harmful environmental effects such as thinning and perforation of the ozone layer. Therefore, taking harmful environmental effects into account is becoming more and more important in the design and development of cooling systems. In order to eliminate the harmful effects of refrigerants on the environment, research efforts are more focused on the development of environmentally friendly refrigerants and alternative cooling technologies. One of the alternative cooling technologies is thermoacoustic refrigerating (TAR), which produces cooling from sound. Devices that cool by using acoustic energy are called thermoacoustic coolers. The basic principle in thermoacoustic coolers is the thermoacoustic effect resulting from the interaction between the solid surface and the compressed fluid. The power of the TAR system depends on the power of the sound waves that create vibrational motion within the molecules of the working fluid.

TAR systems can be thermally or electrically operated. The first is driven by heat energy, while the second is driven by the compressor. Thermoacoustic systems working with thermal energy are used for cryogenic cooling and ambient cooling. The purpose of cryogenic thermoacoustic cooling is to achieve the lowest possible temperature, while the TAR of the other is to achieve the highest cooling effect. In conventional cooling systems, the necessary working pressure is provided by the compressor, while the required working pressure in TAR systems, loudspeakers producing sound energy, etc., is supplied with components. One of the positive effects of TAR systems on the environment is that they can also work with atmospheric air. However, the use of air as a refrigerant gas causes a slight decrease in the cooling effect compared to the use of helium and hydrogen [1].

The only disadvantage of the TAR system compared to conventional mechanical vapor

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compression systems is that it has a lower coefficient of cooling effect. On the other hand, it has advantages such as the absence of moving parts, the use of working fluids that are not harmful to the environment, such as argon and helium, and being safer. In addition, this cooling system also protects the ecosystem by transferring energy from economic sources such as waste heat and solar energy.

The discovery of acoustic cooling dates back about 250 years. The observations made by Higgins [2] in 1777 are the first records of heat-induced oscillations, as Putnam and Dennis (1956) highlighted. Higgins [3] conducted experiments with an open glass tube in which acoustic oscillations were stimulated by the appropriate placement of a hydrogen flame, the so-called "singing flame". The concept of thermoacoustics was first used by Sondhauss (1850) and entered the literature. Later, Rayleigh (1878 and 1945) called this phenomenon the "thermoacoustic effect". About 20 years later, Rott et al. derived linear equations based on thermo-acoustic theory and presented their solutions in their article [4], [5].

A thermoacoustic cooling system consists of four basic components: a stack, hot and cold end heat exchangers, a resonance tube, and an acoustic source [6]. The heat energy is carried over the stack, which is the heart of the acoustic system. The stack is a solid component that contains pores, and its purpose is to cause the working fluid to oscillate when in contact with the solid walls. A temperature distribution occurs on the stack due to the heat carried from one end to the other by the operation of the acoustic source. With the heat exchangers mounted at both ends of the stack, cooling is done by utilizing the decreasing temperature of the stack, and waste heat is given to the outside from the heat exchanger on the side with an increasing temperature. The stack of a thermoacoustic cooler system without heat exchangers is called a thermoacoustic couple [7]. As a result of the interaction between the solid surface of the stack and the gas parcels, a temperature gradient is formed across the stack. The stack or couple temperature difference (ΔT_s) occurs from the hot end close to the pressure antinode to the cold end away from the pressure antinode. Understanding the basic thermoacoustic process that occurs in thermoacoustic couples is crucial for the design and development of thermoacoustic devices.

Experimental studies of thermoacoustic couples (TAC) usually indicate the temperature difference from one end to the other. The thermoacoustic temperature couple forming the basis of the thermoacoustic system TAC was first introduced by Wheatley et al. [8]. In their study, they measured the temperature differences using three different stack materials. The first thermoacoustic coolers were designed by Wheatley and his team and started to be used in the cooling sector. Piccolo and Cannistraro [9] carried out experimental studies on a TAC using a 7-cm-long stack of polyethylene with a thermal conductivity of about 0.11 W/mK. The experimental results were compared with the ΔT_s values predicted by the theoretical model of Atchley et al. [10]. Worlikar et al. [11] developed a numerical model to predict the temperature difference across the thermoacoustic couple. Zoontjens et al. [12] performed numerical modeling of the temperature couple of the different edge profiles of the stack plates. Terdi [13], placed photographic film as stack material inside the resonator tube and experimentally investigated acoustic cooling. In his study, Girgin used polypropylene lemonade straws with a heat transmission coefficient of 0.15 W/mK as a stack and placed the stack in a resonance tube of different sizes (10 cm, 15 cm, and 22 cm), and compared the acoustic cooling effects that occurred. Girgin conducted experiments using atmospheric air and helium as the working fluids and compared the results in both cases [14]. In another study, Somasekher et al. [15] experimentally investigated the effect of tube length on acoustic cooling by using different lengths of resonator tubes in the system.

Teja et al. [16] placed leather as stack material inside the resonator tube and wrapped the skin with nylon fishing line to create a space between the plates. In their experimental studies, acoustic cooling was investigated experimentally by using helium as a working fluid. Mergen [17] numerically investigated the effects of thermophysical properties on thermoacoustic cooling by using five different plastic-derived stack materials, namely PVC, nylon, polyethylene, polyamide, and polypropylene, in standing wave model thermoacoustic coolers. Alcock et al. [18] developed an adjustable-length resonance tube. Wang et al. [19] showed that the multi-stage thermoacoustic cooler designed for operation at room temperature has a better cooling effect than the single-stage case. İlker and Karabacak [20] used air as the working fluid and polypropylene as the stack material and carried out experiments for different sound wave types by changing the diameter of the resonator tube.

In this study, a sinusoidal sound wave with a frequency of 340 Hz was used. With the up-and-down movement of this sound wave, the air passing through the stack is compressed and expanded, and in this way, the air is heated and cooled. The temperature difference between heating and cooling of the air is equivalent to the temperature difference between the ends of the stack. Then, an experimental simple TAC system was established using the design systematics available in the literature [4], [6], [21]. In the experimental setup, a loudspeaker capable of converting electrical power into acoustic power was used as an acoustic source. As a result of the calculations made with the determined frequency, the length of the resonance tube was found to be one quarter of the ideal wavelength. One end of the resonance tube is fixed to the loudspeaker and the speaker is enclosed in a wooden box for sound isolation.

Except for Mylar, cotton and glass wool, which have not been used before in the literature, were preferred as stacking materials. Then, the temperature difference between the two ends of the stack material was measured using temperature gauges.

2. Material and Method

In this study, a simple thermoacoustic refrigerator system experiment set was established by using the design parameters in accordance with the relevant literature. TAR design parameters can be divided into three groups. As seen in Table 1, the first group includes the geometric parameters, the second group includes the thermophysical properties of the working fluid and stack material, and the third group includes the operating parameters.

Table 1. Design parameters of TAR [22].

Geometric Parameters	Material Specific Parameters	Operating Parameters
λ- Wavelength	Working Fluid	$\dot{Q}_c$-Cooling power
L_s- Stack length	K- Thermal Conductivity	ΔT_m-Desired temperature range
x_c- Center of stack	α- Speed of sound	T_m- Average operating temperature
$2y_0$- Stack space	μ-Dynamic viscosity	P_m-Average pressure
2l- Plate thickness	γ- Ratio of isobaric and isochoric specific heats	P_r- Pressure amplitude
A-Cross-sectional area	β- Coefficient of thermal expansion	f - Frequency
	Stack Material	
	ρ_s -İntensity	
	c_s- Specific heat	
	K_s-Thermal conductivity	

2. 1. Design of the system

The heat and work equations on the stack material in a thermoacoustic cooling system are given in equations (1) and (2). [4], [23]

$$\dot{\mathbf{H}}_2 = -\frac{1}{4}\Pi\delta_k\left(\frac{T_m\beta p_1^s\langle u_1^s\rangle}{(1+\varepsilon_s)(1+\sigma)\left(1-\frac{\delta_v}{y_0}+\frac{\delta_v^2}{2y_0^2}\right)}\right)\left[\Gamma\frac{1+\sqrt{\sigma}+\sigma+\sigma\varepsilon_s}{1+\sqrt{\sigma}}-\left(1+\sqrt{\sigma}-\frac{\delta_v}{y_0}\right)\right]-\Pi(y_0K+lK_s)\frac{dT_m}{dx} \quad (1)$$

$$\dot{W}_2 = -\frac{1}{4}\Pi\delta_k\Delta x\frac{(\gamma-1)\omega(p_1{}^s)^2}{\rho_m a^2(1+\varepsilon_s)}\left(\frac{\Gamma}{(1+\sigma)\left(1-\frac{\delta_v}{y_0}+\frac{\delta_v{}^2}{2y_0{}^2}\right)}-1\right)-\frac{1}{4}\Pi\delta_v\Delta x\frac{\omega\rho_m\langle u_1{}^s\rangle^2}{\left(1-\frac{\delta_v}{y_0}+\frac{\delta_v{}^2}{2y_0{}^2}\right)} \quad (2)$$

$$Q_{cn} = -\frac{\delta_{kn}D^2 sin(2x_n)}{8\gamma(1+\sigma)\Lambda}\left[\frac{\Delta T_m\tan(x_n)}{(\gamma-1)BL_{sn}}\frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}}-\left(1+\sqrt{\sigma}-\sqrt{\sigma}\delta_{kn}\right)\right]-K_{pt}[B+(1-B)K^*]\Delta T_{mn} \quad (3)$$

$$W_n = \frac{\delta_k LD^2}{4\gamma}(\gamma-1)Bcos(x_n)^2\left(\frac{\Delta T_{mn}\tan(x_n)}{BL_{sn}(\gamma-1)(1+\sqrt{\sigma})\Lambda}-1\right)-\frac{\delta_{kn}L_{sn}D^2}{4\gamma}\frac{\sqrt{\sigma}\sin(x_n)^2}{B\Lambda} \quad (4)$$

Considering the axial heat conduction effects, these equations are dimensionless and equation (3) and equation (4) are obtained.

$\boldsymbol{\Lambda}, \boldsymbol{K_{PT}}, \boldsymbol{K^*}$ in the equation are given below.

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2}\sigma\delta_{kn}{}^2,$$

$$K_{PT} = \frac{KT_m}{p_m \alpha L_S},$$

$$K^* = \frac{K_s}{K}$$

2.2. Design systematic

The parameters used in the experimental study are given in Table 2.

Table2. Parameters used in the experimental study.

Parameter	Studied value
Wave Structure	Sinusoidal
Resonance tube material	PVC
Resonance tube length	0.25m
Resonant frequency	340Hz
Stack material	Mylar, glass wool and cotton
Stack length	8 cm
Working fluid	Weather

As the resonance tube in the system, a PVC pipe with a length of 25 cm and an inner diameter of 2.3 cm, which is a good insulator, was preferred instead of the glass tube since the necessary holes for the temperature gauge can be opened more easily, the necessary adjustments are made in the length, and there is no heat transfer in the system [23], [24]. The length of the resonance tube is adjusted to be one-quarter of the wavelength [17], [24].

The Length of the Resonance Tube

$$L = \frac{\lambda}{4} = \frac{1}{4} = 0.25 \text{ m} = 25 \text{ cm} \tag{5}$$

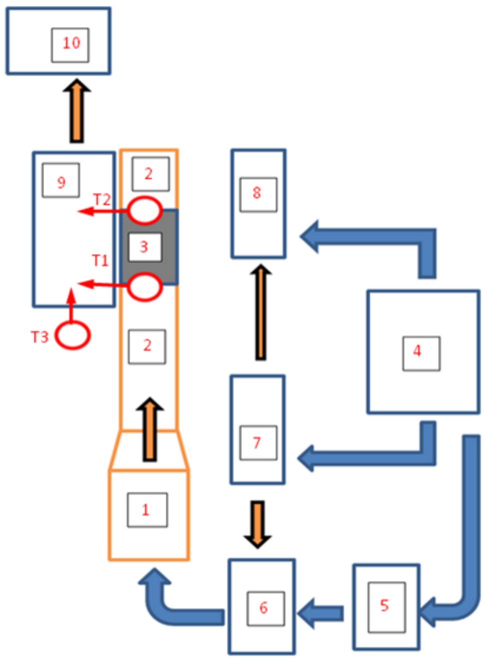
Sound speed; $\quad \nu \cong 340$ m/s and

$$\lambda = \frac{\nu}{f} \tag{6}$$

From the equation (6), the operating frequency in the system is chosen as f = 340 Hz. In the experimental study, air [24], [25] was used as the working gas and three different stack materials were used in the system design. 75-micron-thick mylar [26] with a heat conduction coefficient of 0.16 W/mK was cut into parallel plates of approximately 0.3 cm width and 8 cm length, and wrapped in a tape that functions as a stack holder, and made ready for experimental study. Cotton, the next stack material used in the system with a heat conduction coefficient of 0.07 W/mK and a thickness of 50 microns, was wrapped in a diameter of 2.3 cm, which is the diameter of the resonance tube, and cut into 8 cm in length. The stack is made ready for experimental work by being wrapped in a tape that functions as a holder. The thickness of the Glass wool, which is the last stack material used in the experimental study, is 180 microns, and the heat transmission coefficient is 0.04 W/mK.

3. Experimental setup

The experimental setup, shown schematically in Figure 1, was set up using the design systematic described in the previous section.



1- Loudspeaker, 2-Resonance Tube, 3-Stack, 4-Power Source, 5-DC 12V, 6-Operational Amplifier, 7-Signal Generator, 8-Oscilloscope, 9-Datalogger, 10-Computer, T_1-T_{hot}, T_2-T_{col}, T_3-T_{Amb},

Figure 1. Schematic representation of the experimental setup.

Technical specifications of devices use in this study are shown in Table 3.

Table 3. Technical specifications of devices use in this study.

System Elements	Model	Technicial specifications
Loudspeaker	Suzhou YDD103-04B	Rated power: 15W Maximum power: 20W Sensitivity: 82 ± 3dB Diameter: 100mm 60V DC or 30V AC
Signal generator	EZ Digital FG – 7005C	Mode: Linear Width: Variable from 1: 1 to 100: 1 Rate: 0.5 Hz to 50 Hz (20 mS to 2 S) External VCF Input: Input Voltage: 0 to 10 V Display: 6 digit green LED Frequency Range: 500 mHz to 50 MHz with Auto Range. Accuracy: ± Time base error ± 1 count Input Sensitivity: 100 mVrms Max. Power: 15W Max. Input Voltage: 250 Vpp Temperature: -20° C to +70° C Humidity: below 85% RH
Oscilloscope	EZ Digital DS – 1150	-150MHz bandwidth, 2 CH dual digitizer. -100MS/s simultaneous maximum sampling rate per channel. -200MS/s sampling rate for one channel only. -25GS/s equivalent sampling rate per channel. - 10ns peak detection for glitch capture even in ROLL mode. - Max. 400Vpk input voltage into all channels. - Direct single trigger capture function using a hot-key. - Simultaneous 5 waveform information auto measurement and FFT analysis. - Auto trigger level setting to 50%. - Saving 10 waveforms & 10 setup parameters. - Convenient inserting interface card for RS-232C, hardcopy and USB. - Operating temperature 0 C to +40 C. - Relative humidity <80%.
Digital multimeter	Fluke 87 – V	Rate: 0.1 mV to 1000 V Accuracy: ±(0.7% + 4) true-rms AC bandwidth: 20 kHz with low pass filter; 3 dB @ 1 kHz Max. Resolution: 0.1 mV -Temperature range: Indoor & Outdoor -50 ~ +70 degree (-58 ~ +158°F).
Temperature meter	HTC - 2	-Temperature measurement accuracy: ±1°C (1.8°F). -Humidity range: 10% ~ 99% RH. -Humidity accuracy: ±10% RH.

In the experimental setup, consists of three main parts: the acoustic power supply, resonance tube, and stack. In the setup, a Suzhou brand YDD103-04B model 15 W loudspeaker with a 10 cm diameter was used as an acoustic power source. The resonant tube and the loudspeaker are combined with the help of an aluminum conical piece. In order to provide sound insulation, the loudspeaker was placed in a closed wooden box, and a hole in the diameter of the resonance tube was drilled in the top cover of the box. The loudspeaker is mounted at the bottom of the hole, and in this way, the passage of sound waves into the resonance tube is provided. On the bottom cover of the box, a small hole is made for the output of the speaker cables. The lid of the box was screwed on all four sides in order to provide good sound insulation during the experiment. According to the results of the calculations, the stack material was placed 4 cm below the top of the resonance tube. In this way, sufficient distance is left for the sound waves to return again.

In order to measure the temperatures at both ends of the stack material, HTC-2 brand temperature meters were used. In the system, one of the temperature meters was placed at the top of the stack by puncturing the plug of the resonance tube, and the other was fixed to the bottom of the stack by adjusting it to leave a gap of 12 cm (8 + 4) from the top of the resonance tube. An EZ Digital brand FG – 7005C model signal generator was used as a signal source in the system. The sinusoidal sound waves produced in the signal generator are amplified in an operational amplifier and applied to the loudspeaker. The signal is also sent to the oscilloscope so that the shape of the signal used in the system can be seen. The operational amplifier used in the experimental study is Y – 0014 model, and there are many input and output elements required for a constant symmetrical power supply, signal generator, voltmeters, and Op–Amp applications. DS – 1150 model oscilloscope is used in the system. The horizontal axis of the oscilloscope is set to 2 ms and the vertical axis ∼to 5V. Fluke brand 87 – V model digital multimeter was used to clearly see the sensitivity of the 3.029 amplitude value applied in the system. The measurement was made in the AC volt range of the multimeter.

4. Experimental Results and Suggestions

Since there is no heat exchanger in the experimental setup, heat transfers between the ends of the stack and the fluid and between the stack and the surface of the resonance tube are neglected, and it is assumed that the system does not transfer heat to the environment. Since air is used at atmospheric pressure in the study, the cooling power is low. In addition, although it is very small, there is convection heat transfer with air from the ends of the stack and heat transfer by conduction between the stack and the resonance tube. Frequency and ambient temperature were kept constant in the experiments.

Initially, the temperature values at the top and bottom of the stack are the same. Temperature measurements were made every 10 minutes. The temperature difference between the ends of the stack remained constant after 140 min. Since there was no change in the temperature difference after this value, the measurement was ended. In the experimental study, three different stack materials were used: mylar, cotton, and glass wool, and test results were obtained for each case. It is given in Table 4, Table 5, and Table 6.

Table 4. Measurements with a stack of Mylar material.

	Duration (min)	**T_{hot}(°C)**	**T_{col}(°C)**	**ΔT(°C)**
1	–	24.5	24.5	0
2	10	24.6	24.5	0.1
3	20	24.7	24.5	0.2
4	30	25.1	24.4	0.7
5	40	25.1	24.2	0.9
6	50	25.2	24.0	1.2
7	60	25.3	23.9	1.4
8	70	25.4	23.7	1.7
9	80	25.4	23.3	2.1
10	90	26.2	23.0	3.2
11	100	26.2	22.6	3.6
12	110	26.3	22.4	3.9
13	120	26.7	22.3	4.4
14	130	26.8	22.1	4.7
15	140	27.1	21.9	5.2
		(+) 2.6	**(-) 2.6**	**5.2**

As seen in Table 4, T_{hot} and T_{col} values, which were both 24.5°C at the beginning, were measured as 26.9°C, and 22.2°C, respectively, after 140 minutes. It can be seen from the table that the temperature difference between the two ends of the stack material is 4.7°C

T_{hot} and T_{col} values, which were both 24.5°C at the beginning, were measured as 27.1°C and 21.9°C, respectively, after 140 minutes. It can be seen from the table that the temperature difference between the two ends of the stack material is 5.2°C. The results in the table are shown in figure 2 in graphic form. As can be seen from the graph, the temperature at the lower end of the stack material increased over time, and the temperature at the upper end decreased over time.

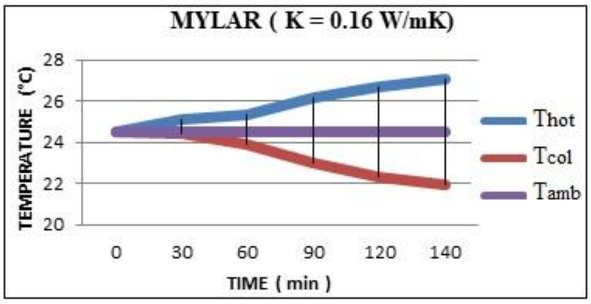


Figure 2. Temperature and time graph of stack with mylar material.

Table 5. Measurements with cotton material stack.

	Duration (min)	T_{hot}(°C)	T_{col}(°C)	ΔT(°C)
1	–	24.5	24.5	0
2	10	24.6	24.2	0.4
3	20	24.7	23.9	0.8
4	30	24.9	23.7	1.2
5	40	25.2	23.7	1.5
6	50	25.4	23.7	1.7
7	60	25.8	23.7	2.1
8	70	26.1	23.5	2.6
9	80	26.1	23.2	2.9
10	90	26.2	23.2	3.0
11	100	26.4	23.0	3.4
12	110	26.5	23.0	3.5
13	120	26.7	22.8	3.9
14	130	26.8	22.8	4.0
15	140	26.8	22.5	4.3
		(+) 2.3	**(-) 2.0**	**4. 3**

The results in the table are shown in the graph in Figure 3. As can be seen from the graph, the temperature at the lower end of the stack material increased with time, while the temperature at the upper end decreased with time.

As can be seen in Table 5, T_{hot} and T_{col} values, which were both 24.5°C at the beginning, were measured as 26.8°C and 22.5°C, respectively, after 140 minutes. It can be seen from the table that the temperature difference between the two ends of the stack material is 4.3°C.

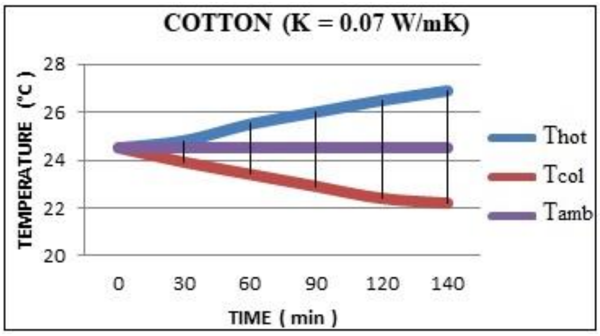


Figure 3. The temperature-time graph of the cotton material stack.

Table 6. Measurements with glass wool material stack.

	Duration (min)	T_{hot}(°C)	T_{col}(°C)	ΔT(°C)
1	–	24.5	24.5	0
2	10	24.6	24.2	0.4
3	20	24.7	23.9	0.8
4	30	24.9	23.7	1.2
5	40	25.2	23.7	1.5
6	50	25.4	23.7	1.7
7	60	25.8	23.7	2.1
8	70	26.1	23.5	2.6
9	80	26.1	23.2	2.9
10	90	26.2	23.2	3.0
11	100	26.4	23.0	3.4
12	110	26.5	23.0	3.5
13	120	26.7	22.8	3.9
14	130	26.8	22.8	4.0
15	140	26.8	22.5	4.3
		(+) 2.3	**(-) 2.0**	**4. 3**

The results in the table are shown in the graph in Figure 4. As can be seen from the graph, the temperature at the lower end of the stack material increased with time, while the temperature at the upper end decreased with time.

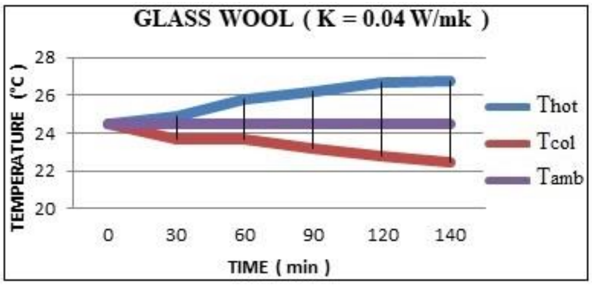


Figure 4 Temperature – time graph of the stack with Glass Wool material.

In the case of using three different stack materials, the variation of the measured temperature values at the cold end of the stack materials with respect to time can be seen comparatively in Figure 5. Initially, the values measured at the hot ends of all three stack materials were 24.5 °C. As seen in Figure 5, the cold end temperatures after 140 minutes were 21.9 °C for mylar, 22.2 °C for cotton, and 22.5 °C for glass wool. It was observed that the lowest cold-end temperature was in the mylar stack material.

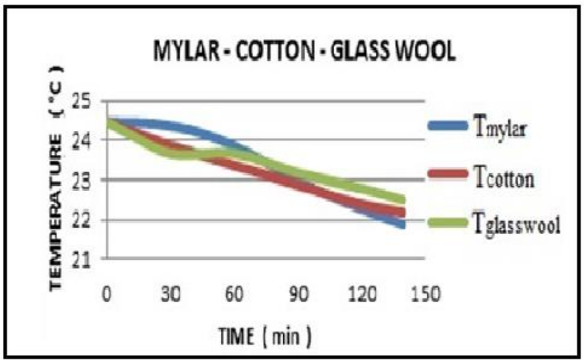


Figure 5. Temperature values at the cold end of the stack.

In Figure 6, the temperature differences between the two ends of the stack are given graphically when different stack materials are used. The highest temperature difference occurred when mylar stack material was used, followed by cotton and glass wool, respectively. With the increase in the heat transfer coefficients of these stack materials, an increase was observed in the temperature differences.

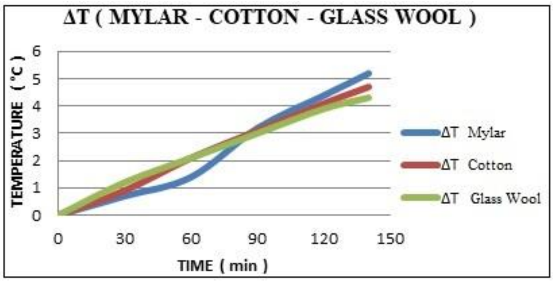


Figure 6. Comparison of temperature difference (Mylar - Cotton - Glass Wool).

5. Conclusion

As a result of the experiments, it has been observed that a temperature difference may occur due to the acoustic effect. These temperature differences are different for each stack material used. In the measurements made within the same time period, it is seen that the acoustic cooling and temperature difference obtained from the mylar material with a high heat transmission coefficient are the highest, the cotton material with a lower heat transmission coefficient than mylar has a lower acoustic cooling and temperature difference than mylar, and finally, the cotton material has the lowest heat transmission coefficient. It has been observed that the temperature difference obtained from the glass wool material, which has the lowest heat transmission coefficient, is the lowest. When the related studies are examined, it is seen that generally the same stack materials are used. In this study, unlike previous studies, glass wool and cotton were used as stack materials for the first time. The temperature differences between the two ends of the stack were compared with each other by using three different materials with different heat conduction coefficients as the stack material.

Prototype development costs are quite high since the performance of acoustic cooling systems is relatively low. For now, it is very difficult to predict whether thermoacoustic coolers will be used commercially. However, as efforts to improve performance in this area progress, the possibility of thermoacoustic coolers competing with conventional coolers will increase.

The efficiency of thermoacoustic devices is not yet at a level that can compete with commercial solutions. For this reason, many studies have been carried out to improve the design and performance of thermoacoustic coolers.

Focusing on theoretical as well as experimental analysis will facilitate the optimization of geometric parameters such as stack location, stack length, resonator length, or operating parameters such as frequency, mean pressure, and temperature gradient. The investigation of TAC between the stack ends will increase the performance of the thermoacoustic refrigerators.

Icons ındex

a	Sound velocity, acoustic velocity (m/s)	**B**	Stack fill rate
c_p	Specific heat at constant pressure (J/kgK)	f	Acoustic frequency
l	Half of the stack thickness (mm)	$\dot{H}_2$	Carried heat
k	Heat transfer coefficient (W/mK)	**I**	Current from speaker
L_s	Stack length (cm)	**L**	Resonance tube length
P	Pressure (kPa)	l_m	Dimensionless stack length
p_1	Pressure variation amplitude	Pm _	Average pressure
Q	Heat (J)	p_1^s	The positive real part of the pressure amplitude
t	Time(s)	**R**	Gas constant
T_1	Acoustic temperature amplitude	s_m	Average entropy
T_s	Temperature of the stack	T_m	Average temperature
x	**x** Axis	T_{kr}	Critical temperature
u_1	Speed amplitude	ΔT_s	Temperature difference
v	y component of speed	**u**	Speed
$\dot{W}_2$	Work	u_1^s	The positive real part of the velocity amplitude
Γ	Ratio of the temperature distribution on the heap to the critical temperature distribution		
δ_k	Thermal penetration depth	y_0	Half the distance between the plates
γ	Specific heats ratio	β	Coefficient of thermal expansion
ε_s	Stack thermal capacity ratio	**Δx**	Plate (stack) length
κ	Thermal dissipation coefficient	δ_v	Viscous penetration depth
λ	Wavelength	ε	Internal energy
ν	Kinematic viscosity	**η**	Efficiency
Σ	Viscous stress tensor	K_s	Thermal dissipation coefficient of the stack
ρ_m	Average density	μ	Dynamic viscosity
ω	Angular frequency	**Π**	The circumference of the plate
σ	Prandtl number	ρ	Intensity

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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