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Review of magnetic refrigeration system as alternative to conventional refrigeration system

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Abstract. The refrigeration system is one of the most important systems in industry. Developers are constantly seeking for how to avoid the damage to the environment. Magnetic refrigeration is an emerging, environment-friendly technology based on a magnetic solid that acts as a refrigerant by magneto-caloric effect (MCE). In the case of ferromagnetic materials, MCE warms as the magnetic moments of the atom are aligned by the application of a magnetic field. There are two types of magnetic phase changes that may occur at the Curie point: first order magnetic transition (FOMT) and second order magnetic transition (SOMT). The reference cycle for magnetic refrigeration is AMR (Active Magnetic Regenerative cycle), where the magnetic material matrix works both as a refrigerating medium and as a heat regenerating medium, while the fluid flowing in the porous matrix works as a heat transfer medium. Regeneration can be accomplished by blowing a heat transfer fluid in a reciprocating fashion through the regenerator made of magnetocaloric material that is alternately magnetized and demagnetized. Many magnetic refrigeration prototypes with different designs and software models have been built in different parts of the world. In this paper, the authors try to shed light on the magnetic refrigeration and show its effectiveness compared with conventional refrigeration methods.

1. Introduction

Nowadays classical vapour compression refrigeration technology is widely used, but there are various limitations in using vapour compression system, because technology is very energy inefficient. These refrigerants have been undesirable for environmental reasons. The major drawback of the vapour compression system is that it requires a compressor to compress a large volume of refrigerant vapour, which requires a large power for its operation. In addition, it has poor COP as compared with the Carnot cycle, environmental hazards limit to the lowest temperature of the refrigeration cycle. For this reason, researchers and engineers working in refrigeration have started to investigate new technologies for refrigeration among which the most promising is magnetic refrigeration.

Magnetic refrigeration is one of such techniques, which promises to be of practical importance even though the concept is still into research. The magnetic refrigeration system works by applying a magnetic field to a magnetic material causing it to heat up. This excess heat is removed from the system by water, cooling the material back down to its original temperature. The study is based on a comprehensive and simple review with details of everything one needs to know about magnetic refrigeration as an alternative to the conventional refrigeration system. In the following sections, the



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authors will try to give comprehensive information about the conventional refrigeration system and magnetic refrigeration system [1, 2].

2. General theory of refrigeration system

There are two laws that are significant to understand the basic refrigeration cycle thermodynamics' first law explains that energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. Energy can be stored within systems in various macroscopic forms: kinetic energy, gravitational potential energy, and internal energy. Energy can also be transformed from one form to another and transferred between systems. For closed systems, energy can be transferred by work and heat transfer. The total amount of energy is conserved in all transformations and transfers. Thermodynamics second law can help us better understand how the basic refrigeration cycle works. One of these laws states that heat always flows from a material at a high temperature to a material at a low temperature [3, 4].

An ideal reversible cycle based on the two temperatures of the system in Figure 1. can be drawn on a temperature–entropy basis. In this cycle, a unit mass of fluid is subjected to four processes after which it returns to its original state. The compression and expansion processes, shown as vertical lines, take place at constant entropy. A constant entropy (isentropic) process is a reversible or an ideal process. Ideal expansion and compression engines are defined. The criterion of perfection consists in the fact that no entropy is generated during the process i.e. the quantity (s) remains constant.

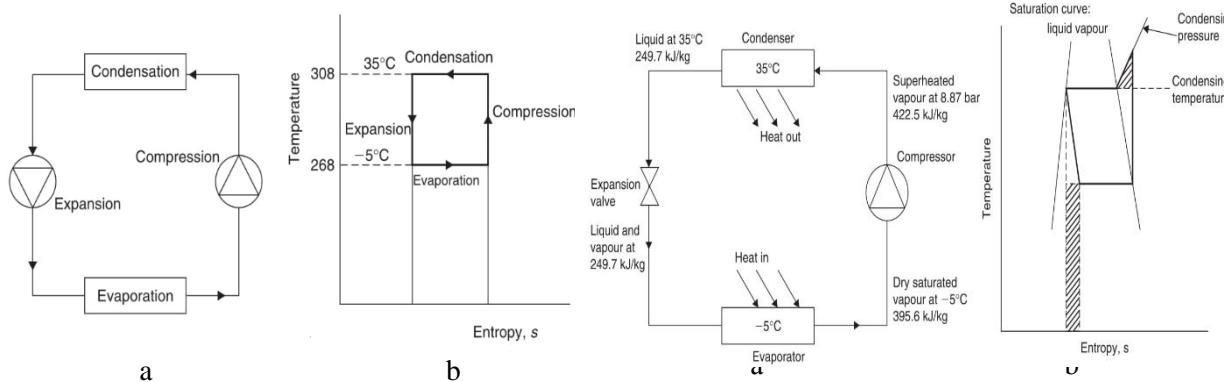


Figure 1. Ideal reversed Carnot cycle: (a) circuit; (b) temperature-entropy diagram

Figure 2. Simple vapour compression cycle: (a) circuit; (b) Temperature-entropy diagram for ideal vapour compression cycle

The vapour compression cycle is used for refrigeration in preference to gas cycles; making use of the latent heat enables a far larger quantity of heat to be extracted for a given refrigerant mass flow rate. When the simple vapour compression cycle is shown on the temperature–entropy diagram in Figure 2, the deviations from the reversed Carnot cycle can be identified by shaded areas. The adiabatic compression process continues beyond the point where the condensing temperature is reached. The shaded triangle represents the extra work that could be avoided if the compression process changed to isothermal (i.e. at constant) temperature at this point, whereas it proceeds until the condensing pressure is attained.

3. The principle work of Magnetic Refrigeration System

The development of magnetic refrigeration started in 1881 when the German physic Emil Warburg discovered the magnetocaloric effect in iron, which has been until recently limited to very low temperature. The use of the magnetic cooling at room temperature was practically made possible with the discovery of materials which show the magnetocaloric effect at room temperature (especially some rare metals and their alloys). The working principle of magnetic refrigerators is based on

magnetocaloric effect, perceived as a adiabatic temperature change or isothermal entropy change. Let us examine the schematic diagram of the theoretical magnetic refrigeration system in Figure 3 and its vapour compression counterpart. The conventional vapour compression system makes use of a compressor, two heat exchangers – an evaporator and a condenser, a throttling device. The refrigerant picks up heat from the space to be refrigerated in the evaporator where it is converted into vapour state. This vapour then passes through the compressor where its pressure and temperature is increased. Refrigerant then emits its heat in a condenser and is converted into a liquid in the magnetic system. The throttling device is used to reduce the pressure of the refrigerant to the evaporator pressure [5,6].

That use of magnets, either permanent or superconducting, effects a change in the magnetic field. The CFC or HFC refrigerant in the conventional system is replaced by a working substance i.e. a magneto-caloric material. As it was mentioned before, in the cold heat exchanger the working substance picks up heat from the space to be refrigerated, then the working substance is brought into a strong magnetic field or is magnetised so that due to magneto-caloric effect its temperature is increased [7,8].

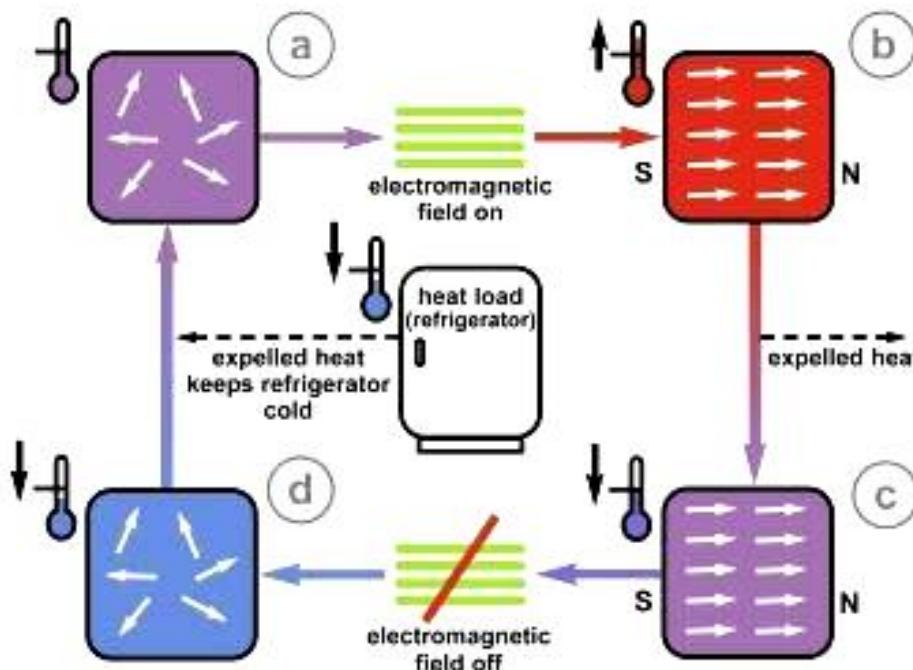


Figure 3. Magnetic Refrigeration Process Graph.

3.1. Magneto-Caloric Effect

The Magneto caloric effect (MCE, from magnet and calorie) is a magneto- thermodynamic phenomenon in which a reversible change in temperature of a suitable material is caused by exposing the material to a changing magnetic field. This is also known as adiabatic demagnetization by low temperature physicists. In that part of the overall refrigeration process, a decrease in the strength of an externally applied magnetic field allows the magnetic domains of a chosen (magneto caloric) material to become disoriented from the magnetic field by the agitating action of the thermal energy (phonons) present in the material. If the material is isolated so that no energy is allowed to (e)migrate into the material during this time (i.e. an adiabatic process), the temperature drops as the domains absorb the thermal energy to perform their reorientation. The randomization of the domains occurs in a similar fashion to the randomization at the Curie temperature, except that magnetic dipoles overcome a decreasing external magnetic field while energy remains constant, instead of magnetic domains being disrupted from internal ferromagnetism as energy is added. One of the most notable examples of the

magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. Gadolinium and its alloys are the best material available today for magnetic refrigeration near room temperature since they undergo second-order phase transitions which have no magnetic or thermal hysteresis involved.

3.2. Magnetic Refrigeration Cycle

The cycle is performed as a refrigeration cycle, analogous to the Carnot cycle, and can be described at a starting point whereby the chosen working substance is introduced into a magnetic field (i.e. the magnetic flux density is increased). The working material is the refrigerant, and starts in thermal equilibrium with the refrigerated environment. In the Carnot cycle an adiabatic magnetization occurs in process (1–2) Figure 4 it continues with a further magnetization in stage (2–3), which is now an isothermal magnetization. During this process generated heat is extracted from the system. The next process step, namely (3–4), is an adiabatic demagnetization process. Connecting the system with a heat source leads to an isothermal demagnetization, resulting in process (4–1). It becomes clear that the Carnot cycle can only be run, if a minimum of four different magnetic fields occur, through which the magnetocaloric material is moved. In the vertical process 1–2 the alteration of the magnetic field has to apply quickly, not allowing heat to diffuse away or be transported out by convection. In (2–3) the isothermal magnetization requires an alteration of the magnetic field and simultaneous rejection of heat. This process will therefore be slower. The area between (1–2–3–4) represents the work required and the area (1–4–a–b) is related to the thermal cooling energy [9,10].

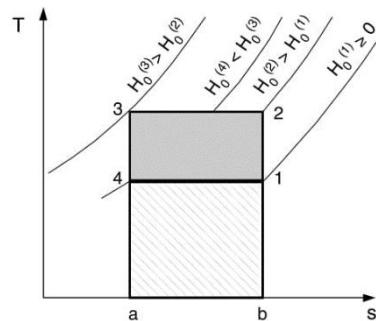


Figure 4. The Carnot cycle operates with mixed processes of alteration of the magnetization in an altering field and heat absorption or rejection.

All the cycles previously discussed are ideal cycles, for the two systems, the different processes shown on the chart are shows in Table 1.

Table 1. Refrigeration process for the two systems

Vapour Compression System	Magnetic Refrigeration System
1-2 ↔ Non-isentropic Compression in a compressor	4-1 ↔ Isothermal heat exchange in cold heat exchanger
2-3 ↔ Isobaric Condensation in Condenser	1-2 ↔ Isentropic temperature rise in high magnetic field
3-4 ↔ Isenthalpic pressure reduction in throttling device	2-3 ↔ Isothermal heat exchange in hot heat exchanger
4-1 ↔ Isobaric Evaporation in Evaporator	3-4 ↔ Isentropic temperature fall in low magnetic field

4. Comparison between the two systems

In Figure 5, the four basic processes of conventional gas compression/expansion refrigeration are shown. These are a compression of a gas, extraction of heat, expansion of the gas, and injection of heat. The two-process steps extraction of heat and expansion are responsible for a cooling process in two steps. The main cooling usually occurs by the expansion of the gas. The magnetic refrigeration process works analogous. By comparing Figure 5 with Figure 6, one can see that instead of compression of a gas a magneto caloric material is moved into a magnetic field and that instead of expansion it is moved out of the field.

The heat rejection and injection in a gaseous refrigerant is a rather fast process as turbulent motion transports heat very fast and efficient. Unfortunately, this is not the case in the solid magneto caloric materials. Here the transport mechanism for heat is the slow molecular diffusion. Therefore, at present filigree porous structures are considered to be the best solution to overcome this problem. The small distances from centre regions of the bulk material to an adjacent fluid domain, where a heat transport fluid captors the heat and transports it away from the material's surface, are ideal to make the magnetic cooling process faster [9, 10].

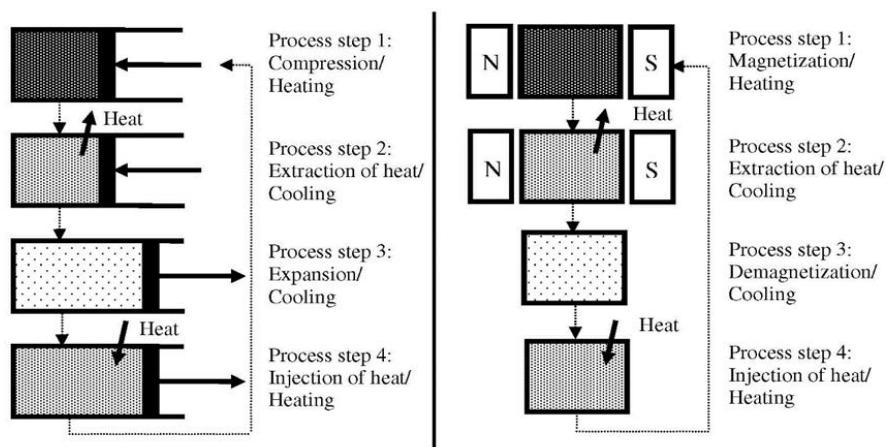


Figure 5. The conventional gas compression process is driven by continuously repeating the four different basic processes shown in this figure.

Figure 6. The magnetic refrigeration cycle works similarly. Compression is replaced by adiabatic magnetization and expansion by adiabatic demagnetization.

5. Results and Discussion

For comparative purposes, as it has been shown previously, the temperature limits for both systems are taken as same. As can be seen from the chart the compression process in a vapour compression is never isentropic. An isentropic process is believed to be the most efficient path for carrying out any process. For higher efficiency one needs minimum disorder in system i.e. minimum entropy. To have minimum entropy it is necessary to carry out a process in a reversible manner i.e. the system must be able to be restored to its original state by an infinitesimal change in its parameter. During the compression process in a vapour compression system, there is much irreversibility involved like friction, heat exchange of the hot refrigerant with the surrounding air, which increases the entropy of the system. Consequently, the process is not the most efficient one and energy is wasted.

As compared with this in a magnetic system the process of increasing temperature of the working substance is completely reversible, since magnetocaloric effect is entirely reversible. This is because bringing the material out of the magnetic field can lower the temperature of the magnetocaloric salt. As a result of this, the entropy generation during both processes 1-2 and 3-4 is zero. Thus, the cycle approaches the Carnot cycle, which is believed to be the most efficient cycle as shown in Figure 4.

As a result of this, even from COP point of view, the new system comes as a good substitute for the conventional system according to the advantages stated below.

5.1. Environmental Friendly Technology

The most important advantage offered by the magnetic system is that it gets rid of the refrigerants present in the vapour compression system, which are mainly Chlorofluorocarbons and Hydrofluorocarbon, which is responsible for the destruction of Ozone layer. Instead, it utilises magneto caloric material and a heat transfer fluid such as water or water + ethanol, which is environmentally friendly and does not have Ozone Depleting Potential (ODP).

5.2. High Thermodynamic Efficiency

Another important advantage offered by the magnetic system is the high thermodynamic efficiency as compared with the conventional system. As seen from figure 4, the magnetic system approximates a reversed Carnot cycle much better than a conventional system.

5.3. Silent, Vibration Free Design

In a conventional system used a compressor, the presence of this device brings a few disadvantages to the conventional system such as the noise and vibrations. In a magnetic system this component is absent and is replaced by a magnet, which operation does not involve any noise or vibration.

5.4. Overall Cost Saving

Magnetic refrigeration setup ensures economical running and negligible maintenance.

6. Conclusion

In this paper, the authors address a very important issue - the magnetic refrigeration, which is a clean environmentally friendly technology that replaces the environmentally hazardous refrigerants in a vapour compression system with a magnetocaloric substance and a heat transfer fluid, which are environmentally friendly in addition to the power consumption reduction by 30-40. With the ever-increasing concern about environmental hazards, it promises to be a technology of the future. In order to make the magnetic refrigerator commercially viable, scientists need to know how to achieve larger temperature swings and also permanent magnets which can produce strong magnetic fields of the 10-tesla order. There are still some thermal and magnetic hysteresis problems to be solved for the materials that exhibit the MCE to become useful.

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