Journal of Research High School

Volume 2022 (1) 7 - 13
ISSN 2688-3651 [online]

Utilization of Thermoacoustics in Developing Energy-Efficient Cooling Technology

Andrew Kim[1*], Caroline Sheffet[1]

[1] Montclair Kimberley Academy, Montclair, New Jersey USA

Received June 11, 2021; Revised February 3, 2022; Accepted, February 7, 2022

Abstract

The considerable amount of energy required to run modern-day air conditioning systems results in the emission of potent greenhouse gases, which poses various potential environmental and health risks. To provide a solution to the disadvantages of standard air conditioning, this paper observes the harmful effects standard air conditioning has on the global environment and describes the development of a possible solution, thermoacoustic technology, which would provide a cleaner method of cooling. It was determined that thermoacoustic cooling technology utilizes the motion of sound waves in a contained environment to allow for the transfer of heat within the device. This paper provides a thorough description of the design and development of thermoacoustic cooling technology, including an explanation of what would physically occur within the system as it operates by analyzing the sound waves and heat transfer; the materials needed to build the structure; and how the materials would be incorporated to create this environmentally clean technology.

Keywords: Thermoacoustics, Air Conditioning, Thermoacoustic Cooling

1. Introduction

1.1 Health Risks Associated with High Temperatures

Heat waves are defined as sustained periods of abnormally excessive heat. Heat waves are considered by the World Health Organization to be one of the most hazardous natural dangers because they pose many threats to human health such as blood clots, acute cerebrovascular accidents, severe dehydration, heat exhaustion, and heat stroke. Heat stroke symptoms include faintness, headaches, swelling, heat rash, lack of energy and weakness, cramps, irritability, and dry, warm skin. Overheating can even lead to death. The World Health Organization reported more than 166,000 deaths globally due to heat waves between 1998 and 2017 (Heatwaves, n.d.). According to the Centers for Disease Control and Prevention (CDC), from 2004 through 2018, heat-related conditions caused 10,527 deaths in the United States (Vaidyanathan et al., 2020, pp. 729-734). Statistical approaches approximate that extreme heat causes more than 1,300 deaths in the United States per year (Climate Change, 2020). A heat wave that occurred in Europe in 2003 led to more than 70,000 deaths alone. Individuals younger than four or older than sixty-five years old, as well as those who routinely consume prescriptions, are most vulnerable to heat waves and have higher chances of dying or experiencing health complications (Heatwaves, n.d.).

* Corresponding Author
andrewjkim2020@gmail.com

Advisor: Dr. Jacquelyn Blum
jblum@mka.org

High temperatures pose immediately apparent health risks, such as heat stroke and heat-related illnesses; however, other less obvious health risks are often overlooked. For example, heat increases the risk of triggering heart conditions, such as heart attacks and respiratory diseases, like pneumonia. As a result, scientists predict that death reports vastly underestimate those related to excess heat exposure (Climate Change, 2020). Several studies suggest that many "heat-related" deaths are not being recorded as such and thus are missing from the calculation, making it difficult to fully interpret data. Data that is available, however, demonstrates that a substantial increase in the occurrence of hot temperatures and heat waves is closely linked to the vast rise in heat-related deaths (Vaidyanathan et al., 2020, pp. 729-734).

1.2 Environmental Effects of Air Conditioning

As a result of global warming, heat exposure is increasing in frequency, duration, and magnitude globally. From 2000 to 2016, population exposure to heat waves increased by around 125 million people (Heatwaves, n.d.). As displayed in the graph, 2006 was one of the hottest years on record in the United States with frequent heat waves, correlates with many more heat-related deaths (Vaidyanathan et al., 2020, pp. 729-734).

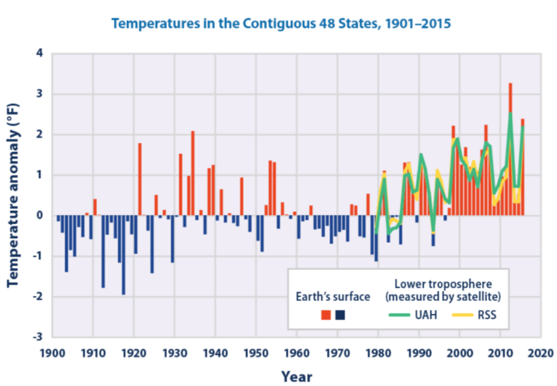

Figure 1. Data Source: Climate Change Indicators: Heat-Related Deaths. (2020, November 2). United States Environmental Protection Agency. Retrieved April 21, 2021, from https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths#:~:text=Some%20statistical%20approaches%20estimate%20that,set%20shown%20in%20Figure%201.

From the 1960s to the 2010s, across 50 metropolitan areas, the mean number of heat waves increased from 2 to 6 per year, and the heat wave season increased by 47 days; 92% of these 50 cities saw a rise in the occurrence of heat waves, and 88% experienced elongated seasons (U.S. Environmental Protection Agency, 1961-2018). These effects are more obvious in metropolitan areas; however, per the urban heat island effect, non-urban communities are also harmed by unusually high temperatures. For instance, heat waves place a strain on energy, transportation, water and food supplies, human health, and emergency services (Heatwaves, n.d.). The Earth continuously warms and heat waves become more frequent. Throughout this cycle, air conditioning remains the standard cooling technology to accommodate rising temperatures, but it also poses a serious threat to the environment by contributing to global warming.

Air conditioners often emit harmful by-product gasses because they run on electricity, which is commonly generated by burning fossil fuels. By 2050, some studies predict, a quarter of global warming will be as a result of this process air conditioning operates on (Mize, n.d.). According to Daikin, the largest selling air conditioning company in the world, air conditioning units require large amounts of energy; the refrigerants destroy the ozone layer and worsen global warming (Response to Climate, n.d.). Before the year 2010, air conditioners constantly emitted hydrochlorofluorocarbons (HCFCs), which are proven to deplete the ozone layer. In 2010, the production, use, and import of HCFCs was banned, with the exception of necessary use for the servicing of existing equipment. As a result, since 2010, Hydrofluorocarbons (HFCs), which do not break down the ozone layer, are the primary refrigerant that air conditioning systems require to operate. Although HFCs do not harm the ozone layer, they are still much more potent greenhouse gases than CO_2 (Phasing out HCFC, 2015). HCFC-22 ($CHClF_2$) and HFC-134a (CH_2FCF_3) are two very potent greenhouse gases that have been a very significant part of air conditioning systems worldwide. According to a study done by the Proceedings of the National Academy of Science of the United States of America (PNAS), the global excretion of these harmful gases has drastically increased over the last 20 years. Since 2000, HFC-134a emission levels consistently surpass the United Nations Framework Convention on Climate Change, even by 60% from the years 2009 to 2012 (Xiang et al., 2014). While HCFCs have been phased out over the past three decades, older air conditioning units are still leaking HCFC gas, and modern units that run on HFCs are still contributing to high energy use and greenhouse gas emissions (Phasing out HCFC, 2015). The banning of HCFCs marks progress towards a cleaner Earth, but HFCs are still easily and commonly leaked at any point in the air conditioning process from manufacturing, to installation, to disposal. R-407C and R-410A are among the most commonly used HFCs for air conditioners. Over a thousand times more potent than CO_2, the disastrous potential HFCs have on Earth's climate is often overlooked (Ospina, 2018).

One solution to the environmental problems resulting from current air conditioning methods is the use of thermoacoustics to provide a cleaner and safer alternative to standard cooling. The thermoacoustic system discussed in this paper requires no moving mechanical parts, no CO_2, no precious materials, and no refrigerants (Blain, 2019), thus serving as a more environmentally safe method of cooling.

2. Development of Thermoacoustic Cooling Technology

This study adopts the design of a standing-wave thermoacoustic refrigerator. Some benefits of thermoacoustic refrigeration include the use of environmentally friendly fluids (mediums) and relatively few moving components in development (Design and simulation of small capacity thermoacoustic refrigerator, 2019). The key parts of the device include heat exchanges, stack, resonator, and a source of energy to drive the device and enable for the transferring of heat energy.

2.1 Stand Waves and Wave Formation

Stand waves are the pattern result of a reflected wave interacting with waves sent from the energy source. This process occurs when both waves cross through a shared medium, the substance the wave is carried by (Formation of Standing Waves, n.d.). Two types of points exist within the stand wave pattern. The first is the node (Figure 2), a location with repetitive destructive wave interference (no displacement), and the second is the antinode, a location with repetitive constructive wave interference (maximum displacement). The properties of stand wave patterns allow for their formation in pipes and tubes. Due to the enclosed tubular design of the thermoacoustic cooling device, stand waves are able to be formed due to the continuous formation and reflection of waves to and from the direct source.

The consistent formation of waves inside the thermoacoustic device are dependent on the medium used and an energy/wave source. The vibration of an object or medium is the source of wave formation. It forces the particles of the medium to vibrate, and the resonance of such vibrations (ability of vibrating systems to force surrounding systems to vibrate) enables the formation of sound waves. As particles continue to vibrate, the waves are transmitted (Sound Waves in Air, n.d.).

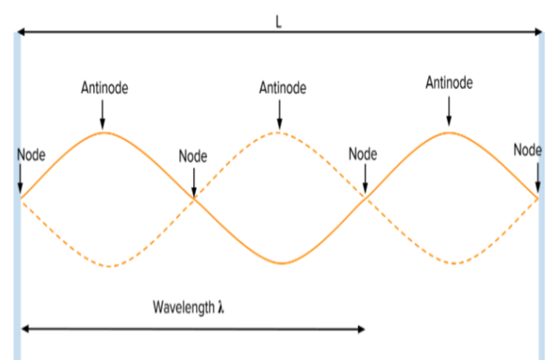

Figure 2. Visual Representation of stand wave and respective node/antinode points; nodes are regions of destructive interface as antinodes are regions of constructive interface (Stand waves review, n.d.).

2.2 Waves and Heat Transfer

The properties of sound waves allow for the transfer of heat within various components of the thermoacoustic cooling device. In air, sound waves are longitudinal waves where the displacement of the medium is parallel to the movement of the wave. Sound waves are also capable of forming pressure variations, allowing for the compression (constructive stand wave interface), rarefaction (destructive interference) and a back-and-forth motion of particles in the medium with respect to the direction of the sound (Sound Waves in Air, n.d.). This process of particle motion is critical for the thermoacoustic capabilities of the device design. When a gas medium is compressed and makes contact with a solid surface, heat is transferred from the gas to the surface. On the other hand, heat is released back to the gas molecules during rarefaction (An Overview of Stack Design for a Thermoacoustic Refrigerator, 2015). This oscillatory pattern is what drives the continuous withdrawal and replacement of heat within the solid surfaces of the thermoacoustic device, allowing for the transfer of thermal energy.

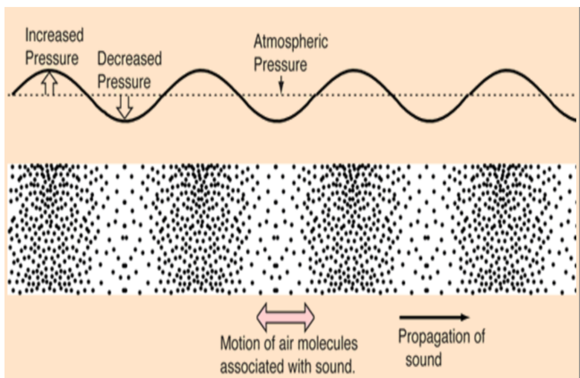

Figure 3. Representation of the compression and rarefaction of sound waves with respect to variations in pressure (Sound Waves in Air, n.d.).

2.3 Visualization of the theoretical product

The figure below (Figure 4) illustrates a sample design of a thermoacoustic cooler that was adapted for the purposes of the study.

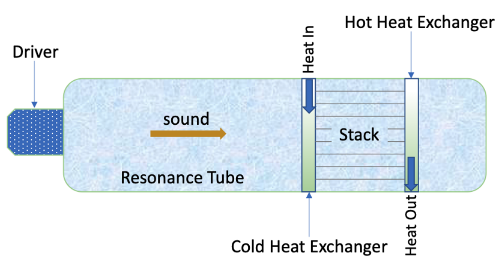

Figure 4. Simple diagram of a thermoacoustic cooler.

2.4 Resonator

The resonator or resonance tube is the location where wave oscillation occurs, specifically a standing wave pattern. Ultimately, it is the outermost component or shell of the thermoacoustic cooling system. The frequency and wave amplitude are each dependent on the design (geometry and dimensions) and material composition of the resonator. The resonance tube should be constructed with light yet durable material to resist the variation in pressure caused by sound wave oscillation (Measuring the performance of different stack materials in thermoacoustic device, 2015). In addition, the length of the resonator often depends on the wavelength of the acoustic wave and can influence the amount of energy lost within the system (Design and simulation of a small capacity thermoacoustic refrigerator, 2015). The resonator is filled with the gas medium and surrounds the stack and heat exchangers, which will be described in the subsequent sections.

2.5 Stack

The stack is responsible for the movement of heat. Both a stand wave pattern and the design of the stack are critical to ensure the transfer of heat from the cold end of the stack to the hot end of the stack (The Reality of a Small Household Thermoacoustic Refrigerator, 1996). Stacks can vary in geometries, such as spiral or pin-array type, but a commonly used design is parallel plate stacks. In the most favorable circumstances, the stack would be produced from material with a low thermal conductivity, compared to the used medium, to avoid heat being conducted back to the cold end of the stack. Literature states that Mylar, a polyester film, is a widely used material used for thermoacoustics due to its low thermal conductivity (An Overview of Stack Design for a Thermoacoustic Refrigerator, 2015). The material of the stack is the solid surface where heat exchange occurs with the compression and rarefaction of waves, as described previously.

When the medium and stack surface make contact, the thermal penetration depth must also be considered to determine an optimal spacing between stacks. Thermal penetration is the depth at which heat can diffuse through a gas. Research concludes that an effective plate spacing length is about 0.3 mm or roughly three times the thermal penetration depth (The optimal stack spacing for thermoacoustic refrigeration, 2002).

2.6 Heat exchangers

There are two heat exchangers in thermoacoustic cooling technology, a hot and cold exchange. They are placed on opposite ends of the stack and are responsible for moving heat in and out of the stack and its surroundings. Heat is pumped from the cold exchanger to the hotter one through the stack. Relative to the design, the cold exchanger is to be set adjacent to the resonator. To ensure the hot changer does not absorb too much heat, it should be able to release excess heat through water cooling (Design of thermoacoustic refrigerators, 2001).

2.7 Source of sound

A driver is required to create the waves inside the resonator medium and allow for the formation of stand waves and, thus, the transfer of heat through the stack. One source would be a loudspeaker. To mimic the process of refrigeration, the end of the loudspeaker should be sealed to the device to avoid leakage (An Overview of Stack Design for a Thermoacoustic Refrigerator, 2015). A standard practice in acoustic technology is implementing a quarter wavelength.

2.8 Choice of Medium

Optimal conditions for the medium gas inside the resonator of which the sound waves pass through include high sound velocity and thermal conductivity to allow for a smooth flow of heat transfer. Helium is an effective medium commonly used for thermoacoustic devices because its low density correlates to a higher thermal conductivity and allows sounds to pass through quicker. Air is less effective than helium but still serves well as a significantly cheaper and accessible substitute that can be mixed with other non-flammable inert gases like argon (Measuring the performance of different stack materials in thermoacoustic device, 2015).

3. Discussion

Upon researching the necessary components of a thermoacoustic refrigerating device, a theoretical model for a thermoacoustic cooler would be composed of the following materials. A tubular resonator that fits the disk shape of a loudspeaker would serve as the outermost layer of the cooler. A stack composed of a series of evenly spaced, parallel Mylar plates would fit inside the resonator. Two cylindrical steel lids with steel fins would serve as effective hot and cold heat exchangers, and would be inserted at both ends of the stack system within the resonator (Development of a thermoacoustic heat pump for distillation column, 2017).

We recognize the development and implementation of an actual thermoacoustic cooling device is a costly procedure and have, therefore, deemed it not yet suitable for domestic and personal use. We believe that the cooling technology will serve best in corporations or large infrastructures with regards to affordability and increased energy efficiency, targeting those that require a substantial amount of energy for daily operations and/or are located in hot climate regions. Given our preliminary design of a thermoacoustic cooler, our future goals involve analyzing more optimal conditions for this device including seeking less expensive alternatives to helium and determining the optimal stack spacing given the thermal penetration depth of various gas mediums. Although, this type of technology is not widely affordable at its current state, it has potential to become a standard household application while maintaining the same cooling properties as standard air conditioning. Thermoacoustics is a growing field of science and much is yet to be uncovered; we are hopeful that the development of a thermoacoustic device will revolutionize the cooling industry and provide an alternative and cleaner method of cooling.

Acknowledgements

We would like to thank Gianna Zou for helping with our research and Dr. Jacquelyn Blum, MKA, Montclair for being our advisor.

References

Bartos, D., Kurzbach, S., Filipiak, Z., & Petro, M. (2015). Measuring the performance of different stack materials in thermoacoustic device. Roskilde University.

Bhansali, P. S., Patunkar, P. P., Gorade, S. V., Adhav, S. S., & Botre, S. S. (2015). An Overview of Stack Design for a Thermoacoustic Refrigerator, International Journal of Research in Engineering and Technology, 04(06), 68-72. https://ijret.org/volumes/2015v04/i06/IJRET20150406010.pdf

Blain, L. (2019, January 25). Electricity-free air con: Thermoacoustic device turns waste heat into cold using no additional power. New Atlas. Retrieved April 25, 2021, from https://newatlas.com/soundenergy-thermoacoustic-cooling/58169/

Climate Change Indicators: Heat-Related Deaths. (2020, November 2). United States Environmental Protection Agency. Retrieved April 21, 2021, from https://www.epa.gov/climate-indicators/. climate-change-indicators-heat-related-deaths#:~:text=Some%20statistical%20approaches%20estimate%20that,set%20shown%20in%20Figure%201

Formation of Standing Waves. (n.d.). Physics Classroom. https://www.physicsclassroom.com/class/waves/Lesson-4/Formation-of-Standing-Waves

Heatwaves. (n.d.). World Health Organization. Retrieved April 25, 2021, from https://www.who.int/health-topics/heatwaves#tab=tab_1

Kajurek, J., Rusowicz, A., & Grzebielec, A. (2019). Design and simulation of a small capacity thermoacoustic refrigerator. SN Applied Science. https://link.springer.com/content/pdf/10.1007/s42452-019-0569-2.pdf

Mize, D. (n.d.). Do Air Conditioners Cause Any Harm to the Environment? Masters Heating and Cooling Inc. Retrieved April 25, 2021, from https://mastersheatcool.com/blog/do-air-conditioners-cause-any-harm-to-the-environment/

Nave, R. (n.d.). Sound Waves in Air. HyperPhysics. http://hyperphysics.phy-astr.gsu.edu/hbase/Sound/tralon.html

Ospina, C. (2018, August 7). Cooling Your Home but Warming the Planet: How We Can Stop Air Conditioning from Worsening Climate Change. Climate Institute. Retrieved April 25, 2021, from https://climate.org/cooling-your-home-but-warming-the-planet-how-we-can-stop-air-conditioning-from-worsening-climate-change/

Phasing out HCFC refrigerants to protect the ozone layer. (2015, July). United States Environmental Protection Agency. Retrieved April 27, 2021, from https://www.epa.gov/sites/production/files/2015-07/documents/phasing_out_hcfc_refrigerants_to_protect_the_ozone_layer.pdf

Response to Climate Change. (n.d.). Daikin Global. Retrieved April 25, 2021, from https://www.daikin.com/csr/environment/climatechange/ #:~:text=Air%20 conditioners%20consumer%20large%20amounts,and%20contribute%20to%20global%20warming

Review of investigation in eco - friendly thermoacoustic refrigeration system. (2017). A. Raut, U. Wankhede. Retrieved from https://www.semanticscholar.org/paper/Review-of-investigations-in-eco-friendly-system-Raut-Wankhede/93a58b81734b90012ee9d9627dbc6927760b5f59

Starr, R., Bansal, P.K., Jones, R. W., & Mace, B. R. (1996). The Reality of a Small Household Thermoacoustic Refrigerator. Purdue e-Pubs. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1343&context=iracc

Tijani, H., Lycklama á Nijeholt, J.A., & Spoelstra, S. (2017). Development of a thermoacoustic heat pump for distillation column. IEA. http://hpc2017.org/wp-content/uploads/2017/05/O.3.7.5-Development-of-a-thermoacoustic-heat-pump-for-distillation-column.pdf

Tijani, H., Zeegers, J., & De Waele, A. (2001). Design of thermoacoustic refrigerators. Cryogenics

Tijani, H., Zeegers, J., & De Waele, A. (2002). The optimal stack spacing for thermoacoustic refrigeration. The Journal of the Acoustical Society of America, 112(1), 128 - 133. DOI:10.1121/1.1487842

Standing waves review. (n.d.). Retrieved June 15, 2021, from https://www.khanacademy.org/science/high-school-physics/waves-and-sound/standing-waves-2/a/standing-waves-review-ap

U.S. Environmental Protection Agency. (1961-2018). U.S. heat wave frequency and length are increasing. U.S. Global Change Research Program. Retrieved April 25, 2021, from https://www.globalchange.gov/browse/indicators/us-heat-waves#:~:text=1.,per%20year%20during%20the%202010s

Vaidyanathan, A., Malilay, J., Schramm, P., & Saha, S. (2020). Heat-Related Deaths — United States, 2004–2018. Morbidity and Mortality Weekly Report, 729-734. http://dx.doi.org/10.15585/mmwr.mm6924a1

Xiang, B., et al. (2014). Global Emissions of Refrigerants HCFC-22 and HFC-134a: Unforeseen Seasonal Contributions. National Academy of Sciences, 111(49), 17379-17384. https://doi.org/10.1073/pnas.1417372111