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Investigation on Thermoacoustic refrigeration using a standing-wave device

KEYWORDS: Thermo acoustic devices, thermo acoustic refrigerator and heat pump, travelling-wave devices, standing-wave devices.

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ABSTRACT *In this paper, we explored the basic principles of thermo acoustic refrigeration; Combined with an understanding of the underlying thermodynamics, the model enables us to spread awareness of the viability of thermo acoustic devices as refrigerator. Thermo acoustics is a field that combines thermodynamics, fluid dynamics and acoustics. In thermo acoustics it is possible to construct thermodynamic engines, prime movers and heat pumps which respectively use heat to create work and use work to create or move heat. There are two classes of thermo acoustic devices: - travelling-wave devices and standing-wave devices. The first use a standard travelling acoustic wave and the second use a resonator in which the acoustic waves interfere causing a standing-wave.*

The paper focuses on the following two main points. To determine practical applications where thermo acoustic refrigeration may prove a strong rival to current methods, and to determine what future developments are required for this technology to be of commercial value.

Introduction:
The thermo acoustic theory as known today was first developed by Rott and reviewed later by Swift. Rott adapted the Navier-Stokes (momentum) equation and mass continuity equation to make them usable in thermo acoustics. Swift continued with Rott's theory and derived equations for the acoustic power in thermo acoustic devices. The thermo acoustic effect was first discovered in the 19th century when heat driven acoustic oscillations were observed in open-ended glass rubes. (From reference 4) These devices were the first thermo acoustic engines, consisting of a bulb attached to a long narrow tube. Thermo acoustics is a relatively new field in physics which combines thermodynamics, fluid dynamics and acoustics. Using heat, acoustic work can be created, or by using acoustic work heat can be moved or created. The acoustic work is the sound power of a wave.

Thermo acoustics is a term used to describe the effect arising from sound waves creating a heat gradient, and vice versa. Thermo acoustic devices are typically characterised as either 'standing-wave' or 'travelling- wave' configurations, where the thermodynamic processes occur in a closed vessel. Sound waves require a medium to propagate. In a gas, sound waves are adiabatically compressed and decompressed. During compression, pressure increases and so does temperature, and during decompression pressure and temperature both decrease.

The adiabatic change can be shown using the ideal law for gases,

$$pV = nRT$$

Where p is pressure, V volume, n amount of the substance, R the gas constant and T the temperature. The following expression can be derived for adiabatic temperature change caused by pressure change

$$\frac{dT}{T_m} = \frac{\gamma - 1}{\gamma} \frac{dp}{p_m}$$

Where γ is the polytrophic coefficient. The formula clearly shows that temperature and pressure change occur simultaneously.

While acoustics is primarily concerned with the macroscopic effects of sound transfer like coupled pressure and motion oscillations, thermo acoustics focuses on the microscopic temperature oscillations that accompany these pressure changes. Thermo acoustics takes advantage of these pressure oscillations to move heat on a macroscopic level. This results in a large temperature difference between the hot and cold sides of the device and causes refrigeration.

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.

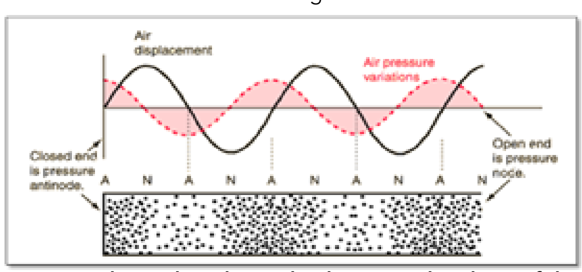

Figure 1: Shows the relationship between the phase of the wave, the pressure, and the actual arrangement of the molecules. The black line shows the phase of the sound wave, the red shows the pressure and the dots below represent the actual molecules. (From Reference 2)

The Basics of Thermo acoustic Refrigeration:
Thermo acoustic refrigeration systems operate by using sound waves and a non-flammable mixture of inert gas (he-

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lium, argon, air) or a mixture of gases in a resonator to produce cooling.

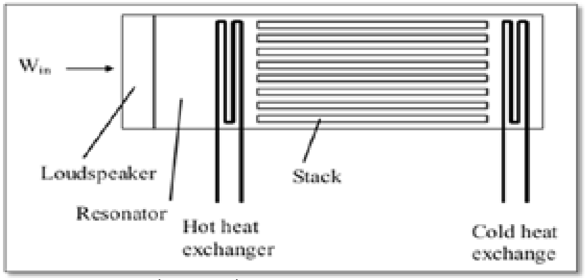

Figure 2: *Sound wave Thermo acoustic engine*

A schematic diagram of a standing wave device is shown in Figure 2. The main components are closed cylinder, an acoustic driver, a porous component called a "stack, and two heat-exchanger systems. Application of acoustic waves through a driver such as a loud speaker makes the gas resonant. As the gas oscillates back and forth, it creates a temperature difference along the length of the stack.

This temperature change comes from compression and expansion of the gas by the sound pressure and the rest is a consequence of heat transfer between the gas and the stack. The temperature difference is used to remove heat from the cold side and reject it at the hot side of the system. As the gas oscillates back and forth because of the standing sound wave, it changes in temperature. Much of the temperature change comes from compression and expansion of the gas by the sound pressure (as always in a sound wave), and the rest is a consequence of heat transfer between the gas and the stack.

In the travelling-wave device, the pressure is created with a moving piston and the conversion of acoustic power to heat occurs in a regenerator rather than a stack. The regenerator contains a matrix of channels which are much smaller than those in a stack and relies on good thermal contact between the gas and the matrix. The design is such that the gas moves towards the hot heat exchanger when the pressure is high and towards the cold heat exchanger when the pressure is low, transferring heat between the two sides.

Working Principle of Thermo acoustic Refrigeration:
A basic thermo acoustic refrigerator consists of a stack of thin parallel plates housed within a resonator, as shown schematically in Figure 3(a). Heat can be pumped from the cold to warm 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).

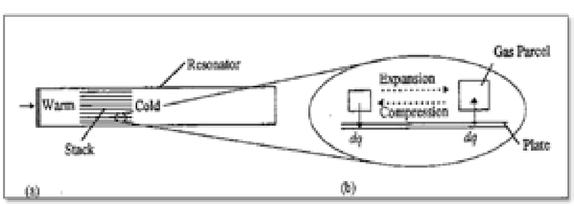

Figure 3. *A simple thermo acoustic refrigerator showing a magnified view of a gas parcel as it transports a small amount of heat* ***dq*** *along the stack.*

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. 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 development of a temperature gradient (from the cold to warm end of the stack). This heat transport between the gas and the stack only occurs within a region close to the stack known as the thermal penetration depth. 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 thermo acoustic refrigerator and starts producing work and thus finally it becomes a thermo acoustic engine. This 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. (From reference 5).

Operation Procedure and Experimental Results:
The thermo acoustic effect along the stack is studied quantitatively recording as a function of time the temperature when the system is driven at its fundamental resonance frequency. This last has been determined in a preliminary phase tuning the frequency at low dynamic pressure until the sound level meter signal reaches a maximum.

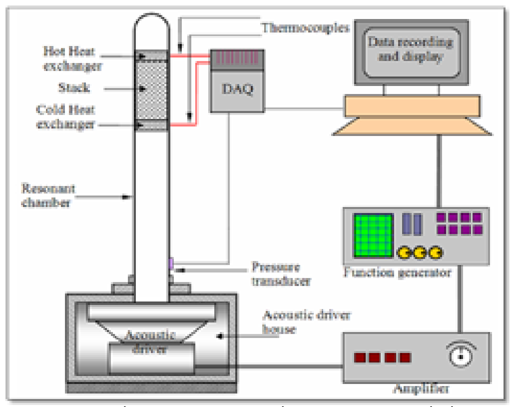

Figure 4: *Thermo acoustic heat pump and the measuring systems*

At the beginning of each set of measurements the entire structure is at room temperature (300 K). Next, the thermoacoustic effect (hydrodynamic heat flow) is started when acoustic power is suddenly applied (at t = 0). As no thermal reservoirs are connected to the stack ends, the thermoacoustic heat flow is sustained from the plates themselves. Each plate, therefore, will cool at C (near the pressure node), where heat is removed and will heat at H (near the pressure anti-node), where heat is reversed.

Figure 5 shows typical experimental results of the time evolution of the temperatures measured at the extremities of the Corning Celcor stack which is 4cm (0.04λ) long and the center of the stack is located 5 cm from the nearest pressure antinode. Right after the acoustic power is supplied, the temperature of the stack end that is close to the closed end of the tube starts to increase (as shown in Fig. 5) and the other end starts to decrease.

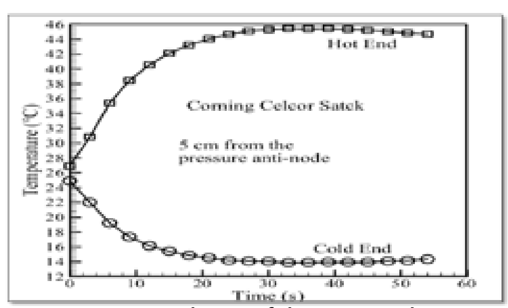

Figure 5: Time evolution of the measured temperatures at

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different locations on the stack when the 4 cm Celcor stack is placed 5 cm from the nearest pressure antinode.

After approximately half a minute, a temperature difference of 31°C is measured across the stack ends, with a cold side temperature of 13.8°C and a hot side temperature of 45°C as shown in Fig. 5. In this heat pump, the acoustic energy is supplied by the loudspeaker, and the gas particles near the stack plates absorb this energy. A hydrodynamic heat flow takes place in the gas near the surface of the stack plate and is directed from the stack end that is closest to the loudspeaker end to one that is near the pressure anti-node.

Because of this hydrodynamic heat flow, a temperature gradient develops across the stack with a cold end near the loudspeaker end and a hot end near the closed end. Figure 5 shows that the temperature difference across the stack increases rapidly in the early stages (during the first 10 seconds) of the hydrodynamic heat flow process, where the growth is highest.

In this early stage of hydrodynamic heat flow process, the diffusive heat flux from the hot end of the stack to that of cold end is not significant. After approximately 30 seconds, the temperature curves become flat, clearly reflects the increasingly role played by a diffusive heat flux through the stack plates and the gas from hot to cold end which tends to balance the hydrodynamic one.

The diffusive heat flow driven by the temperature difference is zero at the initial time where the temperature curves exhibit their maximum slope and maximum at the steady state when curves become flat.

Conclusion:

This paper contains a basic explanation and architectural analysis of thermoacoustic refrigeration systems. Research in thermoacoustic refrigeration has shown that these systems can be as overall efficient as vapour compression cycle refrigeration technology, in many situations.

According to theory thermo acoustic 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.

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