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APPLICATIONS OF MAGNETIC REFRIGERA- TION AND ITS ASSESSMENT

ALTERNATIVE REFRIGERATION TECHNOLOGIES

Final report: Appendix 2

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1. ALTERNATIVE REFRIGERATION TECHNOLOGIES

Experts working on conventional vapor compressor technology are facing different problems: at first it is necessary to replace the harmful refrigerants, and it is important to make efforts to further improve the efficiency of the machines. On the other hand, one observes enormous activities in some alternative fields, such as e.g. magnetic refrigeration. Other activities are related to thermoelectric cooling, where large but still not sufficient improvements were made to realize economic applications in traditional refrigeration markets. Another technology, which some decades ago was judged to be very promising, is the Stirling cooling technology. It shows a potential, at least in some special market niches. However, it will be difficult for this kind of technology to compete with other alternative technologies to conventional compressor refrigeration. Thermoacoustic cooling is also a very important alternative technology. In this Appendix, the technologies of thermoelectric cooling and thermoacoustic cooling are briefly presented, with the emphasis on the first, since it - similar as magnetic refrigeration - is a cooling method based on solid state physics and material technology. Furthermore, the success of a large scale commercialization of both technologies will strongly depend on the applied materials. These materials directly influence the obtainable performances. Other alternative technologies, which are not mentioned here, are vortex tube systems, gas (air) Brayton cycle machines, pulse tube refrigeration, Malone cycle systems, machines based on electro-chemical processes, compressor driven metal hybrid systems, etc.

1.1. THERMOACOUSTIC REFRIGERATION

Thermoacoustic refrigeration is based on standing or traveling sound waves, where temperature oscillations occur as a consequence of the pressure and velocity changes of the wave. The sound levels inside may reach 180 dB but the outside level is similar to the one of a conventional refrigerator. The temperature gradient occurs across a stationary element, which is called the "stack". The heat source and the heat sink exchangers are connected at the ends of the stack to transfer heat in and out of the system.

A common thermoacoustic refrigerator consists of four main components [1]:

- a "stack" of porous material, parallel plates or sheets of a thin material rolled into a spiral
- hot and cold heat exchangers consisting of finned tubes, parallel plates, screens or metallic wool
- a rigid and sealed tube that may incorporate a Helmholtz resonator to allow the device to be shorter and to minimize the losses
- an acoustic energy source, referred to as an electroacoustic transducer (i.e. a loud speaker or a piston).

The working fluid is usually a mixture of perfect gases such as xenon and helium. The driver operates at the resonance frequency of the system to produce fairly large pressure fluctuations that alternately compress and expand the working fluid adiabatically and cause the fluid to oscillate back and forth within the stack and the heat exchangers. The stack serves as a heat regenerator as the working fluid oscillates back and forth, absorbing the heat during the compression phase of the acoustic wave in the working fluid and rejecting the heat back to the gas during the expansion phase.

The initial work on thermoacoustics was centered on developing a standing acoustic wave in a resonant cavity. In an example of a standing wave system [2], a cooling of 400 W was seen with an input of 200 W acoustic power (17% of the ideal Carnot efficiency). The DOE group at Los Alamos National Laboratory (LANL) [2] made a breakthrough developing a thermoacoustic heat engine that used a variation of the Stirling cycle (with a porous regenerator) and used a traveling acoustic wave. Their first heat engine of this design produced power from a heat input with an efficiency of over 40% of Carnot. That is a 150% higher performance than that of the best standard thermoacoustic heat engine (e.g. 42% vs. 17% efficiency).

The thermoacoustic systems should have a low cost and a high reliability since there are no parts in contact with the working fluid that require lubrication. In room temperature applications the thermo-

acoustic systems have lower efficiencies than the conventional vapor compression systems. Still the number of developments in this field has been very high. The thermoacoustic systems also have a relatively large size of power levels that they achieve, and they may require secondary heat transfer loops. According to a report of the Oak Ridge National Laboratory [1], the COP's of thermoacoustic refrigeration machines reach 75-80% of the values, which may be obtained by magnetic refrigerators. These are similar values as those of the transcritical CO₂ conventional compression refrigerators.

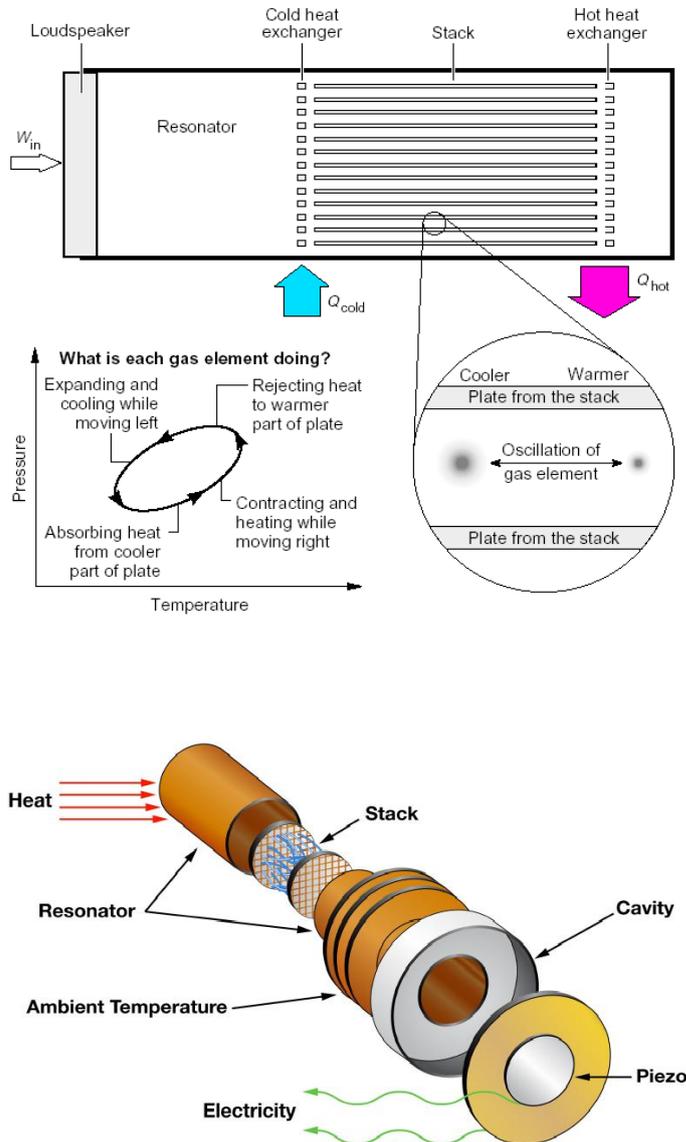


Figure 1: The thermoacoustic refrigerator (from Ref. [3] and [4]) is shown. The sound wave interacts with an array of parallel solid plates, named the stack. The resulting refrigeration can be understood by examining a typical small element of gas between the plates of the stack. As the gas oscillates forth and back, because of a standing sound wave, it changes its temperature. The temperature change is caused by the compression and expansion of the gas by the sound pressure. In the example shown, the length of the resonator is one fourth of the wavelength of the sound produced by the loud speaker. So all the elements of gas are compressed and heated as they move to the right and they are expanded and cooled as they move to the left. Thus each element of gas goes through a thermodynamic cycle in which the element is compressed and heated, rejects heat at the right end of its range of oscillation, and it is depressurized and cooled and absorbs heat at the left end. Consequently each element of gas moves a little amount of heat from the left to the right and from the cold to the hot part during each cycle performed by the sound wave. The combination of the cycles of all the elements of gas transports heat from the cold to the hot heat exchanger. The spacing between the plates in the stack is crucial for a proper functioning. If the spacing is too narrow, the good thermal contact between the gas and the stack keeps the temperature of the gas at nearly the same value as the temperature of the stack, whereas if the spacing is too wide, much of the gas is in poor thermal contact with the stack and does not transfer heat effectively to and from it.

Thermoacoustic refrigerators and heat pumps are known to be members of an environmentally friendly technology, which shows reliability, low cost and an easy maintenance (no moving parts, no lubrication). However, the largest drawbacks are the low efficiency and the low power density. Research results exist that predict efficiencies [2] comparable to those of conventional refrigerators. Another disadvantage of this kind of technology is the large size of its machines. Furthermore, if the standing or traveling waves are out of phase, the cooling effect usually is disrupted. Nowadays thermoacoustic refrigerators are used in special applications, where a temperature difference of 25 K between the heat source and the heat sink may occur [2]. However, there are not so notable research and market activities as this is the case for other cooling alternatives, such as thermoelectric cooling.

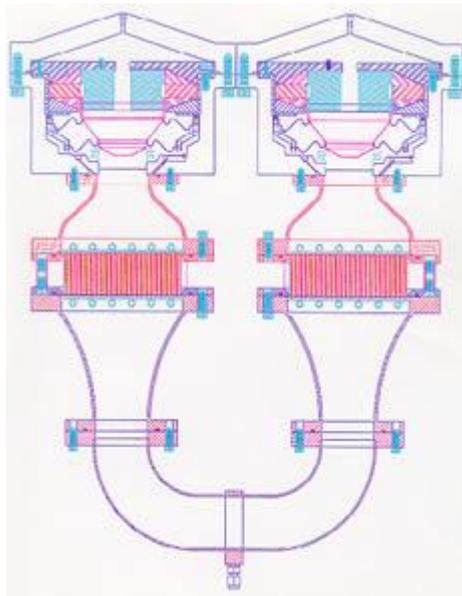


Figure 2: An example of a thermoacoustic refrigerator [5] is shown on the left-hand side.

The thermoacoustic chiller on the photography is operating with only one driver. The frost extends from the bottom of the cold heat exchanger through the entire U-shaped section of the resonator.

Bottom: a cross-sectional diagram of the refrigerator. Two custom-made electrodynamic drivers are coupled to the U-shaped resonator using two dual-convolution electroformed nickel bellows to provide a flexible seal for the pistons. The resonator is "bent" to fit into a standard 19" electronics rack. The resonator includes two stacks (red); each stack has two fluid-backed finned heat exchangers with serpentine tubes (blue) that carries the water used as the heat transport fluids for both the hot and the cold exchangers. The resonator is pressurized at 2.07 MPa with a mixture of 94.4% Helium and 5.6% Argon.

The thermoacoustic refrigerator reaches 419 W cooling power and a temperature span at its ends from 13.6°C to 44.6°C (not including the external heat exchange with the liquid). This is approximately 20% of the Carnot efficiency. For operating conditions of 294 W and a temperature span from -1.3°C to 38.2°C, a Carnot efficiency of 25% is reached.

1.2. THERMOELECTRIC REFRIGERATION

There are several thermoelectric phenomena associated with joining two dissimilar materials. The most familiar is the Seebeck effect. When maintaining a temperature difference between two junctions, an open circuit electrical potential difference V develops. It is proportional to the temperature difference T between the junctions. If a direct electrical current is forced to flow through a junction of two dissimilar materials then the heat energy which is produced or absorbed at the junction is proportional to the current. This was discovered and investigated by Peltier. Whether this heat is absorbed or produced depends on the direction of the current.

With the use of currently commercially available materials, thermoelectric coolers are suited to the applications, where their reliability, absence of moving parts and silent operations outweigh their relatively low efficiency, such as electronic cooling.

The temperature differences required in air conditioning are usually within the capacity of thermoelectric heat pumps, but one might expect their relatively poor coefficient of performance (COP) to be an insuperable disadvantage. However, thermoelectric coolers or refrigerators might become economically competitive, if the heat load is varied frequently, such as in a train carriage. An assessment of thermoelectric air conditioning has been carried out by Stockholm (reported in [6]), who installed a thermoelectric system in a train carriage in France. Another successful large-scale application, which

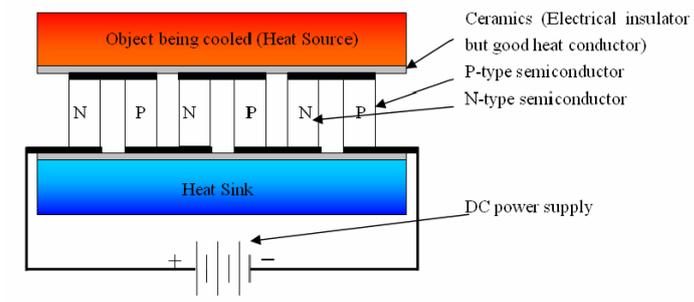


Figure 3: Schematics of a single stage thermoelectric module [6] and photographs of single and multi-stage modules [7]. A single-stage thermoelectric module or device is typically composed of thermoelectric elements (n- and p- types) that are connected electrically in series and thermally in parallel and sandwiched between two ceramic plates. The thermoelectric elements are interconnected with electric conductors (such as copper). The ceramic plates form the cold and hot surfaces of the module, provide mechanical integrity, electrical insulation and thermal conduction to the heat sink and the object to be cooled. There are also very few modules without ceramic plates, which could eliminate the thermal resistance associated with the ceramic plates, but they may cause mechanical fragility.

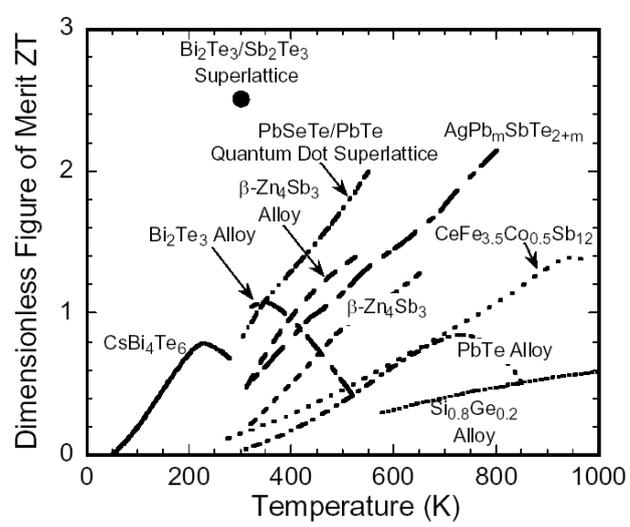
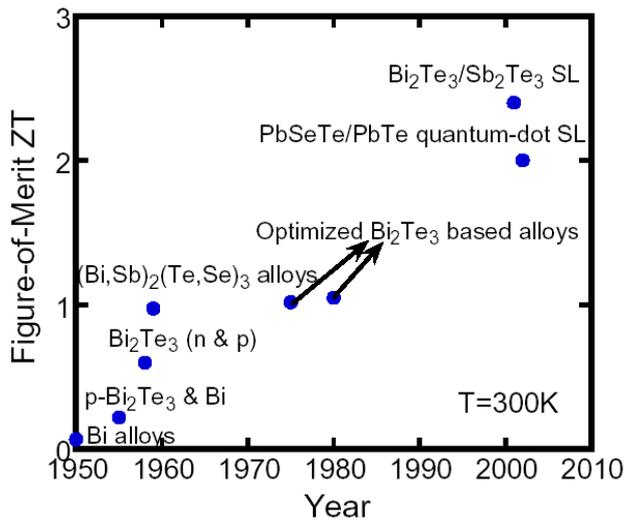


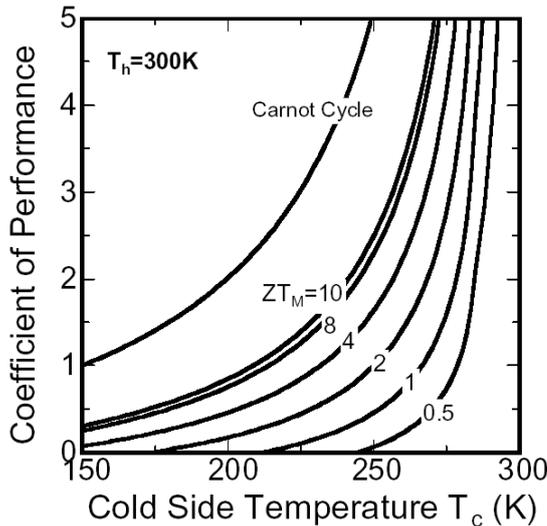
Figure 4: The figure of merit (ZT) factors for different kinds of materials and the historical development of them [6]. The third figure shows also the theoretical dependence of the COP on the ZT factor at different temperature levels.

Thermoelectric refrigeration has been limited by its relative low energy conversion efficiency. Important information when dealing with thermoelectric materials is the figure of merit ZT , which presents a dimensionless thermoelectric efficiency, which is related to the COP value (Coefficient of Performance).



The thermoelectric materials which are most often used in today's commercial thermoelectric coolers are Bi_2Te_3 -based alloys [6] ($ZT \sim 1.0$ at room temperature), PbTe -based alloys ($ZT \sim 0.9$ at 700K), and SiGe alloys ($ZT \sim 0.7$ at 1000K) [6]. The highest ZT to date is reported in $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ and $\text{PbSeTe}/\text{PbTe}$ superlattice thin films [6] and coolers based on such materials typically have a COP between 2 and 3, which are still lower than the COP of 3-4 of conventional refrigerators with compressors at usual temperature conditions.

Current thermoelectric cooling devices have an efficiency of about 10% of the Carnot efficiency [6]. Based on the current thermoelectric materials and design of thermoelectric devices, the thermoelectric refrigeration loses its advantage, if



the cooling load is large. Besides their relatively low COP , the thermoelectric devices have disadvantages, such as a relatively high cost per unit of output power and the requirement of heat sinks and DC powers.

However, there are also certain advantages:

- No moving parts
- Compact sized and light-weighted
- Ability to heat and cool with the same module
- Precise and easy temperature control
- High reliability
- No electrical or mechanical noise
- Operates in any orientation
- Convenient power supply
- Ability to generate electrical power
- Environmentally friendly.

included a 27 kW industrial water cooler, has been described by Buffet and Stockholm (reported in Ref. [6]). Instead of utilizing a full-fledged thermoelectric cooling system, it is possible to use a thermoelectric cooler to improve the performance of an existing vapor compression system. This leads to a hybrid system. The hybrid vapor compression/thermoelectric cooler takes advantage of the temperature lift capability of the thermoelectric elements to enhance the outlet subcooling of a condenser (see Ref.'s [6] and [8]).

According to the report of the Air-Conditioning and Refrigeration Technology Institute [6], the low efficiency of the thermoelectric coolers has limited their application for conventional cooling and refrigeration. As noted in Ref. [6], the main goal of the thermoelectric community is to develop new thermoelectric materials with higher ZT factors. The use of nanostructures for thermoelectric applications was triggered by the conceptual studies on the potential benefits of the quantum confinement of electrons and phonons and the phonon interface scattering in the early 1990s. Since then, much attention has been paid to the development of nanostructures for enhancing ZT . However, the development of new thermoelectric materials is according to [6] a long-shot program.

Instead of utilizing a thermoelectric cooling system, it is possible to integrate the currently available thermoelectric systems into hybrid ones, e.g. to improve the performance of an existing vapor compression system. For example, a hybrid vapor compression/thermoelectric cooler system could take advantage of the temperature lift capability of thermoelectric elements to enhance the outlet subcooling of a condenser. Thermoelectric heat pumps could operate at good efficiency for small temperature differences between the heat sink and the heat source.



Figure 5: Commercially available thermoelectric liquid chiller (left) and air conditioner (right) are shown and their pictures were taken from Ref. [9].

2. CONCLUSION

In this Appendix two alternative refrigeration technologies (thermoacoustic and thermoelectric refrigeration) were selected, briefly described and discussed in comparison with magnetic refrigeration. The present stage of development shows for both technologies limited possibilities of applications. For both technologies, the low *COP* and exergy efficiency are important drawbacks, especially for thermoelectric cooling. On the other hand, because of their lack of harmful refrigerants, both presented technologies are environmentally benign technologies. The thermoelectric cooling seems to have a larger potential to be brought to the market in the near future. But this is true only for certain market niches. Researchers rely on new and better materials, which are developed to reach higher *ZT* factors and could be commercially available in the future.

When compared to magnetic refrigeration/heat pump technology, then it may be stated that the thermoelectric technology is "older". But therefore, there is less hope for big improvements to occur. Since the magnetic refrigeration technology depends on the development of magnetocaloric material and permanent magnet materials research (similar as thermoelectrics on the development of semiconductors), it is very difficult to predict its further development. At the present stage of development of both technologies, mobility and compactness are advantages of the thermoelectric refrigeration, whereas the efficiency of the machines is the important advantage of the magnetic refrigeration technology.

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