## 1.2 Basic principle of the thermoacoustic effect

Acoustic waves consist not only of coupled pressure and displacement oscillations in a gas, but also of temperature oscillations as a response to the pressure variations. The interaction of these effects in gas close to a solid surface generates thermoacoustic oscillations. At the surface heat can be extracted or supplied to the gas. The result of this interaction is that a sound wave is sustained in case of a large temperature gradient along the surface. While in the reverse case acoustic work is absorbed in order to transport heat, generating a temperature gradient.

The mechanism of the thermoacoustic effect can best be visualized by considering a tube containing a gas, closed at one end and at the other an oscillating piston is moving forwards and backwards, compressing and expanding the gas in the tube, as shown in Fig.(1.4). In order to understand how the thermoacoustic cycle works, we follow a small volume of gas (parcel), as indicated by the small square in Fig(1.4), as it moves alongside the wall of the tube. The motion of the piston is sinusoidal but for simplicity and clarity we consider a step by step cycle: (rapid motion-wait-rapid motion-wait-etc). This is indicated in Fig.(1.4) by the steps $[1-2-3-4-1-etc]$. This cycle forms the thermodynamic cycle of the thermoacoustic effect. It consists of two reversible adiabatic steps 1 and 3 and two isobaric heat transfer steps 2 and 4, like in the Brayton cycle.

The heat-pump process (refrigeration) occurs when the temperature gradient on the wall is zero or small, Fig.(1.4a). At the beginning of the cycle (step 1), the piston moves to the right in the direction of the closed end, compresses the parcel of gas which warms up. At this time, the parcel of gas is warmer than the local wall temperature, and heat flows irreversibly from the parcel to the wall (2). In step 3 the piston moves back, the parcel expands and cools. The parcel of gas is now colder than the local wall position, and heat transfer from the wall to the parcel takes place (4). At this moment, the parcel of gas is at the initial position, and the cycle starts again. As a result a small amount of heat is transported by the parcel of gas from the left to the right. After many cycles, a temperature gradient builds up along the tube and the piston end cools down and the closed end warms up. This process takes place as long as the temperature gradient in the gas, as a consequence of compression, is higher than the temperature gradient along the wall (and vise versa for the expansion). The work used to compress the gas in step 1, is returned in step 3, so that net no work is consumed in these two steps. During the heat transfer, step (2), the parcel of gas will contract and the piston has to move a little to the right to keep the pressure throughout the gas constant. In step (4), the piston has to move to the left. A schematic pV-diagram for the refrigeration cycle, where V is the volume in front of the piston, is shown in

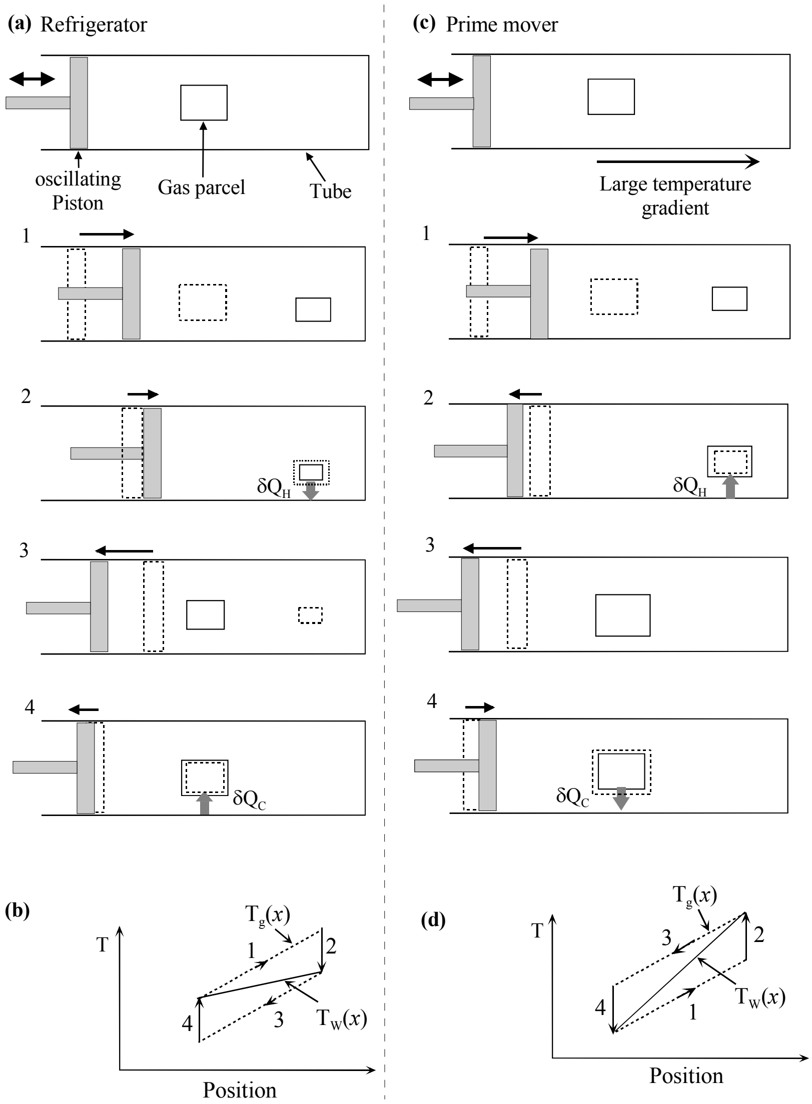


Figure 1.4: *A typical gas parcel executing the four steps (1-4) of the cycle in a thermoacoustic refrigerator (left side) and prime mover (right side), assuming an inviscid gas and square-wave acoustic motion and pressure. In each step, the dashed and solid squares and vertical rectangles show the initial and final states of the parcel and piston, respectively. (b) Gas temperature* $T_g(x)$, *and wall temperature* $T_w(x)$ *versus position for the refrigerator. (d) Gas temperature* $T_g(x)$, *and wall temperature* $T_W(x)$ *versus position for the prime mover.*

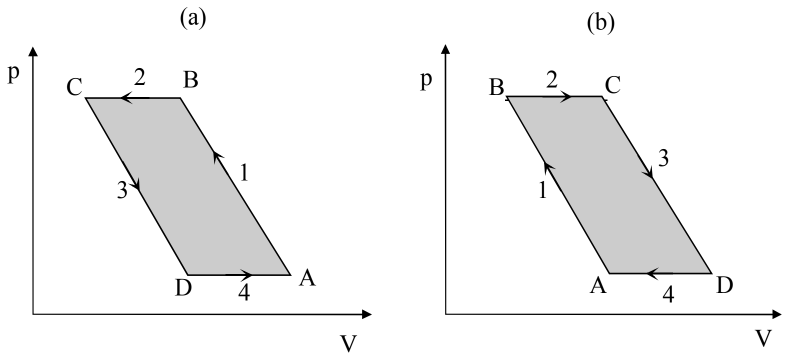


Figure 1.5: *Schematic pV-diagram for the thermoacoustic cycle (Fig.(1.4)). a) Refrigerator; the area ABCD represents the work used. b) Prime mover; the area ABCD represents the work produced.*

Fig.(1.5a). The area ABCD represents the work used during the cycle. Actually, the whole gas alongside the wall of the tube contributes to the heat pump process.

In Fig.(1.4c), the heat generation of sound in the so-called prime mover, is illustrated. The prime-mover cycle also consists of two adiabatic $(1, 3)$ and two isobaric heat-transfer steps $(2, 4)$. The only difference with the heat-pump case is that now we apply a large temperature gradient $\nabla T$ along the tube, so that the directions of heat transfer in steps 2 and 4 are reversed. When the parcel of gas is compressed, it warms up, but is still colder that the local wall position. Heat then flows from the wall into the parcel which expands. As a consequence of this expansion of the gas the piston will be pushed to the left and work is generated. In step 4, after the expansion, the gas element is warmer than the wall and heat flows into the wall. The gas contracts and work is done by the piston. The net work produced in one cycle is given by the area ABCD in Fig. (1.5b). As a result, a standing wave can be sustained by a large temperature gradient along the wall of the tube.

In summary, during the compression step 1, the parcel of gas is both displaced along the wall and compressed. Two temperatures are important: the temperature of the gas after adiabatic compression and the local temperature of the wall adjacent to the parcel. If the temperature of the gas is higher than that of the wall, heat flows from the gas to the wall (heat pump). If the temperature of the gas is lower, heat flows from wall to gas (prime mover). Both heat flow and power can thus be reversed and the heat transfer process can be switched between the two modes by changing the temperature gradient along the wall. A small temperature gradient is the condition for heat pump; a high gradient is the condition for a prime mover. The gradient that separates the two regimes is called the *critical temperature gradient.* For this gradient, the temperature change along the wall matches the temperature change due to adiabatic compression, and no heat flows between the gas and the wall. The *critical temperature gradient* will be defined in the next chapter.

In the heat-pump regime work is absorbed to transfer heat from lower temperature to higher temperature. In this case, an acoustic wave has to be sustained in the tube to drive the process. In the prime mover mode the gas expands at high pressure (heat absorption), and contracts at low pressure (heat release), so that work is produced. In this case, the large temperature gradient sustains the acoustic oscillations.

All periodic heat engines and refrigerators need some time phasing to operate properly. Conventional systems use pistons to compress and displace the gas in a given sequence. In thermoacoustic devices, this time phasing is ensured by the presence of the two thermodynamic media: gas and a solid surface, so that the irreversible heat transfer in steps 2 and 4 introduces the necessary time lag between temperature and motion. The compression and displacement are determined by the acoustic wave, instead of pistons.

At this stage, it is important to note that not all the gas in the tube is equally effective to the thermoacoustic effect. The elements of gas far away from the wall have no thermal contact, and are simply compressed and expanded adiabatically and reversibly by the sound wave. Elements that are too close to the wall have a good thermal contact, and are simply compressed and expanded isothermally. However, elements at about a distance of a thermal penetration depth $\delta_k$ from the wall (c.f. next chapter), have sufficient thermal contact to exchange some heat with the wall and produce a time delay between motion and heat transfer which is necessary for the heat pump process. The quantity $\delta_k$ is the distance across which heat can diffuse through the gas in a time $1/\pi f$, where $f$ is the acoustic frequency. As indicated in section 1.1, Carter et al.[8] realized that the performance of the thermoacoustic Sondhauss tube could be greatly improved by inclusion of a stack of small tubes. This has the effect of increasing the effective contact area between gas and solid over the cross-section of the tube, so that the whole gas contributes to the process.

The appropriate use of stacks and their position in acoustically resonant tubes can produce powerful refrigerators (heat pump) and heat engines. We have to note here that even though the system uses a standing wave to displace, compress and expand the gas in the stack, a small travelling acoustic wave component is necessary to maintain the standing-wave resonance against the power absorption in the system [19]. Systems using only traveling waves, which can be made more efficient, are also possible [19, 25].

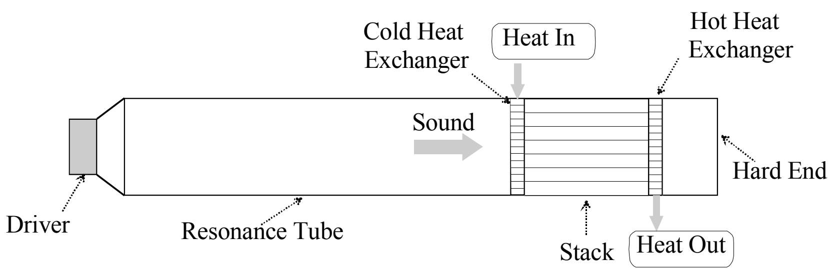


Figure 1.6: *A simple illustration of a thermoacoustic refrigerator.*

## 1.3 Applications

In Section 1.2, the essentials of thermoacoustics were explained. Under favorable conditions, powerful or small size thermoacoustic devices can be built to operate as prime-movers or heat-pumps.

Since the development of the first practical thermoacoustic apparatus in the early eighties at LANL [17, 23], thermoacoustic technology has received an increasing attention as a new research area of heat engines and heat pumps. Since then, many thermoacoustic systems have been built, mostly at LANL, Naval Postgraduate School (NPS) in Monterey (California), and at Pennsylvania State University.

Heat pumps and refrigerators use an acoustic driver (loudspeaker or prime mover) to pump heat from a cool source to a hot sink. A simple thermoacoustic refrigerator is shown in Fig.1.6. Such systems contain a loudspeaker, which drives an intense sound wave in a gas-filled acoustical resonator. A structure with channels, called the stack, is appropriately placed in the tube. The stack is the heart of the refrigerator where cooling takes place.

Two examples of refrigerators that were built and tested at NPS are: The Space Thermoacoustic Refrigerator (STAR) [24], which was designed to produce up to 80 K temperature difference over the stack, and to pump up to 4 watt of heat. The STAR was launched on the space shuttle Discovery in 1992. The second setup is the Shipboard Electronics ThermoAcoustic Cooler (SETAC) that was used to cool radar electronics on board of the warship *USS Deyo* in 1995 [26]. It was designed to provide 400 watt of cooling power for a small temperature span, which is similar to a domestic refrigerator/freezer system.

At Pennsylvania State University, a large chiller called TRITON is being developed to provide cooling for Navy ships [27]. It is intended to produce a cooling power of about 10 kW which means that it can convert three tons of water at $0^0$C to ice at the same temperature in one day.

At LANL, a heat-driven thermoacoustic refrigerator known as the "beer cooler" was built, which uses a heat-driven prime mover instead of a loudspeaker to generate the sound necessary to drive the refrigerator [28]. A similar device, called a ThermoAcoustic Driven ThermoAcoustic Refrigerator (TADTAR) was recently built at NPS. It has a cooling power of about 90 watt for a temperature span of 25 $^0$C. Such a device has no moving parts at all. Also at NPS, a solar driven TADTAR has been built which has a cooling capacity of 2.5 watt for a temperature span of 17.7 $^0$C [29].

At LANL, much of the efforts focused primarily on large thermoacoustic engines, using heat to generate sound, which is used to generate electrical power or to drive coolers to liquefy natural gas. One example of such efforts is a collaboration between LANL and an industrial partner to develop a cryogenic refrigeration technology called ThermoAcoustically Driven Orifice Pulse Tube refrigeration (TADOPTR)[30]. This technology has the unique capability of producing cryogenic temperatures (115 K) with no moving parts. It uses a pulse-tube refrigerator which is driven by a natural-gas-powered thermoacoustic prime mover. A machine with a cooling capacity of 2 kW producing about 0.5 m$^3$/day, has been developed [30]. A second system, using a traveling wave prime mover, is now under construction. This has a higher efficiency [31], and a cooling capacity of about 140 kW. It is expected that it will burn 20 % of natural-gas to liquefy the other 80 % at a rate of about 50 m$^3$/day.

At Tektronix, a TADOPTR was also built to provide cooling of electronic components. The prime mover, used in this cooler, provided 1 kW to the pulse-tube refrigerator with an efficiency of about 23 % of Carnot [32]. The prime mover was driven by an electric heater. Hence the system had no moving parts.

The potential of applications of thermoacoustic devices is substantial, as can be understood from the foregoing examples. Prime movers can be used to generate electricity, or to drive refrigerators. Thermoacoustic heat pumps can be used to generate heating, air-conditioning or cooling of sensors, supercomputers, etc. Their advantage is that they can have one (loudspeaker), or no moving parts, no tight tolerances, making them potentially reliable and low cost. Besides being reliable, they use only inert gases (no CFC's) so they are environmentally friendly. On the other hand, standing-wave thermoacoustic devices have a relatively low efficiency. However, thermoacoustic is still a young technology. Recently, the LANL team has designed a traveling-wave prime-mover which has an efficiency much higher than the standing-wave counterpart. This engine is a Stirling version of the thermoacoustic prime-mover. It has a thermal efficiency of 30 % [30, 31, 33], while typical internal combustion engines are 25 to 40 % efficient. Thermoacoustic refrigerators can also be made using this principle, and reach efficiencies comparable to vapor compression systems. Swift gave an excellent review of the current status of the field of thermoacoustics in his introductory book [30].

## 1.4 The scope of this thesis

Since the seventies, the research in the Low Temperature group focused on dilution refrigerators. Such devices generate cooling by mixing $^4$He and $^3$He. Temperatures as low as 2 mK can be reached. About a decade ago the group's attention shifted to other new cooling technologies and their applications. Presently, the pulse-tube refrigerator forms the main research area of our group. The pulse-tube refrigerator is a successor of the Stirling-cycle refrigerator. The Stirling refrigerator requires two moving parts, one of which is in contact with the cold temperature. In 1963, Gifford and Longsworth[21] discovered a refrigeration type which eliminated the cold moving part. The elimination of the moving part at the cold side is a very important step towards high reliability. Recently, Swift et al.[32] eliminated the remaining piston at ambient temperature, substituting for it a thermoacoustic heat engine, as discussed in Section 1.3.

Since thermoacoustic technology can also lead to devices without moving parts, attention in the Low Temperature group is also focused in this direction for possible applications. The work presented in this thesis is a start in this research direction.

The quantitative (theoretical) understanding of the physical principle underlying the thermoacoustic effect is well established and has been discussed in many papers. But a quantitative experimental investigation of the effect of some important parameters on the behavior of the thermoacoustic devices is still lacking. Important parameters are the spacing between the parallel plates in the stack and the Prandtl number, as they determine the energy flow. Hence, we decided to investigate experimentally the effect of the spacing in the stack by constructing many parallel-plate stacks with spacing varying between 0.15 and 0.7 mm. The effect of the Prandtl number on the performance of the thermoacoustic refrigerator is investigated using gas mixtures of helium-argon, helium-krypton, and helium-xenon. These provided gas mixtures with Prandtl numbers varying between 0.2 and 0.68. The measurements show that the performance of the refrigerator rises as the Prandtl number decreases. The lowest Prandtl number of 0.2, obtained with a mixture containing 30 % xenon, leads to a coefficient of performance relative to Carnot which is 70 % higher than with pure helium. The measurements show also that in our system a plate spacing in the stack of 0.25 mm leads to a maximum in cooling power, and that a spacing of 0.4 mm leads to the lowest temperature. A low temperature of nearly -67 $^0$C is achieved with our cooler which is one of the lowest reported temperatures up to date. In addition, we invented a technique, using the gas in the back of the loudspeaker driving the refrigerator, to optimize the electroacoustic efficiency of the loudspeaker. By tuning the mechanical resonance of the loudspeaker to the acoustic frequency of the resonator, an electroacoustic efficiency of 35 % is obtained, compared with the electroacoustic efficiency of commercial loudspeakers of only 3 to 5 %. This is an important improvement. Combining the above discussed effects, we made a contribution towards more efficient thermoacoustic refrigerators.

This thesis focuses on the design, development, and optimization of a thermoacoustic refrigerator, using the linear thermoacoustic theory as a guideline. In Chapter 2 the basic thermodynamic and thermoacoustic principles will be reviewed. Chapter 3 is concerned with the linear theory of thermoacoustics, first developed by Rott, and reviewed by Swift. The same mathematics will be used in broad lines; the various theoretical expressions, important to the design and experiment, will be given. Chapter 4 gives an expression for the Prandtl number for binary gas mixtures, derived from kinetic theory, and we will show how this quantity can be made lower than 2/3. Chapter 5 is dedicated to the electrical model which is used to simulate the behavior of the loudspeaker in the refrigerator, and illustrate how the performance of the loudspeaker can be improved, along with the practical means to achieve that goal. In greater detail, the conception, design, and engineering of the different parts of the thermoacoustic refrigerator will be illustrated in Chapter 6. The experimental set-up is described in Chapter 7, along with the experimental techniques for the measurements. Subsequently, in Chapter 8, the results of the experiments performed in this work will be described. Finally in Chapter 9, the experimental results are summarized, and some conclusions are drawn, along with some suggestions for future research.