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Comparative study of Thermoacoustic Refrigeration System and vapour Compression Refrigeration System

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Abstract - This paper discusses the thermo acoustic refrigeration cycle and how it can be applied to real world uses, particularly The commercial feasibility of this technology is determined by comparing it to a vapour compression system. The paper has a goals to determine practical applications where Thermo acoustic refrigeration may prove a strong competitor to current methods as vapour compression refrigeration system, and to determine what future developments are required for this technology to be of commercial value. Thermo acoustic refrigeration is an emerging 'green' technology based upon the resolute use of high-pressure wave to provide cooling. Thermo acoustic refrigeration are relatively simple and inexpensive to manufacture. And can operate using heat source. Which leads to their appeal as a suntainble waste heat recovery device? Advance in the development of thermo acoustic refrigeration could provide an alternative solution for cooling vehicles which could use hot exhaust gases as a heat energy source. This paper compares the COP of a thermo acoustic refrigerator to that of a vapour compression based system for a variety of heat loads and temperature spans to investigate under what conditions a thermo acoustic refrigerator might be competitive with current refrigeration systems.

Key Words: **Thermoacoustic Refrigiration,VCR cycle , sound wave , DeltaE etc**

1.INTRODUCTION

The thermo acoustic effect was discovered in the 19th century when heat driven acoustic osciiiations were observed in open-ended glass rubes [1]. These devices were the fast thermo acoustic engines, consisting of a bulb attached to a long narrow tube (see Figure 2). Lord Rayleigh made a qualitative explanation of the effect in 1896 [2], however a quantitatively accurate theory of the phenomena was not established until the 1970's [3]. It was in the 1980's that thermo acoustic refrigeration was developed, when a research group at the Los Alamos National Laboratory [4] showed that the effect could be used to pump heat The technology has seen rapid growth since then, much of this being attributed to the Naval Postgraduate School in Monterey, California, which carried out the development of a reliable spacecraft cry cooler [5].

What thermo acoustic refrigerators offer is both simplicity and reliability? Unlike current commercial devices that require crank shafts and pistons, these devices use only a single moving part - the diaphragm of a loudspeaker. What currently makes them very attractive as an alternative to other approaches is their use of an inert gas as the working fluid, making them environmentally clean. In order for the thermo acoustic refrigerator to become a feasible commercial alternative their efficiency has to be competitive when compared to currently used systems. This paper compares the COP of a thermo acoustic refrigerator to that of a vapour compression based system for a variety of heat loads and temperature spans to investigate under what conditions a thermo acoustic refrigerator might be competitive with current refrigeration systems.

1.1 Sound Waves and Pressure

Thermo acoustics 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. One method to control these pressure disturbances is with standing waves. Standing wave sare 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. Therefore, these "standing waves" seem to vibrate in constant position and orientation around stationary nodes. These nodes are located where the two component sound waves interfere to create areas of zero net displacement. The areas of maximum displacement are located halfway between two nodes

and are called antinodes. The maximum compression of the air also occurs at the antinodes. Due to these node and anti node properties, standing waves are useful because only a small input of power is needed to create a large amplitude wave. This large amplitude wave then has enough energy to cause visible thermo acoustic effects. All sound waves oscillate a specific amount of
times per second, called the wave's frequency, and is measured in Hertz. For our thermo acoustic
refrigerator we had to calculate the optimal resonant frequency in order to get the maximum heat transfer rate. The equation for the frequency of a wave traveling through a closed tube is given by:

$$f = \frac{v}{4L}$$

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

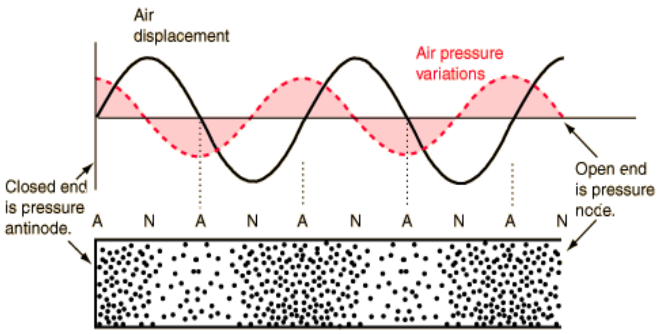


Figure 1: Shows the relationship between the phase of the wave, the pressure, and the actual arrangement of the molecules. The black line shows the phase of the sound wave, the red shows the pressure and the dots below represent the actual molecules. [6]

2.1 The basics of thermoacoustic refrigeration:

A basic thennoacoustic refrigerator consists of a stack of thin parallel plates housed withln a resonator, as shown schematically in Figure 3(a). Heat can be pumped from the cold to wann end of the stack by setting up a standing wave within the resonator. This effect, where heat is pumped up a temperature gradient by the use of sound, may be explained by considering an element of fluid as it oscillates back and forth along the stack, as shown in Figure 3(b). The element experiences a cyclic temperature oscillation about its mean temperature, due to adiabatic compression and expansion of the gas. Irreversibility's caused by a temperature difference between the oscillating working fluid and the stack result in the correct phasing between the pressure and temperature oscillations. The phasing is such that when

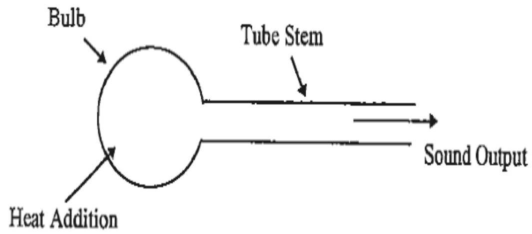
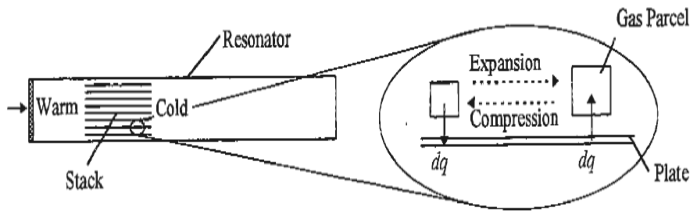


Figure 2. The Sondhauss tube. Heat is applied to the bulb resulting in the production of sound.



(a) (b)

Figure 3. A simple thermoacoustic refrigerator showing a magnified view of a gas parcel as it transports a small amount of heat dq along the stack.

the element is in its right-most position it has been expanded to a temperature that is colder than the local stack temperature, and so absorbs heat from the stack, and when the gas parcel is displaced up the plate to its left-most position .it is compressed to a temperature that is hotter than the stack, thereby rejecting heat to the stack. As all gas elements within the stack behave in a similar manner the net result is the transport of heat up a temperature gradient (from the cold
to warm end of the stack). Tiris heat transport between the gas and the stack only occurs within a region close to the stack known as the thermal penetration depth (δ k).

Work is absorbed by the gas element as the thermal expansion occurs during the low pressure phase and the thermal contraction during the high pressure phase of the acoustic cycle. If a temperature gradient is imposed along the stack and the temperature gradient is large enough, the device ceases to be a thermoacoustic refrigerator and starts producing work.it becomes a thermoacoustic engine. Tiris is because after the gas parcel has been adiabatically compressed it will no longer be hotter than the stack and will absorb heat (instead of rejecting it) at high pressure and expand, thereby doing work. For a review of the theory behind thermoacoustic engines see [7].

2.2 Vapour Compression Refrigeration System.

A basic vapour compression refrigeration system consists of four major components: a compressor, condenser, capillary rube, and evaporator as shown in Figure 4(b). Heat is absorbed at low temperature in the evaporator and rejected

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at the condenser. Work is supplied through the compressor. Non-adiabatic capillary rubes are normally used in household refrigerators where the capillary is soldered to the suction line or run inside the suction side to superheat the suction gas to ambient temperatures. [12] In the future compressors are likely to have variable speed drives, enabling them to run continuously to meet lower load situations but at higher compressor efficiencies.

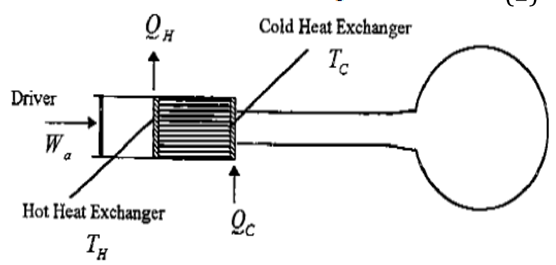
[2.3] Comparison Of Thermo Acoustic And Vapour Compression Refrigeration Systems.

The coefficient of performance (COP) is the standard measure of the efficiency of refrigeration systems. The COP of the thermoacoustic and vapour compression refrigeration systems shown in Figure 4 are respectively:

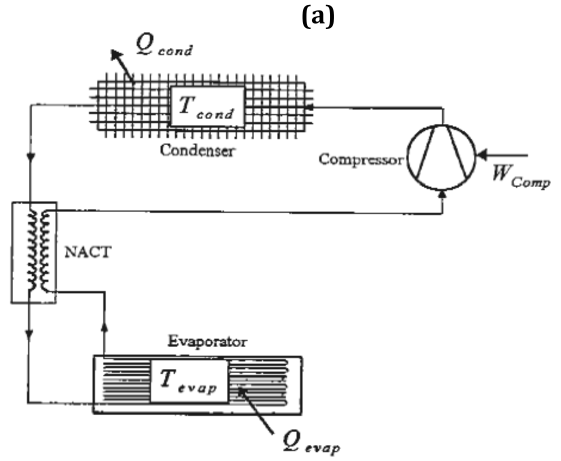
$$cop = \frac{Q_c}{W_a} \qquad cop = \frac{Q_{evap}}{W_{comp}} \qquad (1)$$

where, for the thermoacoustic system, Q_c is the heat load into the cold end of the stack and W_a is the acoustic power into the resonator. For the vapour compression system Q_{evap} represents the evaporator capacity (i.e. the heat load that the refrigerant in the evaporator has to remove to keep the fridge air at the desired temperature; normally 3 C) and W_{comp} the mechanical work into the compressor. For a refrigeration cycle the COP is bounded by the Carnot efficiency which is given by: [13]

$$COP_{carnot} = \frac{T_{evap}}{T_{cond} - T_{evap}} \qquad (2)$$



(a)



(b)

Figure 4. (a) A simple thermoacoustic refrigerator. (b) Component diagram of a vapour compression household refrigerator/freezer with Non-Adiabatic Capillary Tubes (NACT) as expansion valves.

The thermoacoustic system was compared to a vapour compression system for two evaporator temperatures, T_{evap}, of -15 C and -25 C, corresponding to a refrigerator and freezer configuration respectively. The evaporator temperature corresponds to the cold heat exchanger temperature T_c in the thermoacoustic system. These temperatures were chosen in order to keep the internal air temperature at 3 C for a refrigerator and -15 C for a freezer . The condenser temperature, T_{cond} , which corresponds to the hot heat exchanger temperature T_H of the thermoacoustic system, was held at 43 C for both of these evaporator temperatures. From equation (2) the Camot efficiency for the fridge and freezer are respectively 4.45 and 3.65.

[2.4]Thermoacoustic refrigerator model.

The thermoacoustic refrigerator was modelled using DeltaE [8] (Design Environment for Low amplitude themoacoustic Engines). DeltaE is a program which solves the one dimensional wave equation for acoustic and thermoacoustic elements based on a low-amplitude acoustic approximation. Within the stack the wave equation [7] is solved simultaneously with the enthalpy equation [7] in order to :fmd both the temperature and pressure profiles. For other components in the system, the appropriate wave equation is used with continuity of pressure and volumetric velocity applied at the intersection of each section. The program does not take account of non-linear effects. Losses generated within the stack are accounted for as well as losses from the resonator and rough estimates for heat exchanger losses. Losses not included were those from the driver plus those incurred by the need for some external heat exchanger loop to get the heat from the cold refrigerated compartment into the stack and reject the waste heat at the other end of the stack. Before using DeltaE an initial design for a 200 W thermo acoustic refrigerator was obtained using closed form solutions of the short engine equations [7]. These equations do not provide an accurate enough estimate to predict the actual performance, but do give an initial design that can be used by DeltaE.

[2.5] Vapour compression refrigerator model.

It is assumed that future refrigerators will be designed for a maximum capacity (say, Q_{evap} = 200 W) and will have a variable speed control mechanism on the compressor. This will allow them to run continuously (rather than the current on- off approach) at lower speeds to meet lower load conditions. For such a mechanism it is further assumed that the compressor efficiency at the design point (Q_{evap} =200 W) will have a volumetric efficiency, say of about 60% and an isentropic efficiency, say of about 55%, and that these efficiencies will increase in steps of about 10 % and 1% respectively as the cabinet load reduces by 50 W, as shown in Figure 5.

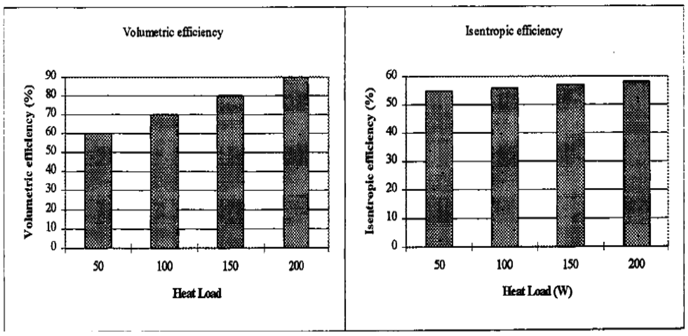


Figure 5. Changes in the volumetric and isentropic efficiency with heat load of a variable speed compressor.

For the system analysed no account was taken of sub-cooling or superheating, however a rise of 27 C in the gas suction line was assumed, with the capillary exposed to ambient air (about 32 C) so that the return gas temperature to the compressor is 32 C. It is also assumed that the pressure losses in both the heat exchangers (the evaporator and condenser) are about 10 %. The computations were made using BICYCLE [9] for both the refrigerator and freezer .

COP Comparison:

A comparison of the COP of each system was made for both the refrigerator and freezer at a variety of heat loads,namely Q_c and Q_{evap} of 50, 100, 150, and 200 W. The results are shown in Figure 6.The amount of heat that the thermoacoustic system could pump was altered by changing the driving ratio as shown in Figure 7(a). The higher the driving ratio, the more heat that could be pumped, but at a lower efficiency. The highest driving ratio obtained was 0.049, which corresponds to a freezer with a 200 Wheat load. Here, non-linear effects are becoming significant, but linear theory still gives reasonably accurate results. [14]As already stated, the heat load in the vapour compression system was altered by varying the speed of the compressor, the appropriate compressor size as calculated by BICYCLE for each heat load is given in Figure 7(b)

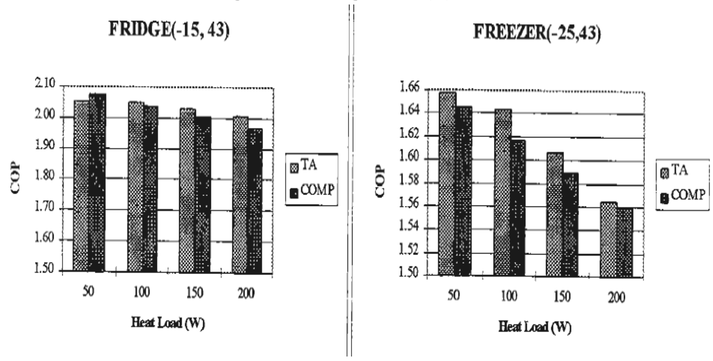


Figure-6. Comparison between the COP of a thermoacoustic (T A) and vapour compression (COMP) refrigerator and freezerforheat loads of 50, 100, 150, and 200 W.

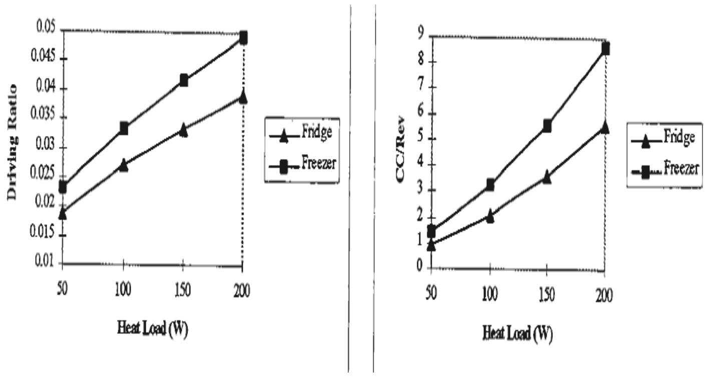


Figure 7. (a) Variation of the driving ratio with heat load for a thermoacoustic refrigerator and freezer, and (b) The CC rating of a vapour compression refrigerator and freezer at different heat loads.

[3] Discussion And Conclusions:

For the relatively small heat loads of household refrigerators and freezers, thermoacoustic refrigeration compares well with the vapour compression system. However, they are not competitive when the application requires large heat loads.This is a result of the inherent irreversibility of the process (the transfer of heat across a non-zero temperature difference) which causes a conflict between the COP and cooling capacity. Only in the limiting case of zero heat load can the process become reversible and reach the theoretical maximum efficiency. They are therefore ideal for applications that require low heat loads, such as the cooling of electronic equipment.

While in theory thermoacoustic refrigerators offer competitive efficiencies for the household refrigeration market, practical applications require that efficient means of getting heat into and out of the stack be developed. This will most likely require some extemalloop which connects the cold end of the stack to the space that needs to be cooled and the hot end to the environment. This loop will of course add additional losses and a further complication to the system. Only by considering these heat exchanger losses can a realistic comparison be made with vapour compression systems. One feature that may prove useful is that Thermoacoustic refrigerators can be driven by a Thermoacoustic engine. This would mean that such a refrigerator would have no moving parts and could use other forms of energy directly, e.g. natural gas, instead of electricity. In areas where electrical energy may not be readily available, either due to isolation or being expensive, Thermoacoustic refrigeration may offer a competitive solution. [15]There is still much that can be done to improve the performance of Thermoacoustic system. One area where the efficiency of these devices can be increased is the reduction of the viscous loss within the stack. The viscous loss is a result of work being required to overcome the viscous shear force as the gas oscillates. Due to the viscous and thermal penetration depths being comparable most of the area within the stack experiences viscous shear. This loss may be reduced by using alternative stack geometries. A general formulation for channel stacks of arbitrary geometry [10] concludes that parallel plate channels are the most efficient. It has been further identified that pin stacks offer even greater improvements in efficiency [11]. Another area of current interest is to extend the theory to include non-linear effects. This is because the assumption of small oscillations made in the linear theory becomes inaccurate for the high drive ratios which allow higher heat loads.

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