DESIGN AND THERMAL ANALYSIS OF THERMO ACCUSTIC REFRIGERATOR

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ABSTRACT

The design and functionality of thermo-acoustic refrigerator have been the focus of considerable attention from the research community since 1980. This environmental friendly technology has the potential to replace conventional refrigerator once the improvements in design and technology are realized. Thermo-acoustic is a term used to describe the effect arising from sound waves creating a heat gradient, and vice versa.In this paper, a typical modified thermo-acoustic refrigerator (TAR) consisting of acoustic driver (loudspeaker), resonator tube, thermocouple, stack, and a heat exchanger is designed. The effects of some design parameters such as wave patterns, frequency, and heat exchanger of thermo-acoustic refrigerator system were studied. It was found that a sine wave pattern lead to superior cooling effects compared to other wave patterns tested. Also adding the heat exchanger contributes significantly in increasing the temperature drop achieved by the modified TAR. Thermal analysis to determine the heat flux and temperature distribution for different materials (glass for tube, copper for heat exchangers, stack for Mylar sheet) different models(tube with spiral type stack, spiral type stack with blower type tube and square tube with square type stack). 3D modeling of thermo acoustic refrigerator in CATIA. Analysis in ANSYS.

Keywords: CATIA, ANSYS, TAR, thermo acoustic, gas, thermal analysis, TAE.

I INTRODUCTION

One ordinarily thinks of a sound wave as consisting only of coupled pressure and position oscillations. In fact, temperature oscillations accompany the pressure oscillations and when there are spatial gradients in the temperature oscillations, oscillating heat flow occurs. The combination of these oscillations produces a rich variety of "thermo acoustic" effects. In everyday life, the thermal effects of sound are too small to be easily noticed; for example, the amplitude of the temperature oscillation in conversational levels of sound is only about 0.0001°C. However, in an extremely intense sound wave in a pressurized gas, these thermo acoustic effects can be harnessed to create powerful heat engines and refrigerators. Whereas typical engines and refrigerators rely on crankshaft-coupled pistons or rotating turbines, thermo acoustic engines and refrigerators have no moving parts (or at most only flexing parts without the need for sliding seals). This simplicity, coupled with reliability and relatively low cost, has highlighted the potential of thermo acoustic devices for practical use. As a result, thermo acoustics is maturing quickly from a topic of basic scientific research through the stages of applied research and on to important practical applications recently, thermo acoustic phenomena have been employed in the medical field for imaging of tissues. Thermo acoustic refrigeration uses advanced acoustic technology to improve cooling capacity without the need for environmentally destructive refrigerants. The mechanism of the TAR is simple, based on the expansion and compression of a gas by sound wave. When a sound wave from a vibrating diaphragm or loudspeaker is sent down a half wave length tube, the pressure pulsations from a standing wave, which cause oscillatory motion of gas in the tube's axial direction. The Combination of pressure oscillation and oscillatory motion of gas causes heat transport wherever the gas is in thermal contact with a stationary surface. If small structure with a large amount of surface area is placed in an appropriate location in an intense standing wave, substantial amounts of heat transport will occur, with one end cooled by heat transport, and the other end heated, This structure is usually called a "stack"; if both ends of the stack make thermal contact with heat exchangers, a functional heat pump or refrigerator can be constructed

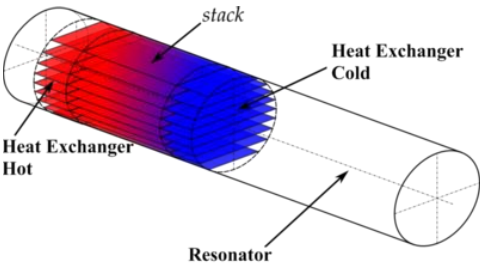


Fig.1. Heat exchanger.

PRINCIPLE OF OPERATION:

When a sound wave is sent down a half-wavelength tube with a vibrating diaphragm or a loudspeaker, the pressure pulsations make the gas inside slosh back and forth. This forms regions where compression and heating take place, plus other cooling.

A thermo acoustic refrigerator is a resonator cavity that contains a stack of thermal storage elements (connected to hot and cold heat exchangers) positioned so the back-and-forth gas motion occurs within the stack. The oscillating gas parcels pick up heat from the stack and deposit it to the stack at a different location. The device "acts like a bucket brigade" to remove heat from the cold heat exchanger and deposit it at the hot heat exchanger, thus forming the basis of a refrigeration unit. The governing mathematical equations of the thermo acoustic phenomenon are given below.

STANDING-WAVE SYSTEMS:

The thermo acoustic engine (TAE) is a device that converts heat energy into work in the form of acoustic energy. A thermo acoustic engine is operating using the effects that arise from the resonance of a standing-wave in a gas. A standing-wave thermo acoustic engine typically has a thermo acoustic element called the "stack". A stack is a solid component with pores that allow the operating gas fluid to oscillate while in contact with the solid walls. The oscillation of the gas is accompanied with the change of its temperature. Due to the introduction of solid walls into the oscillating gas, the plate modifies the original, unperturbed temperature oscillations in both magnitude and phase for the gas about a thermal penetration depth $\delta=\sqrt{(2k/\omega)}$ away from the plate, where k is the thermal diffusivity of the gas and $\omega=2\pi f$ is the angular frequency of the wave. Thermal penetration depth is defined as the distance that heat can diffuse though the gas during a time $1/\omega$. In air oscillating at 1000 Hz, the thermal penetration depth is about 0.1 mm. Standing-wave TAE must be supplied with the necessary heat to maintain the temperature gradient on the stack. This is done by two heat exchangers on both sides of the stack.

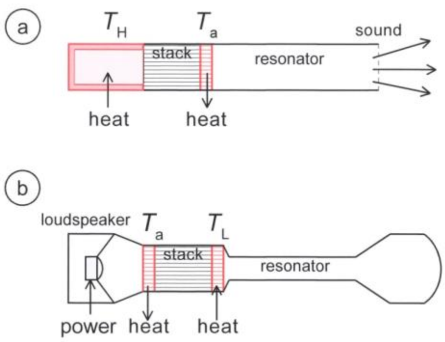


Fig.2. Heat transfer model

If we put a thin horizontal plate in the sound field the thermal interaction between the oscillating gas and the plate leads to thermo acoustic effects. If the thermal conductivity of the plate material would be zero the temperature in the plate would exactly match the temperature profiles as in Fig. 1b. Consider the blue line in Fig. 1b as the temperature profile of a plate at that position. The temperature gradient in the plate would be equal to the so-called critical temperature gradient. If we would fix the temperature at the left side of the plate at ambient temperature T_a (e.g. using a heat exchanger) then the temperature at the right would be below T_a. In other words: we have produced a cooler. This is the basis of thermo acoustic cooling as shown in Fig. 2b which represents a thermo acoustic refrigerator. It has a loudspeaker at the left. The system corresponds with the left half of Fig. 1b with the stack in the position of the blue line. Cooling is produced at temperature T_L.

II SURVEY OF RESEARCH

[1] Alamir, M. A. (2020) Experimental study of the temperature variations in a standing wave loudspeaker driven thermoacoustic refrigerator.

This study investigates temperature variations within a standing wave thermoacoustic refrigerator driven by a loudspeaker. The findings highlight the influence of acoustic power and frequency on the cooling performance, providing insights for optimizing design parameters.

[2] Dhuley, R. C. (2016) Investigations on a Thermoacoustic Refrigerator.

This research presents a comprehensive theoretical analysis of standing wave thermoacoustic refrigerators, including parametric studies and transient state analysis. The study also details the design and construction of a thermoacoustic refrigerator using a commercially available electrodynamic driver.

[3] Dhuley, R. C., & Atrey, M. D. (2016) Cooldown Measurements in a Standing Wave Thermoacoustic Refrigerator.

The paper examines the effect of charging pressure on the cold end temperature of a standing wave thermoacoustic refrigerator. It reports on temperature lift and cooldown times for various pressures, offering valuable data for system optimization.

[4] Hao, H., Scalo, C., Sen, M., & Semperlotti, F. (2017) Thermoacoustics of solids: a pathway to solid state engines and refrigerators.

This study explores the existence of thermoacoustic instabilities in solid media, proposing a theoretical framework for solid-state thermoacoustic engines and refrigerators. The findings suggest potential for developing robust, reliable solid-state cooling devices.

[5] Alam, M. S., & Allam, M. M. (2023) Title: Performance analysis in the design of thermoacoustic refrigeration systems.

The research analyzes the performance of thermoacoustic refrigeration systems, focusing on the transformation of sound energy into heat energy. It emphasizes the importance of design parameters in achieving efficient cooling without mechanical moving components.

[6] Piccolo, A. (2023) Design methodology of standing-wave thermoacoustic refrigerator: theoretical analysis.

This paper presents a theoretical analysis of the design methodology for standing-wave thermoacoustic refrigerators. It discusses the influence of various design parameters on system performance, providing guidelines for efficient refrigerator design.

[7] Alam, M. S., & Allam, M. M. (2024) Numerical study on acoustic matching between driver and resonator in loudspeaker-driven thermoacoustic refrigerators.

The study investigates acoustic matching in loudspeaker-driven thermoacoustic refrigerators, elucidating the coupling mechanism between the driver and resonator. The findings contribute to the optimization of acoustic components for enhanced system performance.

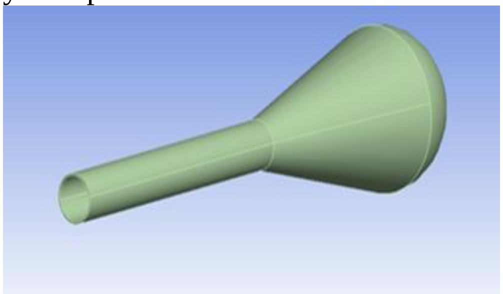


Fig.3. 3D model

III THERMAL ANALYSIS

The working methodology for the design and thermal analysis of a thermoacoustic refrigerator revolves around utilizing the principles of thermoacoustics, which combine sound wave propagation and heat transfer. Initially, the system is designed with critical components such as a resonator, a stack, and an acoustic driver. The acoustic driver generates sound waves within the resonator, producing high-intensity standing or traveling waves. These waves interact with the stack, a porous material placed in the resonator, causing a temperature gradient through the thermoacoustic effect. As the gas particles oscillate along the stack due to the sound waves, heat is transferred from one side of the stack to the other, creating a refrigeration effect. The cooling occurs near the cold end of the stack, while the heat is rejected at the opposite end, often facilitated by heat exchangers.

Thermal analysis is integral to optimizing the system's efficiency and performance. Computational Fluid Dynamics (CFD) simulations or experimental setups are used to study the effects of parameters such as stack geometry, acoustic frequency, and working gas type. These analyses help in identifying optimal configurations for maximum temperature drop and cooling capacity. The design also considers minimizing energy losses due to viscous and thermal damping in the resonator. Advanced materials with high thermal conductivity are often employed for the stack to enhance heat transfer efficiency. This systematic approach ensures a balance between acoustic input energy and effective cooling output, making the thermoacoustic refrigerator a viable alternative to conventional refrigeration systems.

Spiral type stack

Temperature

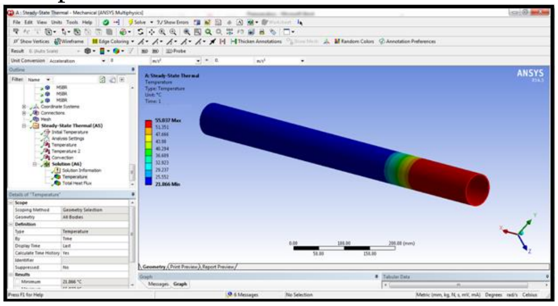


Fig.4. Temperature model

Heat flux

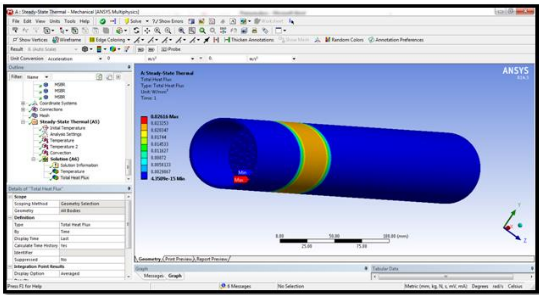


Fig.5. Heat flux model

BLOWER TYPE

Imported model

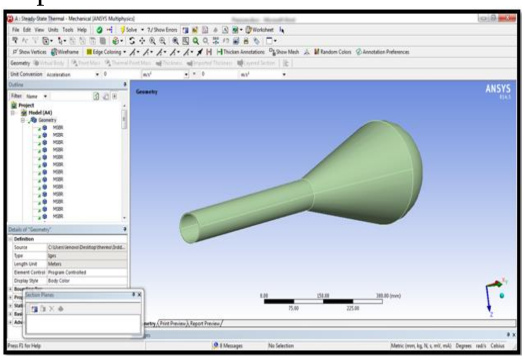


Fig.6. Blower model.

Meshed model

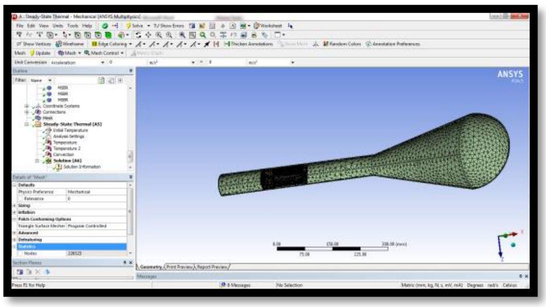


Fig.7. Meshed model

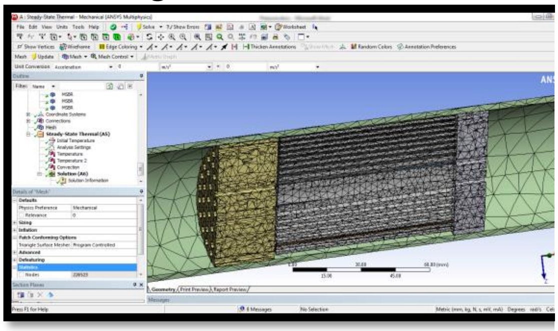
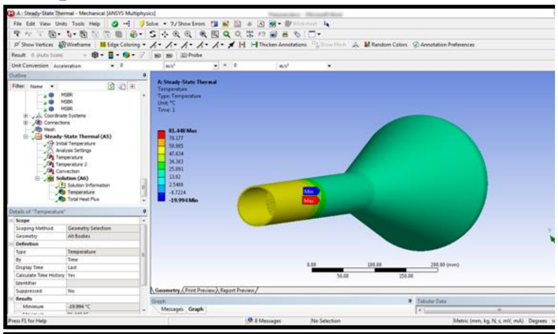


Fig.8. Boundary conditions

Temperature distribution



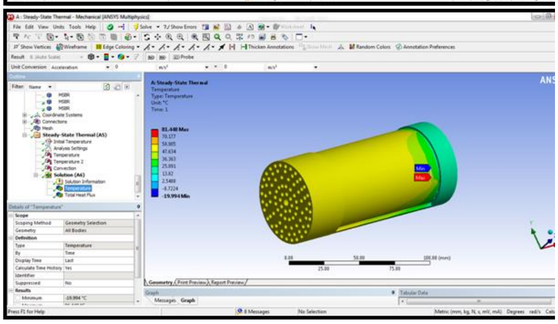
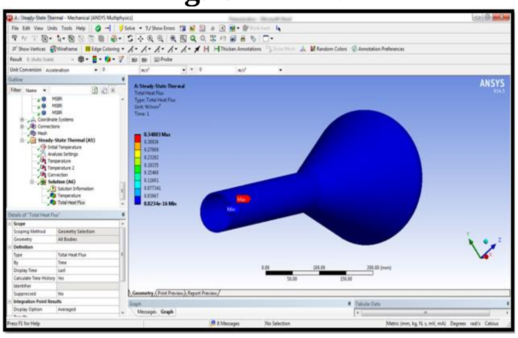


Fig.9. Heat flux



Rectangular type

Imported model

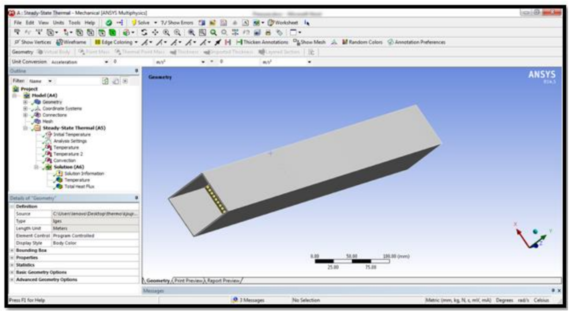


Fig.10. Imported model

Meshed model

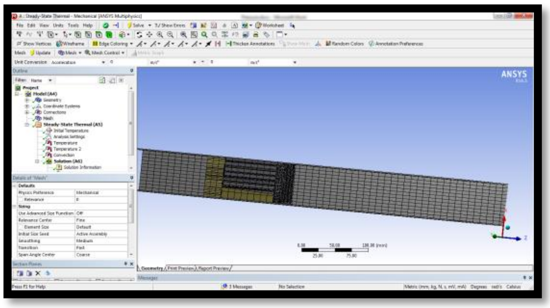
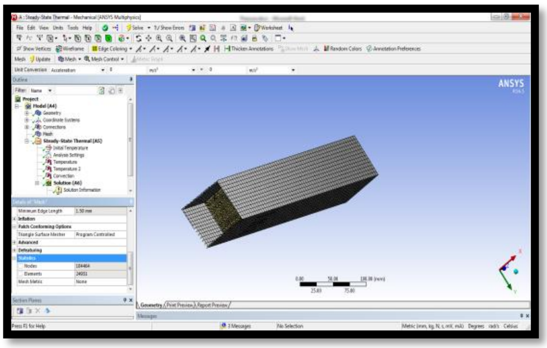


Fig.11. Meshed model for rectangler



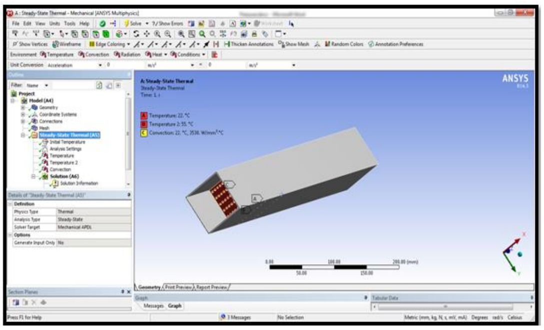


Fig.12. Boundary conditions

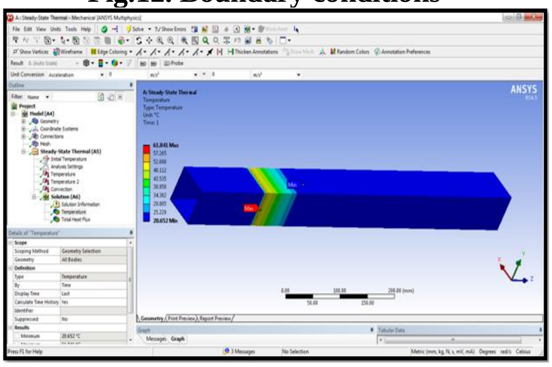


Fig.13. Temperature distribution

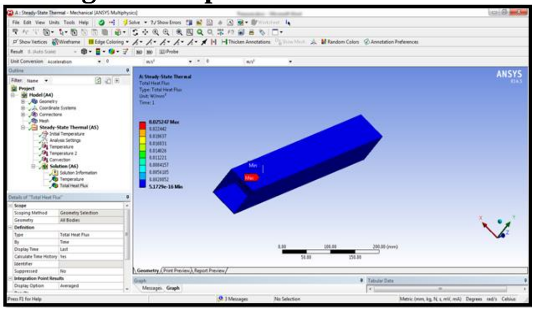


Fig.14. Heat flux

CONCLUSION

The design and functionality of thermo-acoustic refrigerator have been the focus of considerable attention from the research community since 1980. This environmental friendly technology has the potential to replace conventional refrigerator once the improvements in design and technology are realized. Thermo-acoustic is a term used to describe the effect arising from sound waves creating a heat gradient, and vice versa. Thermal analysis to determine the heat flux and temperature distribution for different cross sectional geometries (tube with spiral type stack, spiral type stack with blower type tube and square tube with square type stack). By observing the above thermal analysis results the maximum temperature distribution more for blower type tube with spiral stack.

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