Magnetocaloric heat pumps:

Innovative heating and cooling systems

For HVAC professionals and general audience

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The increasing demand for energy-efficient heating systems and the booming of the air conditioner market create an urge for new cost-effective heating and cooling solutions. Currently, the vapour-compression heat pumps dominate this market. However, these conventional systems present some limitations. New innovative systems based on different caloric effects, such as the magnetocaloric effect, have the potential to overcome those limitations. In the recent years, several prototypes of magnetocaloric heat pumps have been successfully built and tested. They show very promising performances that are similar to that of conventional systems. Nonetheless, more R&D are needed before they become competitive.

Worldwide increasing demand for heating and cooling in buildings

In most of the developed countries, the building sector is the largest energy end-user. In Europe, it accounts for 40% of the total energy demand. Moreover, indoor space heating represents 75% of the building energy needs in cold-winter regions.

On the other hand, cooling is the fastest growing use of energy in buildings. Because of global warming, heat island effect in densifying urban areas, increase of purchasing power, and increase of indoor thermal comfort standards, the cooling demand is booming all over the world, especially in populated countries with warm summer like China, India or Indonesia. The International Energy Agency (IEA) has estimated that air conditioners accounts for nearly 20% of the total electricity usage in buildings today. The energy needs for cooling could triple by 2050, with 2/3 of the households in the world being equipped with an air conditioner.

Consequently, the development of energy-efficient heating and cooling systems is critical to sharply decrease the overall energy needs and tackle the environmental challenges that our societies are facing.

Conventional heat pumps

A heat pump is a device that moves heat from a heat source to a heat sink that has a higher temperature. This is very convenient to cool down (like a fridge or an air conditioner), but it can also be used to heat up buildings or domestic hot water. The main advantage of heat pumps is that they have a high Coefficient of Performance (COP). Current heat pumps typically have a COP of 3–5, which mean that with 1 kWh_{elec} of input energy they can produce 3 to 5 $\text{kWh}_{\text{therm}}$ of useful heating or cooling, while gas, oil or electric boilers can only produce between 0.8 and 1 $\text{kWh}_{\text{therm}}$ of useful heating. Consequently, heat pumps use 3 to 5 times less energy than gas, oil or electric boilers.

To perform heat transfer, conventional heat pumps use of a vapour-compression thermodynamic cycle: a fluid (the refrigerant) is compressed or expanded (which increases or decreases its temperature) and circulated between the heat source and the heat sink. This technology is currently one of the best ways to provide heating and cooling to buildings in a cost-effective manner. However, the refrigerant fluids used in these vapour-compression heat pumps present some environmental issues: they are either flammable, explosive, toxic, or with a large greenhouse effect.

Innovative heat pump systems based on the caloric effects

Several innovative technologies are currently considered as viable alternatives to conventional vapour-compression systems to provide heating and cooling. Among them, the utilization of the caloric effects in certain solid refrigerant materials is gaining a large attention. The caloric effects are physical phenomena occurring in specific materials resulting in a change of temperature (heating up or cooling down) in the latter when a parameter of the surrounding environment changes:

- Electrocaloric effect: temperature change by variation of the electrical field.
- Barocaloric effect: temperature change by variation of the pressure.
- Elastocaloric effect: temperature change by variation of mechanical stress (stretching or squeezing).
- Magnetocaloric effect: temperature change by variation of magnetic field.

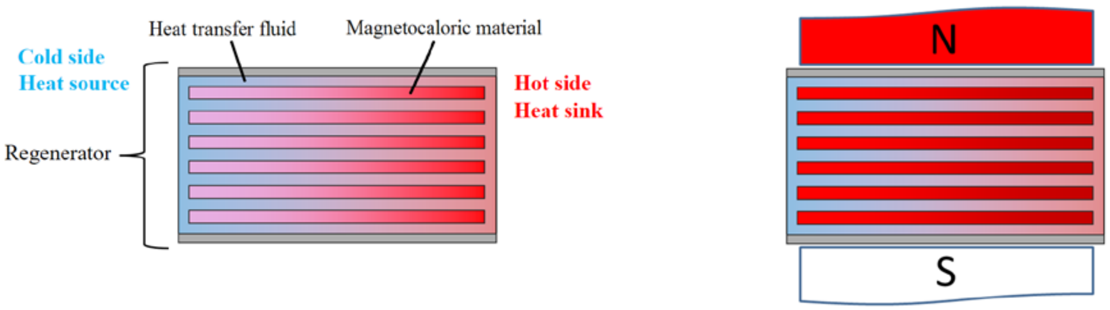
Like the vapour-compression thermodynamic cycle, these caloric effects can be employed to transfer thermal energy and thus produce useful heating or cooling power. However, devices based on caloric effects have the potential to reach higher COPs than conventional heat pumps. Moreover, they do not require any harmful fluid refrigerant, and benefit of a low noise level operation.

Those technologies have very different levels of maturity. Currently, most of the studies are focussing on magnetocaloric devices. However, in the very recent years, many research groups are now working on elastocaloric heat pump prototypes.

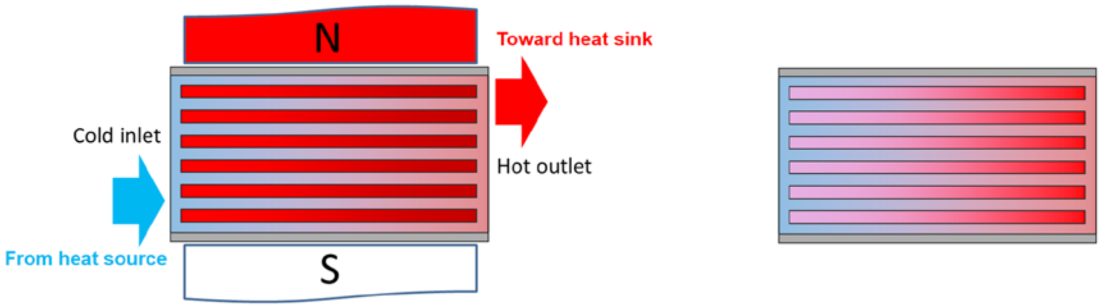
The magnetocaloric heat pumps

The thermodynamic cycle at the core of the current magnetocaloric heat pump technology is the Active Magnetic Regenerator (AMR) cycle. It has been developed and patented in 1982 by John A. Barclay and William A. Steyert, and employs magnetocaloric materials (materials experiencing the magnetocaloric effect) as a solid refrigerant and thermal regenerator. The magnetocaloric material (such as Gadolinium) is contained as a porous media (packed-sphere bed or parallel plate matrix) in a regenerator casing that allows bi-directional circulation of the coolant fluid through it. This fluid is typically a water-based brine. It ensures the thermal energy transfer from the cold side (heat source) to the warm side of the system (heat sink). The alternating activation and deactivation of the magnetocaloric effect in the solid refrigerant are achieved by magnetizing and demagnetizing the regenerator with an external magnetic field source such as an electromagnet or a rotating permanent magnet.

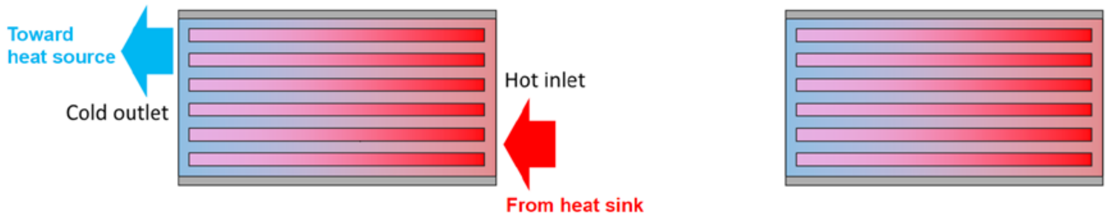
Figure 1 illustrates in details the different steps of this thermodynamic AMR cycle. **Figure 1 (a)**: At the beginning of the cycle, there is a temperature gradient inside the regenerator and no magnetic field is applied. **Figure 1 (b)**: The cycle starts with the magnetization of the magnetocaloric material that leads to a temperature increase in the regenerator. The heated magnetocaloric material then transfers thermal energy to the heat carrier fluid. **Figure 1 (c)**: This fluid is pushed from the cold side to the warm side of the system (cold-to-hot blow). The hotter fluid is circulated into the heat sink and rejects some heat. The colder fluid coming from the heat source cools down the regenerator. **Figure 1 (d)**: The magnetic field is removed, leading to the demagnetization of the magnetocaloric materials, and thus a temperature decrease. Consequently, the cold fluid in the regenerator is cooled down further. **Figure 1 (e)**: At the end of the cycle, the fluid is pushed back from the warm side to the cold side of the system (hot-to-cold blow). The colder fluid is circulated into the heat source and extracts some heat from it. The hotter fluid coming from the heat sink re-heats (heat regeneration) the magnetocaloric material inside the regenerator. **Figure 1(f)**: Once the fluid flow is stopped, the device is back to the initial state of the AMR cycle.



(a) Initial state *(b) Magnetization: temperature increase*



(c) Cold-to-hot blow: heat rejection *(d) Demagnetization: temperature decrease*



(e) Hot-to-cold blow: Heat injection *(f) Back to initial state*

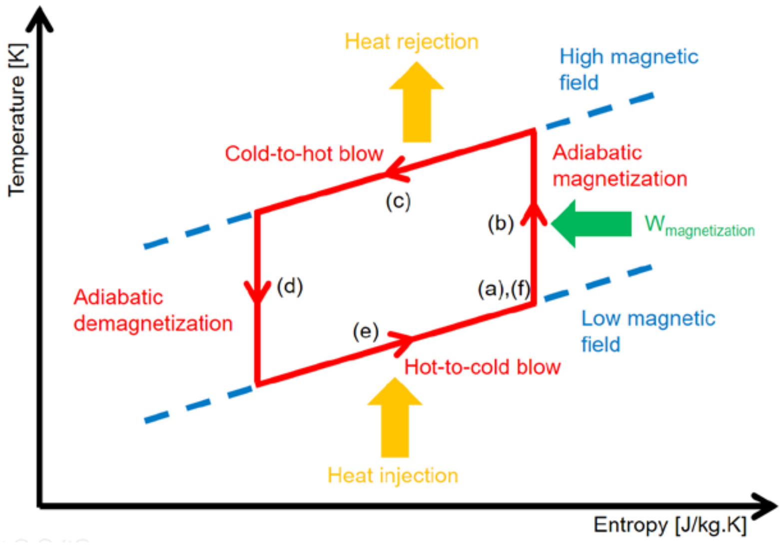


Figure 1. The active magnetic regenerator thermodynamic cycle of the magnetocaloric heat pump.

The active magnetic regenerator configuration is considered to produce the most energy-efficient thermodynamic cycle for magnetic heating and cooling devices. It also enables an operational temperature span between the heat source and the heat sink to be significantly larger than the temperature change induced by the magnetocaloric effect alone.

Since the 1980s, several laboratories have developed innovative heat pumps using the magnetocaloric effect to perform heating and cooling. The performances of those prototypes are encouraging with a gradual improvement of their COPs (now comparable to that of conventional vapour-compression systems) and nominal power. Studies showed that a magnetocaloric heat pump can be integrated into a building and provide for its space heating and domestic hot water needs.

Although a promising technology and a nice piece of engineering, the magnetocaloric heat pumps have yet to prove their competitiveness against the mature technology of vapour-compression systems. The main challenges reside in the development of cheaper magnetocaloric material, and the optimization of some key components such as the rotating magnet assembly and the heat exchangers. ■

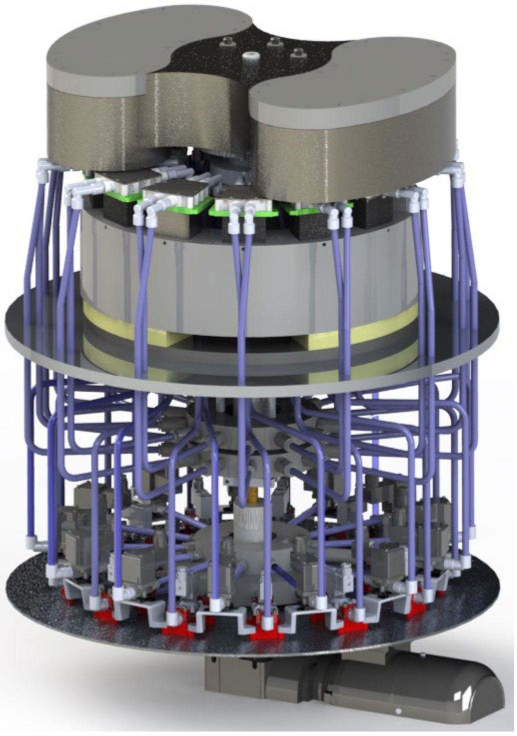


Figure 2. "MagQueen": prototype of a magnetocaloric heat pump designed to provide space heating for a low-energy single-family house in Denmark (ENOVHEAT project).

References

This article is based on two peer-reviewed scientific papers published in international scientific journals:

H. Johra, K. Filonenko, P. Heiselberg, C. Veje, T. Lei, S. Dall'Olio, K. Engelbrecht, C. Bahl. Integration of a magnetocaloric heat pump in a low-energy residential building. *Building Simulation* 11 (2018) 753-763. https://doi.org/10.1007/s12273-018-0428-x

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