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Design and Analysis of Thermo-Acoustic Cooling Setup

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ABSTRACT —*The study of interaction of sound and heat is known as thermoacoustics, where pressure fluctuations are coupled with unsteady heat release. Thermoacoustic cooling setups use the principle of thermoacoustics which generate a temperature gradient by using energy from acoustic vibrations. The pressure waves, when made to travel in small channels known as Stack, create a heat gradient in the apparatus. This can be used to create a cooling effect. The setup consists of acoustic driver (loudspeaker), resonator tube, stack, heat exchanger and buffer volume. The setup uses a quarter wave generated by the driver. The stack and resonator designs are based on Linear Thermo-Acoustic theory.*

This setup provides an environment friendly solution to the conventional method of vapour compression refrigeration system. The advantages provided by the thermoacoustic refrigerators include minimal moving parts, more compact setup and less maintenance.

The parameters have been optimized to minimize losses. This setup could be used as a portable refrigeration system where temperature difference is not large.

Keywords—Thermo-acoustic, Stack, Resonator tube, Acoustic driver

I. INTRODUCTION

Thermoacoustics can be understood as the interaction of heat and sound. It explains how acoustic vibrations can give a temperature gradient across a region. The reverse effect that is conversion of heat into sound, can also be explained using the principle of thermoacoustics. This effect has been observed since quite some time now. It was observed when producing glass blowers which produced sound when blowing a hot bulb at the end of a cold narrow tube. The first scientific observation was made by Byron Higgins who investigated the 'singing flame' phenomena in an open-end tube. Later Rijke put forward a setup which included a heated wire mesh to generate oscillations in a tube. In 1969, Rott proposed the theory of acoustic approximation which was explained with the help of a series of papers that he wrote. This helped in the development of general linear theory of thermoacoustics [1]. In early 1980s engineers at LANL (Los Alamos National Laboratories) in New Mexico accidentally created a thermoacoustic refrigerator. The team of engineers included two people who have contributed to the field of thermoacoustics to a great extent namely, Gregory W Swift and Thomas J. Hofler [2].

A. BASICS OF THERMOACOUSTIC COOLING

Heat transport process at inner wall of a hollow tube enclosing an acoustic field was demonstrated by Gifford and Longsworth (1966) in their device called the "Pulse Tube". To understand the basics of Thermoacoustics, a plate kept in an acoustic field is considered. The particles in the acoustic field oscillate along the length of the plate. The maximum pressure variation will be at the left part of the plate, where the driver is placed. This is the position of pressure antinode. The pressure node will be observed at the right end of the plate. The mean temperature of the plate as well as the gas is 'T_m' and mean pressure of the gas is 'p_m'. A typical gas parcel oscillates over a distance '$2d_1$' about its mean position. Its pressure varies between $p_m - p_1$ and $p_m + p_1$. The

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activity of a typical gas parcel is shown below in Fig. 1, 2, 3, 4.

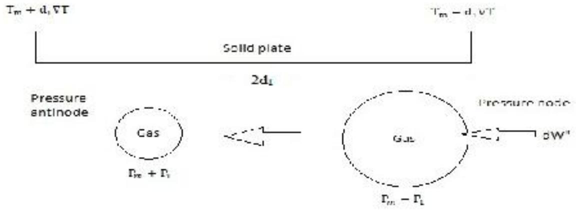

Fig 1: Compression of gas on stack surface

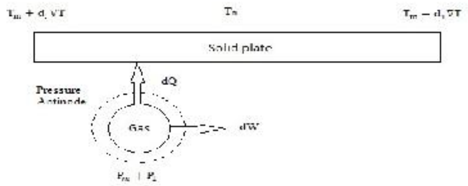

Fig 2: Heat transfer from gas to stack at hot end

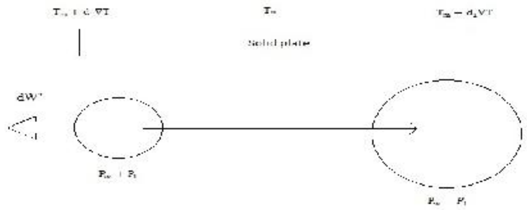

Fig 3: Expansion of gas on stack surface

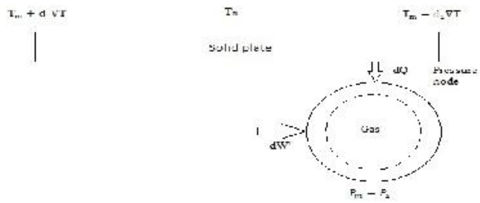

Fig 4: Heat transfer from stack to gas at cold end

The gas parcel at the right end absorbs acoustic power and moves by a distance '$2d_1$' to the left as in Fig. 1. During this displacement it gets compressed and its temperature rises. This parcel then loses heat to the plate till its temperature equals that of the plate (Fig. 2). As a result, the left end of the plate becomes a little warmer. The parcel then moves again to right end where its pressure as well temperature falls (Fig. 3). The cold parcel warms up by picking heat from right end of the plate, making the right end of the plate colder (Fig. 4). Thus, in one cycle the gas transports 'dQ' amount of heat over a temperature difference of 'Tm', absorbing dW - dW'' amount of acoustic power.

B. DESIGN CONSIDERATIONS

The Linear Theory of Thermoacoustics was developed by Rott. The effect of Thermoacoustics is considered only in one direction since pressure variation will take place along the length of the tube. The effects in other directions can be neglected because the space across the width is small. Thiswill help in simplifying the analysis of the setup to a great extent. Hence linear Thermoacoustic theory is used.

Following assumptions are made in the analysis:

1. The solid stack is kept such that the length, that is, longer dimension is aligned parallel to the vibrations of standing wave. In order for velocity and pressure oscillations to be uniform the length of the stack is taken such that it is very less as compared to the wavelength of the acoustic waves.
2. The thermal properties of stack and the gas do not vary with temperature.
3. The viscous boundary layer is absent as the fluid is non-viscous which results in planar pressure wave-front.
4. Velocity of oscillation of gas molecules does not vary in the direction perpendicular to the length of the stack.
5. Heat transfer does not take place along the stack because heat capacity of the stack material is high.
6. Heat conduction by gas and solid in the direction perpendicular to the length of the stack considered to be zero.

Temperature oscillations occur with pressure oscillations in an adiabatic acoustic field. Consider the length of the stack to be 'l' and thickness is taken to be very small. Vibrations are taken to be occurring along the length of the stack. Local pressure and velocity are given as,

$$p_1 = p_a \sin(kx) \qquad (1)$$

$$u_i = i\left(\frac{p_a}{\rho_m}\right) \qquad (2)$$

Where,

i = 90^0 phase difference between pressure and velocity oscillations due to standing wave.

p_a= atmospheric pressure.

x= distance from the driver along the length of the stack.

II. DESIGN OF THE EXPERIMENTAL SETUP

The working gas is chosen as Helium as it has the highest thermal conductivity and the speed of sound is also significantly higher than the speed of sound in other gases. The material of the stack is chosen as Mylar because of its low thermal conductivity and high heat capacity. Low thermal conductivity will help in reducing power losses. Higher specific heat capacity than that of the working gas will ensure that the temperature descent will be steady and not erratic. Some have used ACCURA-60 as the material of stack but this material was difficult to 3D print as the setup required lower wall thickness values and the material would not have been able to withstand the pressure generated in the setup.

The choice of mean pressure is done by theoretical parametric analysis, while the operating frequency is chosen so as to keep the resonator length within reasonable limits. The operating parameters, properties of working gas and the stack material are given below:

Table 1. Properties of Working Gas and Stack Material

Operating Parameters		Working Gas Properties (@T_m)		Stack Material Properties (@T_m)	
p_m	10 bar	k	0.152 W/m-K	k_s	0.16 W/m-K
f	400 Hz	c_p	5193.4 J/kg-K	c_s	1110 J/kg-K
T_m	308 K	a	1020 m/s	ρ_s	1347.5 kg/m^3

p_m = mean pressure
T_m = mean temperature
μ= viscosity of helium
a= speed of sound in helium

f = frequency
k = conductivity of helium
ρ_s = density of Mylar
k_s = conductivity of Mylar
c_s = heat capacity of Mylar

The model developed such that a plane wave-front is obtained in the resonator tube. The condition for plane wave propagation thorough a hollow pipe with diameter D is:

$$f < \frac{1.8 \quad a}{\pi} \qquad (3)$$

The design algorithm is as follows:

Step 1: Operating parameters such as mean pressure, mean temperature, frequency, and the pressure amplitude are chosen. To avoid turbulence in the flow, an appropriate pressure amplitude is chosen, which is taken care of by keeping the acoustic Reynold's number less than 500. The acoustic Reynold's number is given by,

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$$Re_a = \frac{\rho_m u_l \delta_v}{\mu_m} \quad (4)$$

ρ_m – density ; u - local velocity ; μ - viscosity ; δ_v - viscous penetration depth

The working gas and stack material are chosen. Plate spacing that is distance between two layers of Mylar sheets will be found out with the help of thermal penetration depth (δ_k). It is 2.5 times δ_k.

Step 2: Calculate the resonator length so as to obtain a standing wave phasing between oscillatory pressure and velocity. The length-frequency relation is given by,

$$L = n\frac{a}{4} \qquad n = 1, 3, 5, \ldots \qquad (5)$$

Step 3: The optimal length of the stack and heat exchangers equals twice the displacement amplitude.

Calculations-[1]-[4]

1) To find the length of resonator tube (For Quarter Wave):-

$$f = \frac{(2n-1) \times a}{4(2 * l)}$$

Where,

f = Frequency = 405Hz.

n = Harmonic = 1.

a = Velocity of sound in helium = 1020m/s.

l = Length of resonator tube.

$$405 = \frac{[2(1)-1] \times 1020}{4(2 * l)}$$

$$l = \frac{[2(1)-1]}{2 * 1.588}$$

$$\therefore l = 0.3148\text{m}$$

2) To find thermal penetration depth: -

$$f < \frac{1.8 \ \times a}{\pi D} \text{[3][3]}$$

Where,

D = Diameter of stack.

$$\delta_k = \sqrt{\frac{2k}{\rho_m C_p \times 2\pi f}}$$

Where,

δ_k = Thermal penetration depth ; k = Thermal conductivity ; Temperature of surrounding = 300K

Universal gas constant for helium = 2077J/kg K ; Pressure of helium = 10^6bar

ρ_m = Density of helium = $\frac{1 \ \ ^6}{3 \ \ \times 2}$.

$$= \sqrt{\frac{k}{\rho_m C_p \times \pi f}}$$

$$= \sqrt{\frac{0.151 \times 300 \times 2077}{\pi \times 5.19 \times 10^{3} \times 405 \times 10^{6}}}$$

$$\therefore \delta_k = 0.12\text{mm}$$

Spacing = 2.5 × δ_k = 0.3mm [1]

A. STACK AND STACK HOLDER

A spiral stack is chosen because it is quite easy to make. It is made from a 0.18 mm thick sheet of Mylar. To keep the sheets from coming in contact with each other, 0.3 mm diameter fishing lines are used. A distance of 5 mm is kept between two fishing lines as a means of equal spacing and to ensure that the gas pathways are uniform. The length of the stack is 100 mm and its diameter is 32 mm. The model can be seen in Fig. 5.

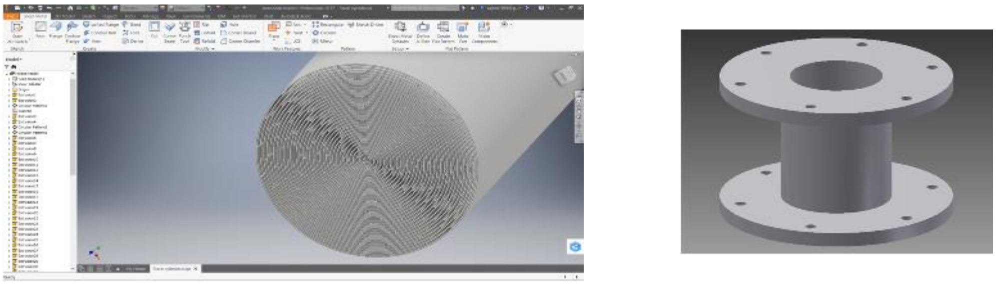

Fig 5: Model of the stack and stack holder

The stack holder houses the stack and is sandwiched between the heat exchangers. It is used to hold the stack in place and not allow any movement that might cause disturbance to the normal functioning of the setup.

B. RESONATOR TUBE

The resonator tube allows the vibrations to travel through it as it is hollow. The tube has a conical taper from 32 mm to 12.6 mm. The total length of the resonator tube is 205 mm. The calculations of the length of the tube have been shown above.

C. HEAT EXCHANGERS

The heat exchangers are present to allow heat transfer between the gas and the surroundings. The measurement of temperatures can be done with the help of sensors which can be mounted on the heat exchangers to form a closed loop system. Effective design of the heat exchanger will be realized when actual fabrication of the setup is done.

D. BUFFER VOLUME

The buffer volume is modelled as per the requirements of an open end quarter wavelength resonator. The quarter wavelength resonator is chosen because it has significantly less losses as compared to the half wave resonator. The total height of the buffer volume is 100 mm, the larger and smaller diameters are respectively 120 mm and 12.6 mm. The assembly of the final model is shown in Fig 6.

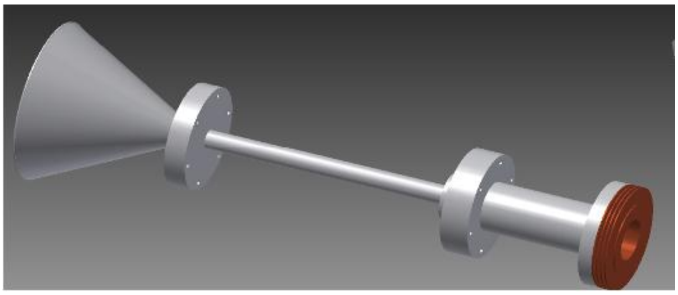

Fig 6: Model of the assembly

III. SIMULATION

The stack was modeled in Inventor 17 and then imported to ANSYS© for simulation. Simulation was tried using FLUENT 15. Meshing proved to be difficult for the model of the stack. Expected results were not achieved since meshing turned out to be a cumbersome task. This could be due to lack of sufficient computational capacity of available resources or high complexity of the model of stack. Meshing of stack has been shown in the Fig 7.

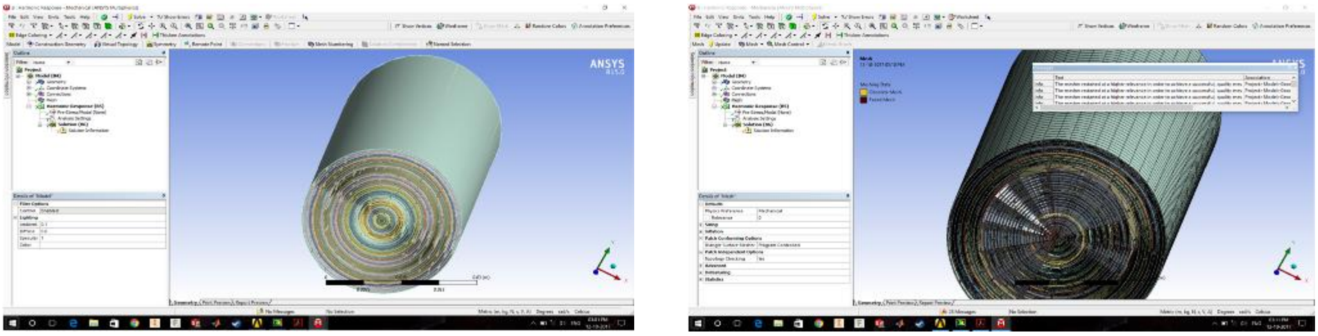

Fig 7: Model of stack imported in ANSYS© and meshed view of stack (with errors)

IV. CONCLUSION

The design and analysis of the setup is done. Theoretical investigation of standing wave thermoacoustic cooling setups has been done in depth beforethe design. The stack was designed according to the linear thermoacoustic theory. Various equations were used to find the optimal lengths and other dimensions of the components of this setup like length of the resonator tube and thermal penetration depth. Helium was used as the gas medium and stack material chosen was Mylar.

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