Journal of Naval Science and Engineering
2012, Vol.8, No.1, pp.14-32

THERMOACOUSTIC SYSTEMS AS AN ALTERNATIVE TO CONVENTIONAL COOLERS

İbrahim GİRGİN[1*] , Mehmet TÜRKER[2]

[1]Turkish Naval Academy Mechanical Engineering Department*
Tuzla, Istanbul,Turkiye
[2]Ministry of National Defence
Ankara,Turkiye

igirgin@dho.edu.tr, mturker2030@yahoo.com

Abstract

Acoustic waves hold oscillations of pressure, displacement and temperature. The interaction of these effects in gas close to a solid surface generates thermoacoustic oscillations. Some prototypes of coolers are being constructed using the principles of thermoacoustics nowadays. Even though the coefficient of performance of thermoacoustic systems is lower than the conventional coolers, the concern on the thermoacoustic systems has been increased since these systems are cheap, simple and do not use harmful gases for the atmosphere and do not have any moving parts compared to the conventional coolers. Thermoacoustic coolers are one of the potential cooling technologies of the future.

KLASİK SOĞUTUCU ALTERNATİFİ OLARAK TERMOAKUSTİK SİSTEMLER

Özetçe

Akustik dalgalar içerisinde basınç, pozisyon ve sıcaklık salınımları mevcuttur. Bu etkilerden dolayı akışkan ve akışkana temas eden katı yüzey arasındaki ısıl etkileşimler termoakustik olarak adlandırılır. Bu etkileşimlerden faydalanılarak inşa edilen ısı ve soğutma makineleri prototip olarak görünmeye başlamışlardır. Termoakustik sistemlerin, maliyetlerinin düşük, yapılarının basit olması, atmosfere zarar veren gazlar kullanmaması, hareketli parçalarının bulunmaması gibi sebeplerle, klasik *soğutma sistemlerine göre pratikteki verimlerinin düşük olmalarına rağmen üzerlerindeki ilgi artarak devam etmiştir. Termoakustik soğutucular geleceğin potansiyel soğutma teknolojilerindendir.*

Keywords: Thermoacoustics, Thermoacoustic Coolers.
Anahtar Kelimeler : Termoakustik, Termoakustik Soğutucular

1. THE HISTORY AND APPLICATIONS OF THERMOACOUSTICS

The studies on thermoacoustics have continued seriously for more than two hundred years. Some part of heat that is transferred in a system in appropriate conditions causes acoustical vibrations, which is a form of work. Glass blowers sometimes observe emitted sound from glass when the hot glass sphere comes together with the cold cylindrical glass. Sondhauss worked on the dimensions of this cylindrical glass and the frequency of the sound emitted [1]. Sondhauss tube in Figure 1 was investigated as a thermoacoustic engine in 1850, and Rijke tube in 1859 [2]. Lord Rayleigh

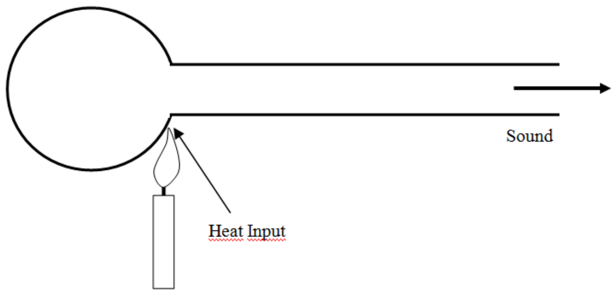

Figure 1 : Sondhauss Tube

explained Sondhauss tube correctly in 1896 [3]. But a theoretical definition would be missing half a century more. In 1962, Carter et al. found out that the performance of Sondhauss tube increased when appropriate parallel plates were placed inside the tube[4]. It was a great discovery in thermoacoustics, because the heat transfer between the gas and the plate would be accomplished by many parallel plates and a great deal of work would be produced from small systems. Feldman completed his Ph.D. thesis on Carter's work [5] and produced 27 W of acoustical work using 600 W of heat.

Theoretical studies on thermoacoustics were commenced with Kirchoff who calculated the acoustical vibration from a heat source in 1868 [6]. Rott et al. introduced the equations correctly for the first time which expressed the displacement, pressure distribution and energy transfer in a channel that included a temperature gradient and sinusoidal oscillations[7]. The theory of Rott was verified by Yazaki with helium [8], Müller and Lang with air [9], and Hofler with high pressurized helium [10] as the working gases. The comparison of the results to Rott's theory was very good.

Transferring heat by using acoustical oscillations is much newer compared to producing sound by using heat. Gifford and Longsworth produced a great deal of cooling by applying high-amplitude low-frequency pressure oscillations to a gas in a tube [11]. They called the invented machine "Pulse Tube Cooler". In the 1980s, Swift et al. made many studies on thermoacoustic coolers in Los Alamos Laboratory (LANL) in the U.S.

Thermoacoustics attracted people as a new technology after the developments in the first few years of the 1980s. Many thermoacoustic systems were constructed especially at Penn State University, Los Alamos National Laboratory (LANL) and Naval Postgraduate School (NPS) in California. A thermoacoustic cooler (STAR) developed in the NPS which was designed to transfer 4 W of heat at 80 C temperature difference on stack was mounted on the space shuttle *Discovery* [12] in 1992. Another thermoacoustic cooler (SETAC) that was supported by US Navy was mounted on USS Deyo for cooling Radar circuit elements in 1995. The system which was operating with helium-argon mixture as the working gas at 20 atm, supplied 419 W cooling performance by using 216 W acoustical power. The cooler supplied 17% of carnot efficiency at the lowest temperature (4C) it worked. Even though it could have been reached to the

26% of the Carnot's efficiency, the efficiency had been diminished because of the ineffectiveness of heat exchangers [13].

After the success of SETAC in USS Deyo, American Navy ordered a thermoacoustic cooler with cooling capacity of 10 KW. The cooler was designed at Penn State University and called TRITON since it could convert

Figure 2 : TRITON Cooler

three tons of water to ice at 0^oC in a day. TRITON project was initiated in 1996 and the design was completed in 1998. It was completed in 2005, and reached to 19% of Carnot cycle performance coefficient by using helium-argon gas mixture in 30 atm with 10 kW of cooling power. The cooler is seen in Figure 2. [14]

LANL performs mostly big sized industrial applications. In these applications acoustical power is produced using heat thermoacoustically. Then, either electricity or cooling power is produced using the acoustical power. One of the cooling systems constructed by LANL is thermoacoustically driven thermoacoustic cooler (TADOPTR). It was constructed in 1989, and it burns 30-40% of natural gas to produce acoustical power. Following that it uses this power to liquefy the rest of 60-70% of the natural gas. The system is cheap with no moving parts in it and it reaches to 115 K temperature.

Tijani, Zeegers and Waele nondimensionalized the parameters in the thermoacoustic equations and they offered a systematic approach to design a thermoacoustic cooler [15]. They designed, constructed and did the performance measurements of a thermoacoustic cooler. They used 10 bar helium gas as working gas and reached to -65C temperature.

Qiu et al. reached to 80 K with a thermoacoustically driven thermoacoustic cooler that used helium gas at 2.08 MPa. That was the lowest temperature that had been reached till that time [16].

There are also some studies in Turkey about thermoacoustics. Hoşöz and Özgüç made the power analysis of a thermoacoustic engine that they had constructed [17]. Girgin and Özgüç studied the pressure distribution inside the resonator, the effect of the frequencies near the resonance frequency and the stack position on the performance of a thermoacoustic cooler [18].

2. THERMOACOUSTIC EFFECT

Temperature oscillations related to pressure oscillations occur in acoustical waves. These effects create thermoacoustic interactions on a solid surface inside a gas that includes acoustical vibrations. Such effects also occur in daily life, but cannot be noticed since the temperature oscillations in air caused by a normal level sound is about the orders of 10^{-4} ^{o}C. Much more powerful waves are used in thermoacoustic systems to create heat transfer on the solid surfaces. The piston oscillates at a constant frequency in Figure 3a, where the other end of the cylinder is closed. As a result of pressure variations, the temperature of the gas also increases/decreases and heat is transferred between the gas and the neighboring solid surface. In Figure 3b, piston shifts to the right, and moves a rectangular-shaped gas particle to the right. The temperature of the particle increases as the pressure increases. In Figure 3c, the temperature of this gas particle gets higher than the

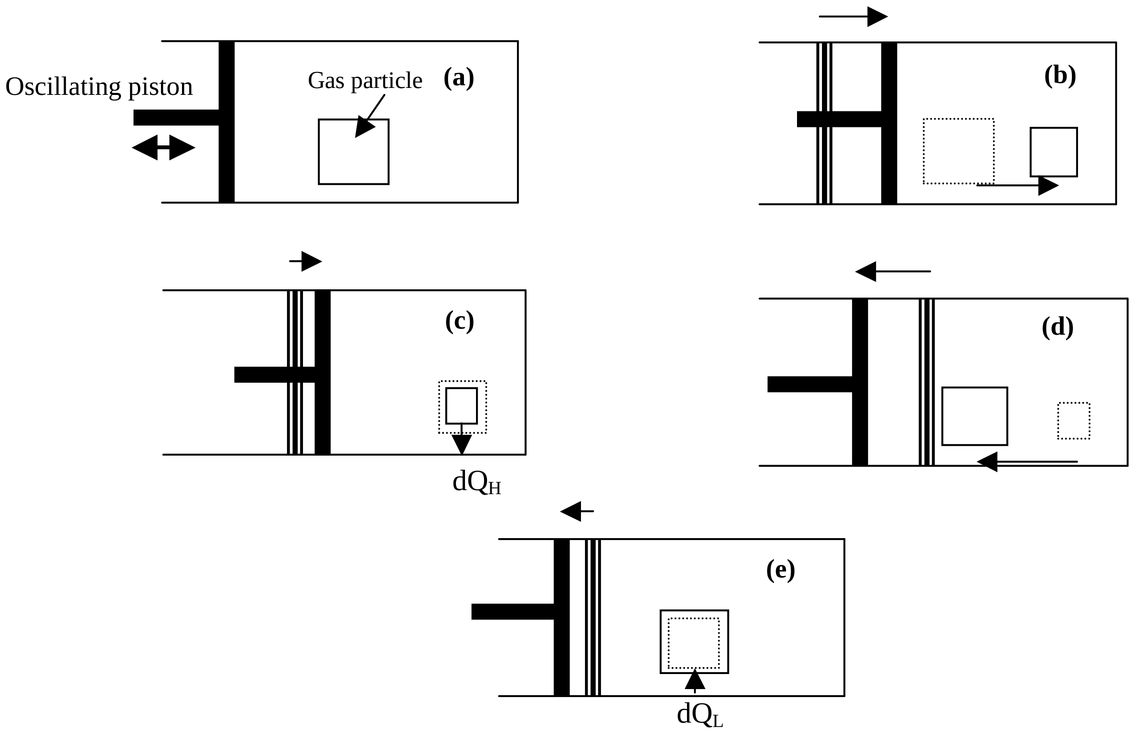

Figure 3 : Thermoaccoustic effect in an oscillating piston-cylinder system

temperature of the adjacent surface and heat is transferred to the solid surface from the gas particle. In Figure 3d, oscillating piston moves left and the temperature of the particle decreases as its pressure decreases. In Figure 3e heat is transferred from the surface to the particle since the gas particle has lower temperature. The whole particles near the wall act in the same way and heat is transferred from left to right. As a result, a temperature gradient from left to right is created. The interaction between the gas particle and the surface occurs in a narrow region that is called *thermal penetration depth* which is at the order of millimeter.

In thermoacoustic coolers, a piston/speaker system or a thermoacoustically driven thermoacoustic engine is used to create acoustical oscillations.. There is more than one stack in thermoacoustically driven thermoacoustic coolers because acoustical oscillations are created in one of the stacks by applying heat, and these oscillations are used in another stack to create cooling effect. The frequency of the acoustical wave is arranged to make it equal to the frequency of the oscillating gas. So resonance occurs, and the tube is called as *Resonator* or *Resonance Tube*.

The thermal penetration depth, δ_k is at the order of millimeter. So heat transfer area has to be augmented for practical use of the cooler. For this reason, a component named *stack* is used. Stack is made of parallel plates whose distance between the plates is at least twice of thermal penetration depth. As the speaker works, a temperature distribution in the stack is formed as a result of heat that is transferred from one side of the stack to the other side. Heat exchangers are used on both sides of the stack, and cooling is provided on the cooling side of the stack, and heat is transferred to the environment on the other side. A simple thermoacoustic cooler and velocity and pressure distributions inside the system is seen in Figure 4. Assume that there is an acoustical source inside the system. As *Velocity node,* where the velocity of the particles are zero, occurs at the two ends of the tube, *Velocity antinode,* where the velocity oscillation is maximum, occurs at the center of the tube. The maximum pressure amplitude, *pressure antinode,* occurs at both ends of the tube, and *pressure node*, where there is no pressure oscillation, occurs at the center of the tube.

To be able to understand thermoacoustic effect better, the behaviours of a particle moving inside an acoustical oscillation between the plates that have a temperature distribution ∇T_m will be investigated.

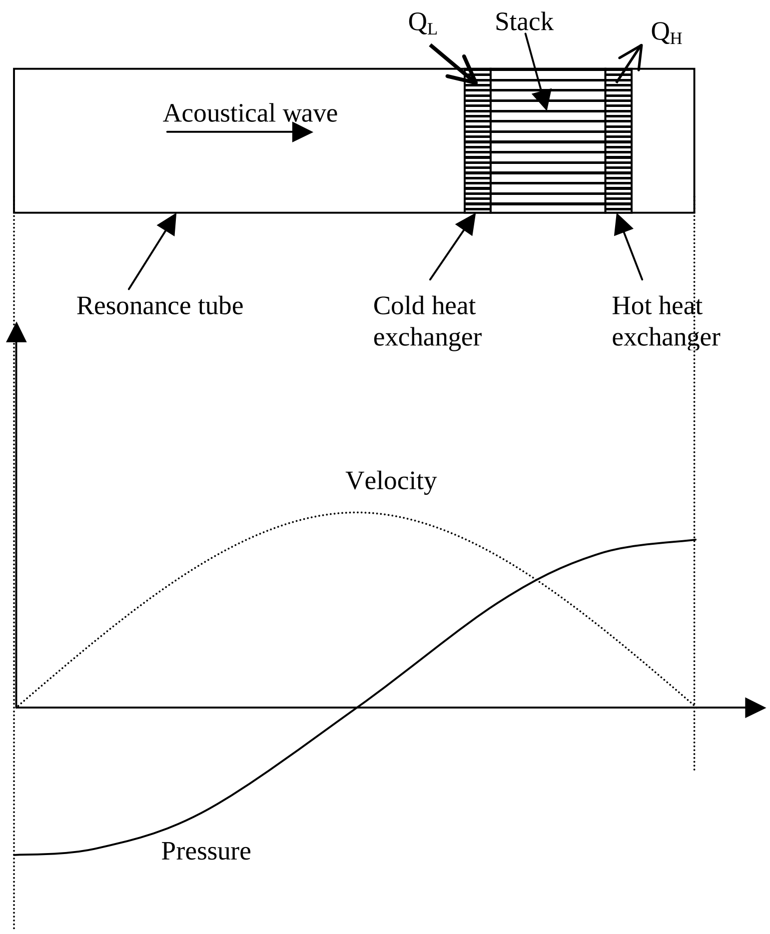

Figure 4 : Velocity and pressure distributions inside a simple system

The direction of heat in Figure 5b and Figure 5d determines whether the system is a heat pump or a heat engine. In Figure 5 (a), as the fluid particle moves, the temperature of the particle increases due to the increase in pressure. Two temperatures are important for this travelling particle: The temperature after adiabatic compression and the surface temperature adjacent to the particle after compression. If the particle temperature is greater than the surface temperature, heat is transferred to the surface from the particle. If there is a temperature gradient applied to the surface and the temperature of particle is lower than that of the surface, heat will be transferred at the reverse direction. These two different situations determine whether the system works as a heat pump or a heat engine.

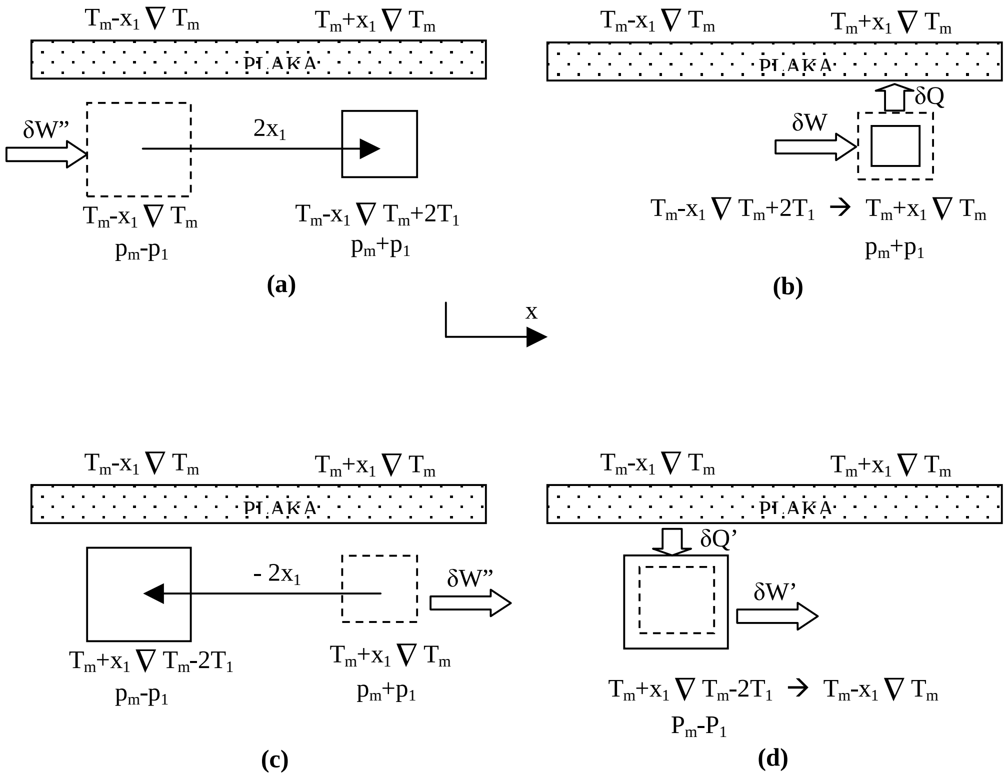

Figure 5 : Temperature and pressure oscillations of a particle inside a heat pump [19]

In Figure 5b, as the temperature of the fluid particle moving to the right is higher than that of the surface, heat is transferred to the surface. In Figure 5c, the pressure of the particle declines, and the temperature of the particle declines for $2T_1$ as a result. In Figure 5d, the temperature of the particle is lower than that of the surface, and heat is transferred from the surface to the particle. So there is a clear heat transfer in +x direction by the particle. [19].

The displacement of the particle is usually shorter than the length of the stack. Therefore, heat is transferred from one end to the other end by many particles side by side. The heat extracted by a particle is equal to the heat given to that point a half cycle ago[20]. The plates are used to store heat temporarily. In Figure 6, it is seen how the heat is carried by the fluid particles. As a result of heat transfer towards the pressure antinode, the plates at the pressure node are cooled, and the pressure antinode side is heated. The heat at this side is emitted to the environment, and the side which is being cooled is used for cooling. The transfer of heat on the plates from one end to the other occurs in thermal penetration depth. The particles in the region outside of thermal penetration depth are compressed and expanded adiabatically and reversibly.

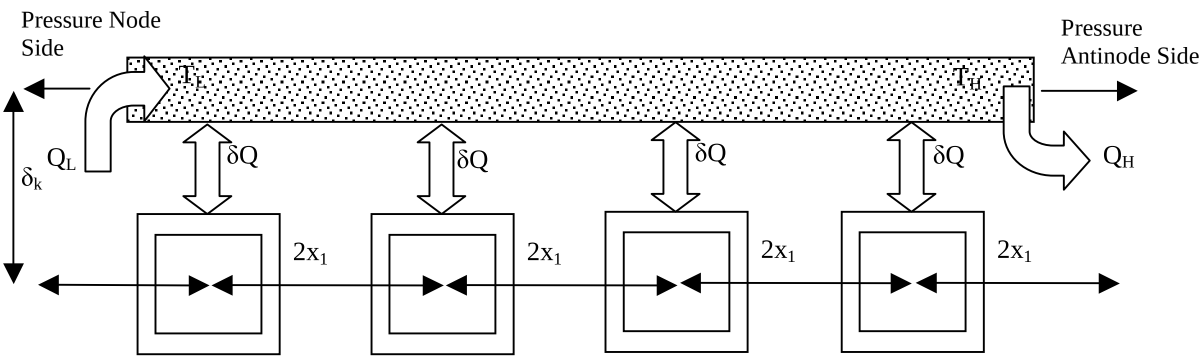

Figure 6 : The transfer of heat on the stack plates from one side to the other.

The thermal penetration depth, δ_k can be defined as the thickness of gas that the heat is penetrated into from the surface in the time period $1/\omega$ [19]:

$$\delta_k = \sqrt{\frac{2\kappa}{\omega}} \quad \textbf{(1)}$$

where $\kappa = K/\rho_m c_p$ is thermal diffusivity, $\omega = 2\pi f$ is angular frequency, K is thermal conductivity. δ_k is about 0.3 mm in the atmospheric air at 300 K temperature and 100 Hz frequency.

3. TERMOACOUSTIC SYSTEM COMPONENTS

3.1 Gas

The heat that is carried on stack is proportional to expression $p_m aA$ [21], where p_m is average gas pressure, a is sound velocity in gas, and A is the cross-sectional area of stack. Then the cooling power is proportional to average gas pressure p_m inside the system.

The thermal penetration depth can be written as:

$$\delta_k = \sqrt{\frac{2\kappa}{\omega}} = \sqrt{\frac{2K}{\rho_m c_p \omega}}$$

It is seen in the equation that as the density gets higher as a result of increase in pressure, the thermal penetration depth decreases. Then constructing the stack gets harder since δ_k gets smaller.

Cooling power is also proportional to sound velocity in gas. The higher is the sound velocity, the larger is the cooling power. The sound velocity in gases like hydrogen and helium is high. Since helium also has a high thermal conductivity, it is an appropriate gas to be used in these systems. As the thermal conductivity of gas gets higher, the heat transfer between the fluid particles and the stack plates gets easier. Therefore the thermal penetration depth increases with thermal conductivity and building the stack gets easier.

Hydrogen also has good properties for using in thermoacoustic systems. But it should be used carefully since it is flammable.

Some types of heavy gases like argon and xenon are blended with helium to increase efficiency. A small portion of these types of gas increases the Prandtl number. As the result, the friction between the gas and the solid surfaces inside the system decreases and coefficient of performance of the system increases. As an example, the blending of 20% xenon inside helium decreases the Prandtl number from 0.67 to 0.2. As the result, the efficiency of the system increases. But since the sound velocity of these gases are lower than that of helium, the resultant sound velocity gets smaller and the cooling power of the system decreases.

3.2 Stack

Stack is the most important part of a thermoacoustic system. The transfer of heat from a low temperature to high temperature heat source occurs on the stack plates. As the heat is carried towards to the pressure antinode by the working gas, it is temporarily stored on stack. The heat transfer between the gas and the plate occurs inside the thermal penetration depth. To get a high amount of cooling power from a system, a great heat transfer area should be used. Therefore stack is made of many parallel plates that have a distance between about $2\delta_k$ to $4\delta_k$.

The cooling power of a thermoacoustic system is also proportional to p_1u_1 where p_1 is pressure amplitude and u_1 is velocity amplitude [19]. Therefore there will not be cooling at the points where pressure amplitude or velocity amplitude is zero. So the stack should not be at these positions to be able to get cooling. The stack should be at an appropriate position between pressure and velocity nodes. As the stack gets closer to velocity antinode, the coefficient of performance decreases because of the frictions. To get a high performance coefficient, stack should be close to pressure antinode where the velocity oscillations are low. But it causes the cooling power to be low. So the stack should be positioned at an appropriate point by taking into account both the coefficient of performance and the cooling power.

As the heat is carried by the working gas on stack from one end to the other, it also happens an opposite heat conduction on stack from high to low temperature which decreases the performance of the system. To minimize this effect, the thermal conductivity of the stack should be low like heat resistant plastic, paper or metal with low conductivity [21].

Stack can be prepared in many types. A spiral type of stack is seen in Figure 7. There should be enough distances between the parallel plates forming the stack.

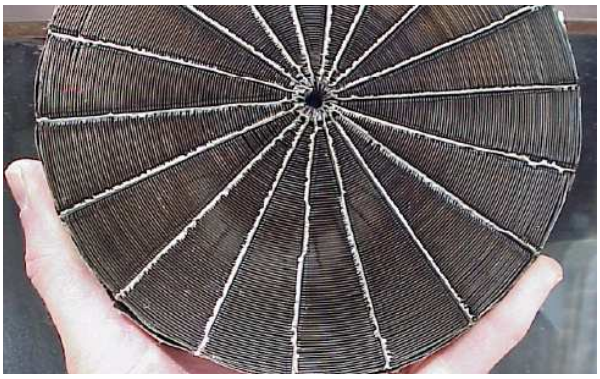

Figure 7: A stack made of steel with 0.4 mm distance between the plates[21]

3.3 Heat Exchangers

Heat exchangers which are placed at both ends of the stack provide heat transfer with the environment. The thermal conductivity of heat exchanger material should be as high as possible. Copper has a high thermal conductivity, and it is a good heat exchanger material. Heat exchangers are made of parallel plates like stack. It should be noticed not to obstruct gas oscillations when they are placed near stack.

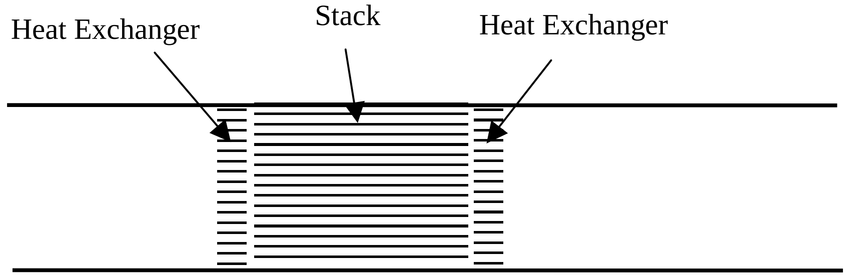

Figure 8 : The positions of stack and heat exchangers

The positions of the stack and heat exchangers are seen in Figure 8. The heat transfer by the fluid particles between the stack and the heat exchangers are seen in Figure 9. Three particles that transferring heat are seen in the figure. While the particle 1 carries heat from the left heat exchanger to the stack, the particle in the middle carries heat on the stack from left to right. The particle 3 transfers heat from stack to the right heat exchanger. Since the amplitude of the displacement of the particle is $x_1 = \frac{u_1}{\omega}$, the length of the heat exchanger should be $2x_1 = \frac{2u_1}{\omega}$ at that position, where x_1 is the amplitude of displacement, u_1 is the amplitude of velocity and *w* is angular frequency.

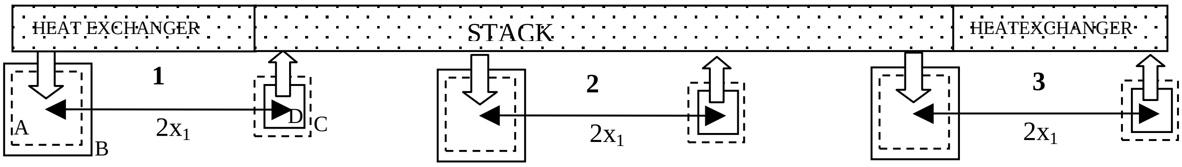

Figure 9 : The transfer of heat between the stack and the heat exchangers

3.4 Resonance Tube

Resonance tube covers stack, heat exchangers, acoustical source and working gas. The most common resonance tubes are $\lambda/2$ and $\lambda/4$ length resonance tubes, which are the half length and quarter length of wavelength. The gas inside the resonance tube can be thought as three different parts: The first part of the fluid is adjacent to the plates and transfers heat. The second part is very close to inside surface of the resonance tube, and has dissipative effects. The rest of the particles are adiabatically compressed and expanded. To reduce the dissipative effects inside the resonance tube, $\lambda/4$ length tube can be used instead of $\lambda/2$ length tube. Some types of resonance tubes are seen in Figure 10.

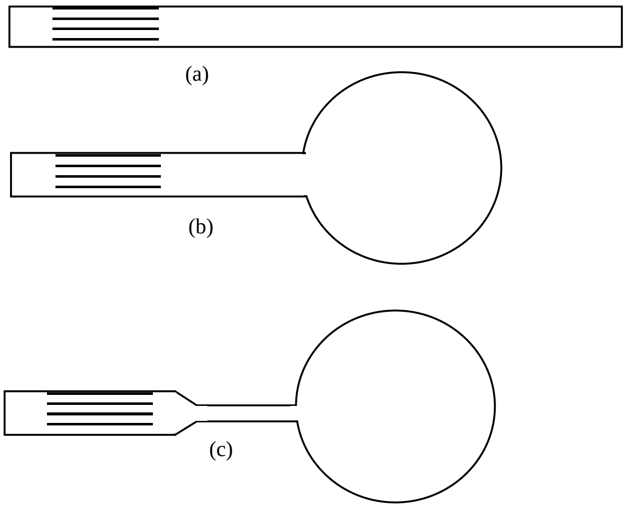

Figure 10 : Some types of resonance tubes

A half wavelength length resonance tube is seen in Figure 10a while a quarter wavelength length tube is in Figure 10b. A Hofler resonance tube is seen in Figure 10c. Since the Hofler resonance tube has the smallest area, the losses in this system are the lowest. These types of tubes are commonly used in thermoacoustic systems

3.5 Acoustical Source

Thermoacoustic coolers need an acoustical source to drive the system and to transfer heat. As well as the system can produce acoustical power itself, it can also use an external acoustical source, such as a speaker. Electroacoustical efficiency represents the ratio of sound produced to electricity used. The efficiency of commercial speakers that you can buy from an ordinary store is usually about 4-5%. That means as the speaker use a hundred units of electricity, it can only convert 4-5 units to pressure waves while the rest 95% is converted to heat. Therefore specially designed high efficient acoustical sources are used in thermoacoustical systems. The efficiency of SETAC thermoacoustic cooler has reached upto 80%. The higher the electroacoustical efficiency, the more coefficient of performance you get from the system. Tijani has showed that while the resonance frequency of the speaker gets closer to the working frequency of the system, the acoustical efficiency of the speaker gets higher [22].

4. THE ADVANTAGES AND DISADVANTAGES OF THERMOACOUSTIC SYSTEMS

4.1 Advantages

The biggest advantage of a thermoacoustic system is that its structure is very simple and it has no moving parts. While a conventional cooling system is drived by a gas compressor, thermoacoustic systems do not have such a compressor. In thermoacoustically driven thermoacoustic coolers, the acoustical wave needed is produced by a stack applying a temperature difference on it. Then the acoustical wave is used on another stack for cooling. These types of systems have no moving parts. But while the system is driven with electricity, then the pressure waves are created by an external acoustical source, such as a speaker.

Since the structures of thermoacoustic systems are simple, their initial costs are lower than the conventional coolers. They can be preferred to conventional coolers if the initial cost is much more important than the efficiency.

By using simple thermoacoustic coolers, cryogenic temperatures can be reached easily. Qiu et al. has reported that they reached to 80 K by using a thermoacoustically driven thermoacoustic cooler with a working gas of helium at 2.08 MPa.

One of the biggest advantage of a thermoacoustic system is that they do not use harmful gases for the atmosphere. Helium is commonly used in thermoacoustic systems for having these advantages. It can also be used with the mixtures of other noble gases, like neon, argon, xenon etc., to increase efficiency.

3.2 Disadvantages

The biggest disadvantage of thermoacoustical coolers is their coefficient of performance are lower than the conventional coolers. But more efficient systems are tried to be made. Another disadvantage is that these systems are too noisy, but using a proper sound isolation, this disadvantage can be overcome.

5. RESULTS AND DISCUSSION

Many scientists have done researches on thermoacoustics worldwide. Many prototypes of thermoacoustical coolers have been constructed until today. There are also some commercial systems produced. These systems which are simple, at low initial cost, not harmful for the environment get the interests they deserve. If their coefficient of performance gets higher in the future, they can be commonly used in everywhere as an alternative to the conventional coolers. There are also some studies on these systems in our country., but they are not enough. The studies should be increasingly continued.

REFERENCES

[1] Sondhauss, C., Ueber die Schallschwingungen der Luft in erhitzten Glasröhren und in gedeckten Pfeifen von ungleicher Weite, Ann. Phys., 79, 1,1850.

[2] Rijke, P. L., Notiz über eine neue Art, die in einer an beiden Enden offenen Röhre enthaltene Luft in Schwingungen zu versetzen, Ann. Phys., 107, 339,1859.

[3] Lord Rayleigh, The Theory of Sound, 2nd ed., Vol.2, Sec.322, Dover, Newyork, 1945.

[4] Carter, R.L., White, M. and Steele, A.M., (Private communication of Atomics International Division of North American Aviation, Inc.), 1962.
[5] Feldman, K.T., A study of heat generated pressure oscillations in a closed end pipe, PhD Thesis, University of Missouri, 1966.
[6] G. Kirchhoff, Ueber den Einfluss der Warmeleitung in einem Gas auf die Schallbewegung, Ann. Phys., 134, 177, 1868.
[7] Rott, N., Thermoacoustics, Adv. Appl. Mech., 20, 135, 1980.
[8] Yazaki, T., Tominaga, A., and Narahara, Y., Experiments on Thermally Driven Acoustic Oscillations of Gaseous Hellium, Jour. Low Temp. Phys., 41, 42-52, 1980.
[9] Müller, A. and Lang, E., Experimente Mit Thermisch Getriebenen Gas-Flüssigkeits-Schwingungen, Z. Angew. Math. Phys., 36, 358-360, 1985.
[10] Hofler, T.J., Thermoacoustic refrigerator desing and performance, PhD Thesis, Physics Department, University of California, San Diego, 1986.
[11] Gifford, W.E. and Longsworth, R.C., Surface heat pumping, Adv. Cryog. Eng.,11, 171, 1966.
[12] Garret, S.L., Adeff, J.A. and Hofler T.J., Termoacoustic refrigerator for space applications, J.Thermophysics and Heat Transfer, 7, 595, 1993.
[13] Ballister, S. C. and McKelvey, D. J., Shipboard Electronics Thermoacoustic Cooler, Master of Science Thesis, Physics Department, Naval Postgraduate School, Monterey, 1995.
[14] Johnson, R. A., Garrett, S. L., and Keolin, R. M., Thermoacoustic Cooling for Surface Combatants., Naval Engineers Journal, 112, 335, 2000.
[15] Tijani, M.E.H., Zeegers, J.C.H. and de Waele, A.T.A.M., Design of thermoacoustic refrigerators, Cryogenics, 42, 49-57, 2002.
[16] Qiu, L.M., Sun, D.M., Yan, W.L., Chen, P., Gan, Z.H., Zhang, X.J. and Chen, G.B., Investigation on a thermoacoustically driven pulse tube cooler working at 80 K, Cryogenics, 45, 380-385, 2005.
[17] Hoşöz, M., Termoakustik Güç Üretiminin Analizi, Doktora Tezi, İstanbul Teknik Üniversitesi, 1998.
[18] Girgin, İ., Özgüç, A.F., Termoakustik Soğutucu Analizi, İtü Dergisi, Vol.8, Sayı.2, 81-92, 2009.
[19] Swift, G.W., Thermoacoustic Engines, J. Acoust. Soc. Am., 84, 1145-1180, 1988.
[20] Swift, G.W., Analysis and performance of a large thermoacoustic engine, J. Acoust. Soc. Am., 92, 1551-1563, 1992.
[21] Swift, G.W., Thermoacoustics: A Unifying Perspective For Some Engines and Refrigerators, 5th Draft, Condensed Matter and Thermal Physics Group, Los Alamos National Laboratuary, 2001.
[22] Tijani, M.E.H., Loudspeaker-driven thermo-acoustic refrigeration, Ph.D.Thesis, Technische Universiteit Eindhoven, 2001.