CFD simulation and construction of Thermoacoustic device

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Abstract- *Thermoacoustic refrigeration is simple and inexpensive alternative for generation of cooling effect. This paper deals with the design, construction and performance of Thermoacoustic refrigerator. The optimum design is finalized with the help of computational fluid dynamic analysis. The device consists of the glass vessel, pressure wave generator of particular amplitude, electronic measuring apparatus and the stack. This pressure wave compresses the working gas medium to produce cooling effect across the stack. The CFD had played vital role in the choosing the working gas medium, length of stack etc. No moving parts, reliability and long life span makes this device commercially successful. The aim of this work is constructing a small, and useful model of a thermoacoustic refrigerator. The thermoacoustic refrigerator was built with lesser cost and useful cooling effect. Additionally, this experiment did yield some findings regarding the efficiency of thermoacoustic refrigeration. On other hand, CFD software was used to simulate the performance of thermoacoustic refrigerator especially the temperature and velocity inside the refrigerator.*

Keywords- Thermoacoustic, CFD simulation, Fluent Software

I. INTRODUCTION

Over the past two decades, physicists and engineers have been working on a class of heat engines and compression-driven refrigerators that use no oscillating pistons, oil seals or lubricants. These so called thermo acoustic devices which take advantage of sound waves reverberating within them to convert a temperature differential into mechanical energy or mechanical energy into a temperature differential. Such materials thus can be used, for example, to generate electricity or to provide refrigeration and air conditioning. Because thermo acoustic devices perform best with inert gases as the working fluid, they do not produce the harmful environmental effects such as global warming or stratospheric ozone depletion that have been associated with the engineered refrigerants such as CFCs and HFCs. Recent advances have boosted efficiencies to levels that rival what can be obtained from internal combustion engines, suggesting that commercial thermo acoustic devices may soon be a common place.

Refrigeration relies on two major thermodynamic principles. First, a fluid’s temperature rises when compressed and falls when expanded. Second, when two substances are placed in direct contact, heat will flow from the hotter substance to the cooler one. While conventional refrigerators use pumps to transfer heat on a macroscopic scale, thermoacoustic refrigerators rely on sound to generate waves of pressure that alternately compress and relax the gas particles within the tube.

The model constructed for this research project employed inexpensive, household materials. Although the model did not achieve the original goal of refrigeration, the experiment suggests that thermoacoustic refrigerators could one day be viable replacements for conventional refrigerators. The entire features mentioned above is possible only because sound waves in thermo acoustic engines and refrigerators can replace the piston and cranks that are typically built into any machinery. These thermo acoustic devices produce or absorb sound power, rather than the shaft power characteristic of rotating machinery making it mechanically simple.

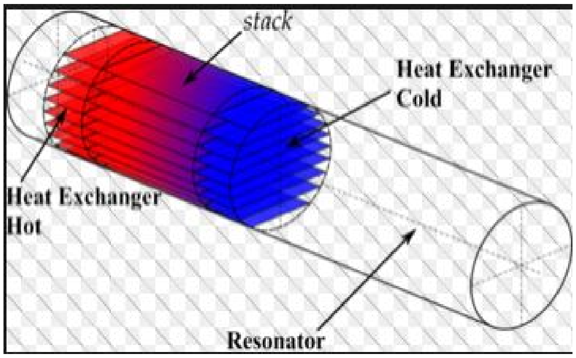

Figure 1 – Thermoacoustic device

Also project deals with the computational fluid dynamics analysis of flow in a Thermoacoustic refrigerator showing the optimum results. The CFD is used to study the changes in the position of the stack, length of the stack and frequency input. This involves with the two dimensional analysis of flow through of TAR having inlet and closed outlet. The software used for this purpose are ANSA and FLUENT. The 2 D model of the parts of the TAR are made by ANSA and analysis are to be carried out by FLUENT. The models are first generated using the data and then are meshed and then various velocity and pressure contours are to be drawn and graphed in this paper to analyze the flow.

Theoretical Background

Thermoacoustics is based on the principle that sound waves are pressure waves. These sound waves propagate through the air via molecular collisions. The molecular collisions cause a disturbance in the air, which in turn creates constructive and destructive interference. The constructive interference makes the molecules compress, and the destructive interference makes the molecules expand. This principle is the basis behind the thermo acoustic refrigerator

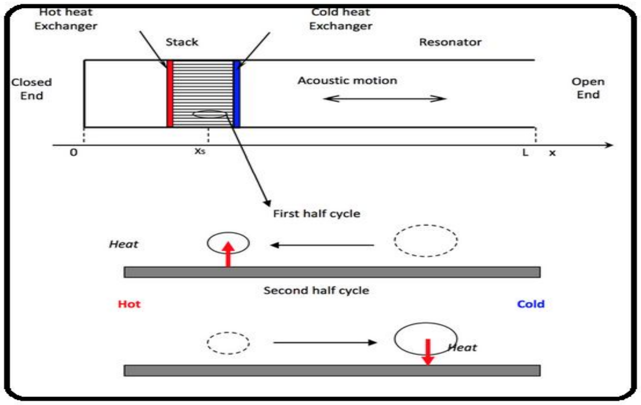

Figure 2 – Heat conduction in the stack

Standing waves are natural phenomena exhibited by any wave, such as light, sound, or water waves. In a closed tube, columns of air demonstrate these patterns as sound waves reflect back on themselves after colliding with the end of the tube. When the incident and reflected waves overlap, they interfere constructively, producing a single waveform. This wave appears to cause the medium to vibrate in isolated sections as the traveling waves are masked by the interference.

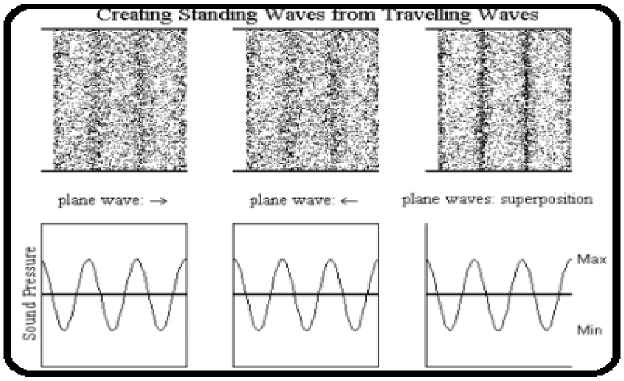

Figure 3 – Standing wave pressure distribution

The equation for the frequency of a wave traveling through a closed tube is given by:

$$f = v/4L$$

Where,

f is frequency,
v is velocity of the wave,
L is the length of the tube.

The thermal penetration depth is the distance heat can diffuse in a gas over a certain amount of time. For example, if a block of aluminum is at a constant low temperature and suddenly one side is exposed to a high temperature, the distance that the heat penetrates the metal in 1 second is the heat penetration. As time passes, the heat penetrates farther into the material, increasing the temperature of the interior sections.

The thermal penetration depth for an oscillating heat source is:

$$\delta_k = \sqrt{\frac{k}{\pi f \rho Cp}}$$

Where:

f: frequency of the standing wave;
k: the thermal conductivity;
ρ: of the gas density;
Cp: the isobaric specific heat per unit mass of the gas.

The critical temperature is the temperature at which no heat will be transferred through the stack. If the temperature difference induced by the sound wave is greater than this critical temperature, the stack will function as a refrigerator, transferring heat from the cold end of the tube to the warm end. If the temperature is less than the critical temperature then the stack will function as an acoustic engine, moving heat from the warm region to the colder region and creating sound waves. The function for the critical longitudinal temperature gradient is the stack will function as an acoustic engine, moving heat from the warm region to the colder region and creating sound waves. The critical temperature is the temperature at which no heat will be transferred through the stack.

$$\nabla T_{crit} = \frac{p}{\xi \rho Cp}$$

Where:

p is the acoustic pressure;
ξ is the acoustic displacement amplitude.

II. SCOPE FOR EXPERIMENTATION

A lot of parameters govern the performance of thermoacoustic device but focus will be concentrated here on the operating conditions and geometrical parameters.

Thermoacoustic devices are subcategorized into three devices; thermoacoustic engines; thermoacoustic refrigerator; and thermo-acoustically driven thermoacoustic refrigerator (TADTAR). The objectives of this thesis will be:

1) To develop application for refrigeration system from the acoustic waves generated;
2) Understand the effects of the geometrical parameters of the device, namely the stack spacing, stack position and stack length.

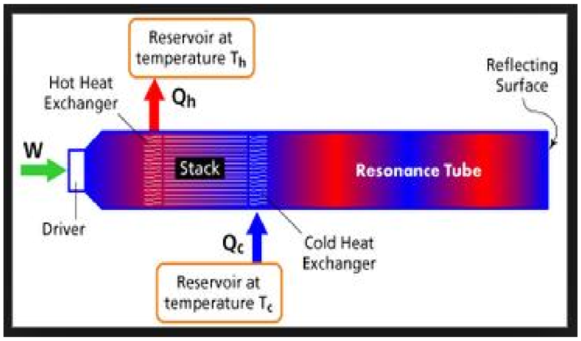

Figure 4 – Representative model

The goal of this study is to design, fabricate, test and optimize thermoacoustic refrigerator which utilize waste heat using helium as the primary working fluid. A numerical study is to be done on this system to show its advantages in producing greater thermoacoustic effects.

III. EXPERIMENTAL SETUP

Fig. 4 shows a schematic diagram of the thermoacoustic refrigerator.

We began by creating the stack, which we constructed with film and glass fiber. The design specified an optimal thermal penetration depth of 4; however, we were restricted by material constraints and achieved an acceptable penetration depth of 2.5. This was achieved with 15-lb nylon fishing wire with a diameter of 0.34 millimeters. The glass capillaries are wound in the round shape. The capillaries are stacked to the wounding material with help of adhesive. This allowed for a straight application of the glass capillaries to the film.

Next, we connected a frequency generator to a 40w amplifier and connected this to the speaker via a BNC to RCA connector. After, we inserted the machined aluminum stoppers, roughly 20 mm in diameter, which were needed to create the closed tube necessary for standing waves. Next, we determined the proper frequency needed to achieve a standing wave. This is supposed to be at the first harmonic, or, when the wavelength is 4 times the length of the tube. We measured the length of the tube to the bottom of the aluminum cap and multiplied by 4 and divided the speed of sound at room temperatures, or roughly 349 m/s, by the length of tube. We determined the frequency to be around 340 Hz.

Once we found the optimal resonant frequency for our refrigerator, we used a tone generator, which outputs a sound at a specific frequency. Basically, the generator vibrates the speaker cone at that frequency, which subsequently vibrates the air and causes the heat transfer to occur. We listened to verify for the sound of the harmonic, and when verified, we increased the intensity of the frequency and then recorded the temperatures of the two thermocouples.

The stack is used to convert heat into acoustic power as well as the opposite, acoustic power to heat The stack material should have a high heat capacity and high thermal conductivity in the y direction. The thermal conductivity in the x direction however, should be very low. Heat pumping requires the heat storage and this requires high thermal conductivity in the y direction to be accessible. A low thermal conductivity in x direction is necessary to minimize losses through conduction from hot to cold side. As becomes clear, a material with anisotropic thermal conductivity would be best.

Stacks of different shape exist. Some stacks have parallel plates, some rectangular pores. For a parallel plate stack, the plate spacing and the thickness of the plates are important dimensions.

We have used three stack configurations viz. Glass capillary tube stacks, Glass fibre with nylon spacers and Glass fibre with glass capillary spacers

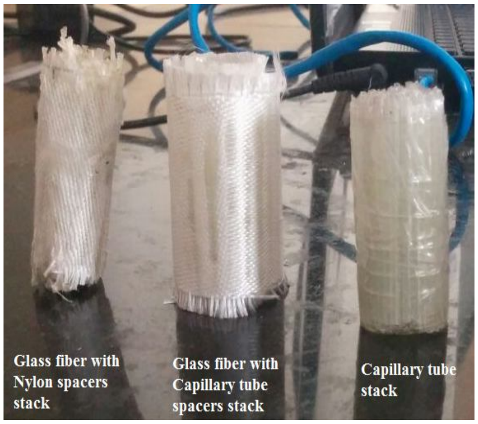

Figure 5 –Stack used for thermoacoustic experiment

The shape, length, weight and the losses are significant parameters in resonator design. Length of resonator is determined by the resonance frequency and minimal losses at the wall of the resonator. The length of resonator tube corresponds to quarter of the wavelength of the standing wave:

Length of resonance tube,

$L= v/4f$

Where,

Velocity of sound in air, $v = 340$ m/s

Frequency of Sound wave, $F=350$ Hz

$L= 340/(4*350)$

$= 0.242$ m

Where, a is the speed of sound,

L is the length

And F is the resonance frequency

Acoustic driver supplies total acoustic power used by the refrigerator. The acoustic driver converts electric power into acoustic power. A loudspeaker with maximum power of 60 watts and 8Ω at the operating frequency of 350 Hz is selected as the acoustic driver for this study.

Figure 6 – Acoustic wave generator

The Air is chosen as working gas medium. A high mean pressure, a high velocity of sound and a large cross-sectional area would mean more thermoacoustic power. For this reason, helium is commonly used in thermoacoustic devices. Helium’s velocity of sound is much higher than that of air and helium will not condense or freeze at low temperatures.

IV. RESULTS

Design and development of a thermoacoustic refrigerator is a challenging work, because it requires a thorough understanding of thermoacoustic phenomenon. Significant efforts are needed to bring this technology to maturity and develop competitive thermoacoustic devices. This study mainly considers the coefficient of performance (defined as the ratio of the cooling effect to the acoustic power input) as the main criterion for comparison when dealing with any of the devise’s parameters. Consideration is also given to some other factors like the cooling capacity, operating frequency, and temperature difference generated across the stack. Obviously the cooling capacity is considered as it is the main output of the thermoacoustic refrigerator and we may need a powerful point in some application. The frequency is considered as it will be a requirement from the acoustic driver (loudspeaker) which is equivalent to the amount of input power. The temperature difference is very important as in some application a large temperature difference may be required on the expense of the cooling capacity

We successfully created a thermoacoustic refrigerator. Our results showed that we were able to create a high temperature gradient above room temperature, but were unable to significantly cool the air. We tested three thermoacoustic refrigerators that we built. The third had the heat sink modification that was described in the modifications section.

We collected the data for these results by sampling the temperatures at the top and bottom thermocouples of the refrigerators as they ran every ten seconds, stopping when it became apparent that there would be no more significant change.

CFD experiments are conducted at different charging pressure, by changing stack length and porosity.

V. CFD ANALYSIS OF THERMO ACOUSTIC DEVICE

Main Dimensions Resonator Length	240mm
Diameter	20mm
Frequency	350Hz
Stack spacing	0.8mm
Stack position	150mm
Stack length	50mm
Temperature difference	310-298 K

Table 1 The geometric specification of the model

This is the first step in building and analyzing a flow model, including building the model within a computer-aided design (CAD) package, creating and applying a suitable computational mesh, and entering the flow boundary conditions and fluid materials properties. CAD geometries are easily imported and adapted for CFD solutions in ANSA.

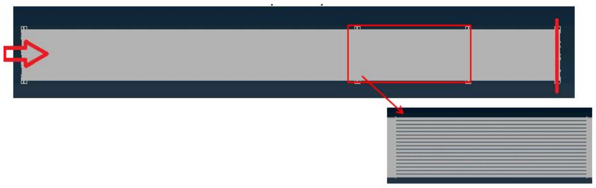

Figure 7 the two dimensional geometry for CFD analysis

We have used the quadratic mesh for the analysis. The quadratic mesh gives better results as compare to other types of meshes such as triangular mesh or hybrid mesh. The local refinement is provided at the critical area of the model. The critical areas are identified as, the area near stacks inlet and stack outlet. The mesh is created in such a way that, the mesh quality should not be hampered because of the local mesh refinement

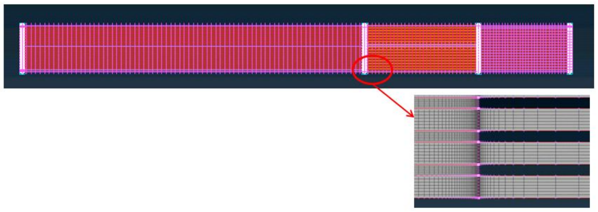

Figure 8 Meshing on two dimensional model

Also the mesh refinement should not be too fine otherwise it will increase the computational cost. Approximately 30000 elements are created in the model.

The FLUENT CFD code has extensive interactivity, so one can make changes to the analysis at any time during the process. This saves one time and enables one to refine designs more efficiently. The graphical user interface (GUI) is intuitive, which helps to shorten the learning curve and make the modeling process faster. It is also easy to customize physics and interface functions to one specific need. In addition, FLUENT's adaptive and dynamic mesh capability is unique among CFD vendors and works with a wide range of physical models. This capability makes it possible and simple to model complex moving objects in relation to flow.

FLUENT provides the broadest range of rigorous physical models that have been validated against industrial scale applications, so one can accurately simulate real-world conditions

We have used segregated solver with implicit formulation. We need to analyze the flow for long time duration, so choose the unsteady flow option.

We have chosen the standard k-epsilon model to analyze the flow, as it best suited model for compressible flow.

By default the material selected was air with properties.

Viscosity, µ = 1.7894 x 10-5 kg/ms
Density, r= 1.225 kg/ m3.
Thermal Conductivity, K=0.0242 W/mK
Specific heat, Cp= 1.00643kJ/kg K
Molecular weight= 28.96

Pressure inlet: The user defined function for pressure inlet is used to model the acoustic behavior.

Stack inlet, it is modeled as glass wall with the heat flux of -6oow/m2. Stack outlet, the outlet modeled as wall with the heat flux of 1500w/m2.

Post processing: This is the final step in CFD analysis, and it involves the organization and interpretation of the predicted flow data and the production of CFD images and animations. All of Eluent software products include full post processing capabilities.

We have created the surface monitor for pressure, temperature and velocity variables.

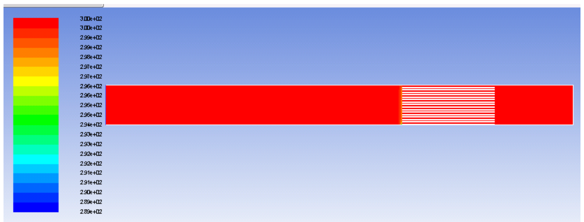

Figure 9 Temperature contours of CFD analysis

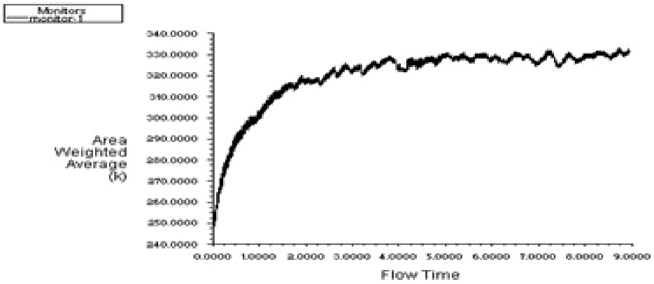

Figure 10 Weighted area average vs flow time plot

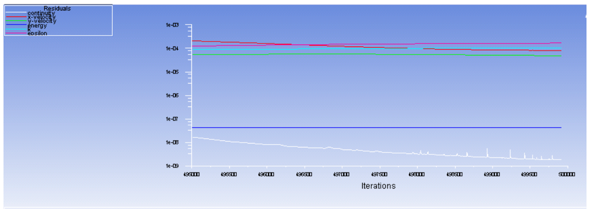

Figure 11 Residual plot during the analysis against the number of iterations

VI. CONCLUSION

Our device worked as a proof of concept device showing that a thermoacoustic device is possible and is able to cool air, work for only a short period of time. If we were able to build the device with better materials, such has a more insulating tube; we might have been able to get better results. In order to create a working refrigerator we probably would have to attach a heat sink to the top of the device, thus, allowing the excess heat to dissipate to the surroundings. However, our device did demonstrate that thermoacoustic device have the ability to create and maintain a large temperature gradient, more than 10 degrees Centigrade, which would be useful as a heat pump.

In future let us hope these thermo acoustic devices which promise to improve everyone’s standard of living while helping to protect the planet might soon take over other costly, less durable and polluting engines and pumps. The latest achievements of the former are certainly encouraging, but there are still much left to be done.

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