PATXI DUTHIL*, JEAN-PIERRE THERMEAU*, THIERRY. LE POLLES**
*Institut de Physique Nucléaire d'Orsay
**Société HEKYOM

Thermoacoustics
is going to make a lot of nnnnnnnoise

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Thanks to "thermoacoustics", we know that a difference in temperature can generate a sound, and that a sound can carry heat. The notion that a change in temperature can transport heat is not just an association of ideas, but a whole new idea in itself! It involves, for example, generating cold from heat with the aid of a wave. This process gives a thermoacoustic refrigerator.

Photo : Générateur thermoacoustique d'onde en cours de montage et installé au bâtiment 109 de l'IPNO.

Glass blowers have known for centuries that a "humming sound" is generated in cold glass-blowing pipes heated at one end by molten glass. Only during the 1960s, however, did Nicolas Rott provide a theoretical explanation for the generation of a sound wave is generated within a resonator due to a temperature gradient (or change in temperature). The era of modern thermoacoustics began when Rott explained the phenomenon of Taconis waves* in liquid helium cryostats in mathematical terms. At the beginning of the 1980s, Weathley, at Los Alamos National Laboratory in the United States, began experimenting on the reverse process: generating a temperature difference, or gradient, by applying a sound wave to a surface, leading to the development of new types of heat pump. The same research group, and in particular, one of its more active members, Greg Swift, provided in 1988 a detailed description of thermoacoustics, and was responsible for many technological breakthroughs in this domain. Across the world, various research groups have since steadily advanced the science of thermoacoustics from the theoretical and research stages to the pre-industrial stage. In China, thermoacoustics became a "key program" of Research and Development in 2006. In the Netherlands, the Energy Research Center of the Netherlands began making a major effort in this direction in 2000, at the University of Eindhoven. Today, it is one of major players in this field within Europe. In France, the Acoustics Laboratory of the University of Maine (LAUM), the Fluid Mechanics and Acoustics Laboratory (LMFA) in Lyons, and the Computing Laboratory for Mechanics and Engineering Sciences (LIMSI-CNRS) have been working in this area since 1995. The Nuclear Physics Institute at Orsay (IPNO) joined this team in 2003. This research work has also paved the way for technology transfer to applications, through the start-up company Heykom.

Thermoacoustic techniques

Thermoacoustics is located at the interface between several scientific disciplines and techniques, and its practical implementation is relatively straigthforward. Above all, it involves amplifying the thermacoustic phenomenon, beginning with the sound wave. The fluctuations in pressure caused by the human voice, for example, amount to only a few tens of Pascals, resulting in changes in temperature of the order of a few ten thousandths of a degree (0.0001°C). Large changes in pressure are required to make a thermal device: of the order of a bar (10,000 times higher). A resonance tube that can amplify the acoustic effects in the same way that a sound wave is amplified in the body of a woodwind instrument is therefore required. The gas in the acoustic resonator must also be placed under pressure (a few dozen bars). Finally, the area of interface between the fluid and the solid must be increased, with stacks* of plates in parallel planes or with a porous medium used as a regenerator* **(Figure 1)**, to maximise the amount of thermal power transported.

It remains difficult to find a reliable source of sound waves, because loudspeaker technology is not yet efficient enough to meet the needs of thermoacoustics. More powerful wave generators, such as piston motors, are therefore required. This approach creates several technological difficulties, including the possible contamination of the system with oil and limitations on running speed due to the mechanical inertia of the pistons. However, thermoacoustics has another trick up its sleeve to overcome these problems, based on the same principle, but applied in the opposite direction, making it possible to generate a sound wave from a heat source. This makes it possible to couple a system for generating a thermoacoustic wave to a thermoacoustic heat pump, to create cold from hot, or hotter from already hot **(Figure 2)**. Thus, a heat source can be used to produce a sound wave, which can then be used for cooling or heating!

Cryodynamics

Many advances have been made in recent years, including the development in the last decade of closed loop systems, making it possible to use Stirling or Ericsson cycles with high thermodynamic yields **(inset 2)**. Thus, thermoacoustics, although still relatively unknown, is likely to become a major discipline in the field of refrigeration, given its obvious advantages. Thermoacoustics does not require the use of CFCs* and the heat source can be selected by the user (burning of gas or refuse, solar radiation, etc.). However, with this type of device temperatures as low as -170°C can nonetheless be obtained, using a single regenerator. This is because thermoacoustic systems, unlike evaporation-based systems, are not dependent on phase changes, which impose a

FIGURE 1

A stack of flat plates used in a thermoacoustic system.

fixed temperature. They can therefore be used as air-conditioning units or refrigerators (positive-temperature coolants) or as condensers and freezers (negative-temperature coolants). Moreover, these devices can produce between one Watt and several tens of kilowatts of power, and are therefore extremely versatile as cooling devices. They are reliable and require very little maintenance, as they have no moving parts. Thermoacoustic devices thus have considerable potential for commercial applications.

An acoustic refrigerator at Orsay

As part of its scientific and technical research activities in low-temperature conditions, the IPNO has focused its study of thermoacoustic systems on cooling processes **(inset 3)**.

In 2003, a pilot project based on the liquefaction of natural gas was launched by IPNO, *Université Pierre et Marie Curie* (UPMC) and LIMSI, with funding

1 The principle behind thermoacoustics

The thermoacoustic (TA) procedure uses a sound wave to achieve local heat exchange between the gas in which it propagates and a solid medium. Heat transfer occurs simultaneously along the length of the solid walls of the structure in which the gas is held. A sound wave is the propagation of a disturbance, the passage of which induces a reversible variation in the local physical properties (temperature, pressure) of the medium in which it propagates. It transports energy, but not matter. The propagation medium undergoes macroscopic displacement in the same direction as the propagating wave, and is therefore a longitudinal wave.

As it moves, the membrane of a loudspeaker or a piston set in motion by a connecting rod compresses and expands a small volume of fluid (a pocket of gas molecules) against a neighbouring volume, which in turn compresses and expands another volume, and so forth, until the gas reaches our ears. Compression heats the gas, whereas expansion cools it. Each cycle of compression and expansion is associated with an increase followed by a decrease in temperature **(Figure A)**. The pressure wave causes the volumes of gas to oscillate around a mean value. Thus, half-way through the cycle, the gas is on one side of this mean and is compressed and hot, whereas at the end of the cycle, it is on the other side of the mean and is expanded and cold. If a solid medium, such as a metal plate, is used, this solid medium is likely to accumulate heat or to slow heat transfer **(Figure B)**. With each compression phase, the heated gas warms the solid medium, whereas, during expansion phases, it absorbs heat from the solid phase. At the macroscopic level, heat is transferred from one end of the solid medium to the other, creating a temperature difference between the two ends. A heat exchanger can then be placed at each end of the plate to remove heat from a given medium to cool it (refrigerator) or, conversely, to provide the medium with heat to warm it (heat pump).

FIGURE A

Left : an expanded volume of fluid; Right : a volume of fluid subjected to a sound wave. The fluid heats up during the periods of contraction, and cools down during the periods of expansion, whilst moving backwards and forwards.

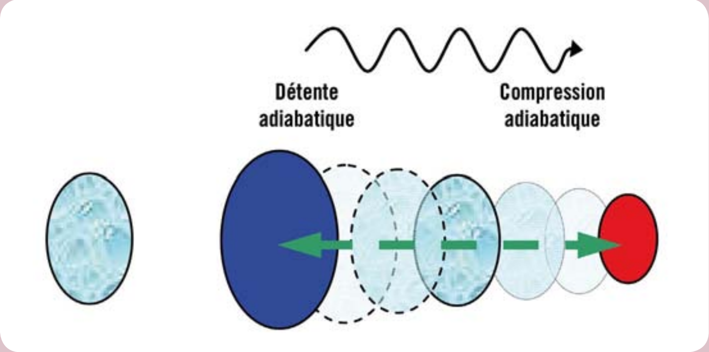


FIGURE B

Propagation of a sound wave along a solid wall. During the phases of compression and expansion, heat is exchanged with the wall, generating a difference in temperature between the two ends. The volume of fluid acts like a sponge absorbing water spilled on a table when it expands; when it contracts, it acts like the sponge releasing the water elsewhere on the table. One cycle of expansion and contraction is a bit like using a sponge to transport water from one end of the table to the other.

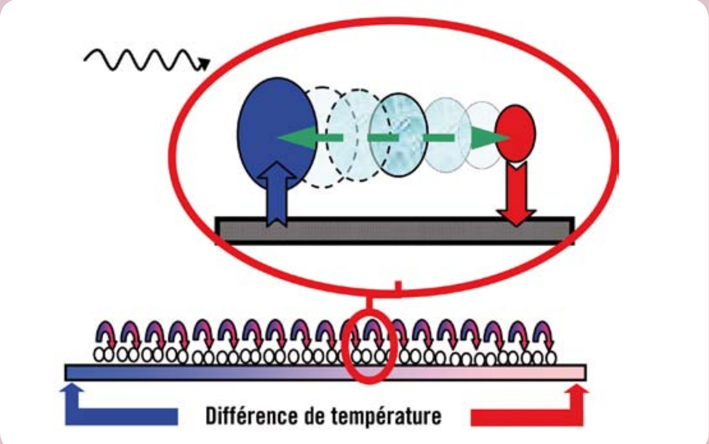
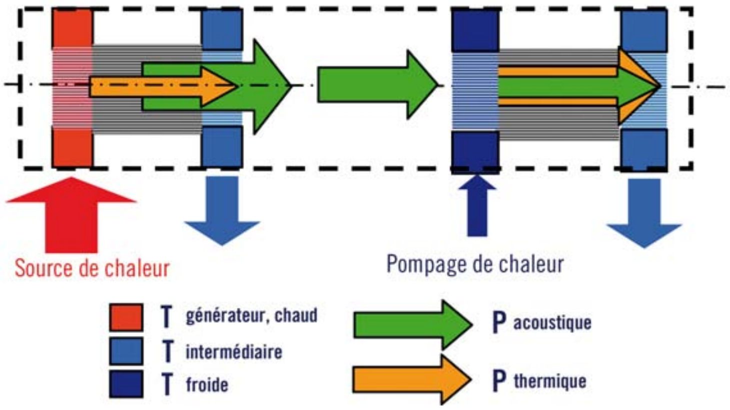


FIGURE 2

A thermoacoustic refrigerator. A thermoacoustic wave generator (left) uses heat to produce a wave that can be used to pump heat for cooling purposes (right).



2 Thermodynamic cycles and the topology of resonators

In a system for converting energy, the operating fluid (here a gas) undergoes thermodynamic transformations: variations in pressure, volume, heat transfer, displacement, etc. These changes result in a transition, with the system changing from one state to another. The thermodynamic cycle refers to the set of transformations undergone by the gas to return to its initial state. In an internal combustion engine, for example, a mixture of petrol vapour and air is compressed, burned and expanded as the piston moves up and down in a single revolution or cycle. The various transformations follow a strict sequence that determines the nature of the thermodynamic cycle. Unlike conventional systems for converting energy through the use or production of mechanical energy, as in a car engine, thermoacoustic devices do not rely on moving mechanical parts to complete a thermodynamic cycle. The sound wave replaces the piston and the camshaft. It carries out the compression and expansion, inducing temperature variations and heat exchanges, and triggers the displacement of the gas. It also controls the timing of the transformations required for a thermodynamic cycle. The features of the sound wave, which depend on the acoustic resonator in the thermoacoustic system, determine the type of thermodynamic cycle taking place, and the energy performance or yield of the system. Two properties of wave propagation can be distinguished as a function of the type of resonator:

• For a resonator closed at both ends (Figure 7, left), a standing wave induces a Brayton cycle (with the forward wave perfectly superimposed on the reverse wave. This cycle is not perfect due to irreversible events during heat transfer, so energy conversion is inefficient.

• For a toroidal resonator (forming a loop, see Figure 7, right) or a coaxial resonator, the wave is progressive (forward wave slightly out of phase with the reverse wave). The thermodynamic cycle induced therefore tends to be of the Ericsson type, similar to a Stirling cycle. Stirling cycles are theoretically reversible and convert energy very efficiently.

These propagation characteristics are usually superimposed in real systems (rate of the stationary or progressive wave), complicating device construction.

FIGURES

Topological forms of various acoustic resonators.
Left: a linear resonator; right: a resonator forming a loop.

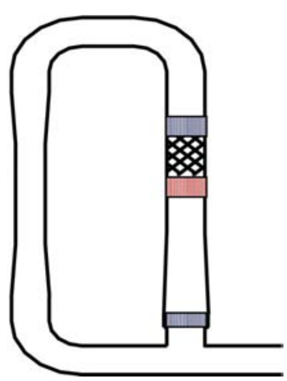
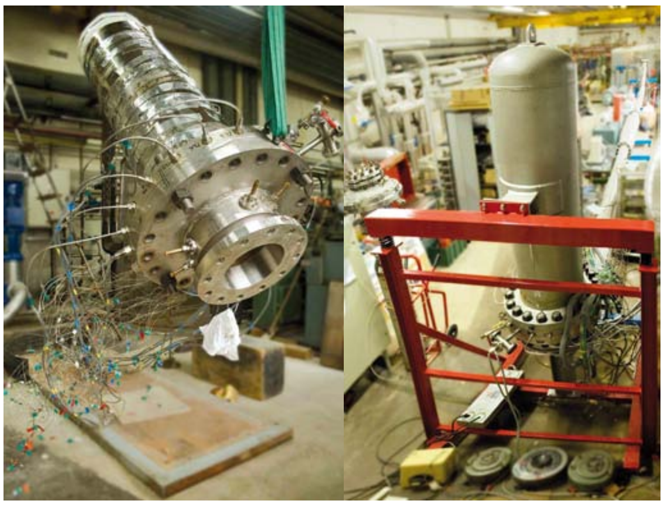


FIGURE 3

A thermoacoustic device: a trithermal system for the production of low temperatures, operating in Building 103.

FIGURE 4

A thermoacoustic prototype for liquefying natural gas: a thermoacoustic wave generator being assembled and installed in Building 109 at IPNO.



from the CNRS, the National Institute for Nuclear and Particle Physics (IN2P3), the *Conseil Général de l'Essonne*, and Oséo-Anvar Ile de France. A refrigerating device was designed for the production of 2 kW of cold at a temperature of 120 K (about -150°C). This device, built at the IPNO on the Orsay campus **(Figure 4)**, is currently being tested. Although designed for a specific application, this device remains a highly interesting research platform and has led to the development of new avenues scientific and technological research. This work will be pursued further by the various research teams at Orsay, to meet the challenges of tomorrow. This pilot device represents a real change in the level of acoustic power and in the thermoacoustic generation of cold temperatures in France. Indeed, it is the second most powerful thermoacoustic device yet produced in the world. In addition to inspiring and motivating new avenues of research at the Orsay campus, this project has provided IPNO with new experimental means, making this experimental platform the most comprehensive of its kind in France. It includes systems for generating and amplifying waves and refrigeration devices. These advances have been achieved in collaboration with Heykom and LIMSI.
Two new projects will begin in 2009. The first, funded by the as part of its research programme devoted to ecotechnologies and sustainable development (PRECODD2008), aims to develop a solar-powered thermoacoustic refrigerator. Co-ordinated by IPNO, this project will be carried out in collaboration with Heykom, the Materials and Solar Energy Processes (PROMES) Laboratory and the Heat, Energy and Procedures Laboratory (LaTEP). The second project has received funding from the European

3 Applications

Thermoacoustic energy conversion techniques can be used to transform heat energy into mechanical work in the form of a sound wave (wave generator). The power generated is then used to heat, cool, or to produce mechanical and chemical power. This approach has major advantages for meeting new energy needs in a context of sustainable development and meets the economic challenges associated with new technologies. Theoretically, thermoacoustics could be integrated into any application involving heating, cooling and or electricity production. In particular, thermoacoustic systems may be used for:

- Heat pumps for domestic use;
- Heat pumps for the recovery of lost heat;
- Devices for converting solar radiation into electrical energy;
- Devices for the condensation and revaporisation of natural gas;
- Co-generation systems;
- Tri-generation systems (electricity, heat, refrigeration);
- Solar-based refrigeration systems;
- Devices for converting geothermal heat into electricity;
- Devices for cooling electrical circuits.

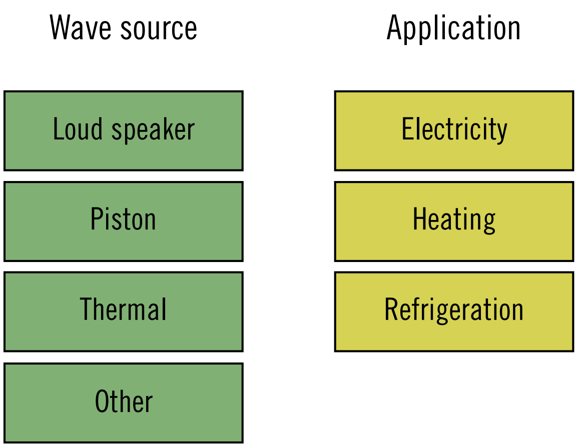
However, the characteristics of each particular situation determine whether a thermoacoustic system is more appropriate than a conventional system. Figure 8 provides a comprehensive illustration of possible thermoacoustic applications.

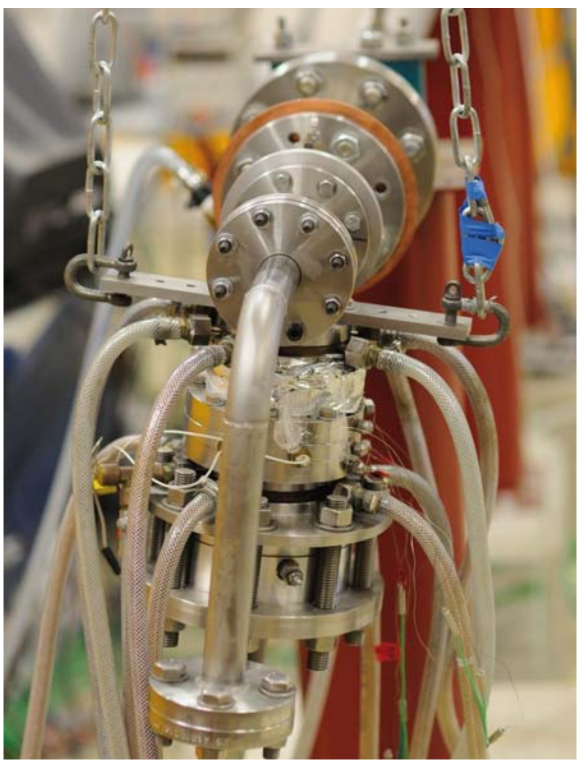
Thermoacoustics is based on a complex physical principle drawing on many scientific disciplines (acoustics, fluid mechanics, thermodynamics, heat transfer, dynamic systems, solid-state physics and electronics), but its application is relatively straightforward. Thermoacoustic devices can be manufactured from a limited number of basic components (regenerators, heat exchangers, resonators, etc.). These components must be of a size appropriate for the particular application for which they are destined, but all are based on the same scientific and technological principles. Thermoacoustic systems do not use moving mechanical parts to convert energy, and are therefore very reliable, with low maintenance costs. Only the operating gas, which is pressurised, moves. These devices are also environmentally friendly, because the gases used are usually noble gases, such as helium or nitrogen.

Union 7th Framework Programme for Research and Development (FP7), for innovative technologies. These projects should lead to several technological breakthroughs and should advance more fundamental research, relating to the study of non-linear acoustic streaming, for example. LMSI and Heykom are also participating in this European research program. Thanks to the projects undertaken by the various scientific and industrial partners in these projects, Orsay has become a European leader in research into thermoacoustic devices. ■

FIGURE 5

Designing a thermoacoustic system for a particular application.





Glossary

CFC (Chlorofluorocarbon) :
CFCs are chemical compounds commercially known as Freon. The two principal derivatives of CFCs are halons and HCFCs. CFCs damage the ozone layer in the stratosphere that protects the earth by absorbing high-energy ultraviolent radiation. They are therefore considered to be greenhouse gases. In Europe, the sale of CFCs has been prohibited since October 1st 2000, CFCs are banned from the market, and there has been a requirement to recover and destroy these compounds since January 1st 2002 (DEEE).

Taconis wave :
In the field of cryogenics, Taconis waves are created when a tube is partly submerged in a bath of liquid helium. The temperature difference between the part of the tube submerged in the liquid helium (cold) and the part that remains in the warmer "free helium" gas results in the production of a sound within the tube. The downside of this is that the sound wave transports heat to the bath. A considerable amount of heat may be transferred, with potentially disastrous consequences, due to the evaporation of the liquid in the bath. However, the sound emitted can serve as an indicator of the presence in the bath of liquid helium when the end of the tube is submerged. The Taconis wave thus indicates the level of the helium in the bath.

Regenerator :
This device stores heat and is subject to a high temperature gradient. Unlike "classical" Stirling machines, it is never completely crossed by the gas. This makes it possible to go through several elementary thermodynamic cycles imposed by the sound wave.

Resonator :
This is a mechanical device for amplifying a sound wave by concentrating all of its energy into a single frequency, known as the resonance frequency. The pipes of a pipe organ work on this principle. Another example is provided by the humming noise that can be generated by blowing across the top of an open bottle.

Stack :
This is a stack of flat parallel plates (usually made of stainless steel) spaced a few tenths of a millimeter apart. It plays a key role in thermoacoustic energy conversion. Surrounded by two heat exchangers, the stack produces a sound wave when a temperature gradient is established across it or may act as a heat pump when a wave is propagated within it.

Pulse tube refrigerator :
A refrigerator that uses oscillations in pressure and the displacement of a volume of gas to pump out heat without phase transition of the gas. These devices were invented in the 1960s. They have since been considerably developed and now play an important role in the field of cryogenerators. When the operating frequency of the device corresponds to resonant frequency of the system, these devices form part of a thermoacoustic system, and can be studied as such. This specific feature also makes these devices very powerful (capable of generating several kW of cold).