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Magnetic Cooling

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Abstract

The magnetocaloric effect works by changing the magnetic entropy in a magnetic solid. The magnetic field causes the solid to rise in temperature as the entropy is changed. It can be explained by the Maxwell's relations of thermodynamics. As the temperature in the solid rises above the ambient it will start losing heat to it. Then as the magnetic field is turned off the magnetic entropy must again change but now the temperature in the solid will drop below the ambient. As the solid's temperature drops it can absorb heat from an enclosed volume such as that in a refrigerator and in that way cool it.

A way to measure the magnetocaloric effect is called the adiabatic temperature change, ΔT_{ad}, and it tells you the temperature difference when the solid heats up and cools down. Theoretically there should be a giant magnetocaloric effect, it has been given this name since it is a larger version of the magnetocaloric effect but only happens when the change in the magnetic field due to a change in temperature becomes large. This happens for magnetic materials when they reach their Curie temperature.

As a refrigeration cycle it has been proven that a theoretical efficiency of 60% could be possible and this outmatches the vapor-compression cycle who has at best around 40%. Magnetocaloric effect is not something new but the interest for it has recently increased as it has the potential to outrival the vapor-compression cycle.

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Introduction

The living standard is increasing worldwide and countries like China and India which have a lower living standard then most of the western countries and have an enormous population with around or over one billion make them two markets with extreme potential.

An essential part of the living standard is the possibility to cool or heat your household, and that is why an increase in living standard is directly proportional to an increase in energy consumption. The world's energy production is already under heavy stress to produce environmentally friendly energy. Because most of the worlds energy production comes from either fossil or nuclear fuels which both have their disadvantages in the form of either a release of greenhouse gases or radioactive wastes. That's why the price of energy is on the rise and products with higher efficiency may become more interesting from a consumers point of view as they get more for their money.

The most dominant way of refrigeration today is the Vapor–compression cycle. This cycle can be used for either refrigerators or air conditioning systems. The cycle is dependent on the compression of a liquid medium that transports heat from an enclosed volume to the ambient air. The compression of the liquid consumes energy and therefore lowers the efficiency of the cycle. That is why looking for a compression free refrigeration cycles is a natural approach for finding a cycle with higher efficiency.

Magnetic cooling offers just this and could be used for refrigerators as well as air conditioning systems. Other positive aspects are that there is no noise from the compressor or environmentally dangerous liquid coolant like Freon needed. Freon is not commonly used anymore but there are still old refrigerators being used even in countries with higher living standard.

Magnetocaloric effect

Understanding the magnetocaloric effect

After being discovered in iron by Emil Warburg, the magnetocaloric effect, (MCE), was later theoretically explained by both Debye and Giauque. They proposed a process called “adiabatic demagnetization” and it can be used to reach low temperatures near zero Kelvin [1]. The magnetocaloric effect works by changing the magnetic entropy of the solid by the use of a external magnetic field. This causes the solid to heat up and as it does it loses heat to the ambient. When the magnetic field is turned off the entropy stabilizes and goes back to normal and as a result of this the solids cools [2].

$$\left(\frac{\partial S(T,H)}{\partial H}\right)_T = \left(\frac{\partial M(T,H)}{\partial T}\right)_H \tag{1}$$

and comes from Maxwell’s thermodynamic relation that states that under adiabatic conditions a change in the magnetic entropy must be compensated by an equal change in the lattice entropy. This change must be equal but opposite, as they compensate each other. This results in a temperature change within the solid and this is what’s called the adiabatic temperature change, ΔT_{ad} [2]. This temperature change can be theoretically derived from equation 1.

$$S_M(T,H) = \int_{H_1}^{H_2} \left(\frac{\partial M(T,H)}{\partial T}\right)_H dH = -S_{Lattice}(T) \tag{2}$$

Equation 2 states that the change in magnetic entropy is the derivate of the magnetic field, at constant field, with respect to the temperature and the change in the magnetic field. In other words how the magnetic field changes due to a change in temperature times the change in the magnetic field. From the first law of thermodynamics we can define the change of heat in a adiabatic system equals the absolute temperature times the systems change in entropy.

$$\partial Q = T \cdot dS \tag{3}$$

Another way to describe the change in heat in the system is to do it in terms of the solids heat capacity, C, which also comes from the laws of thermodynamics.

$$\partial Q = C \cdot dT \tag{4}$$

By combining equation (2), (3) and (4) the temperature change in the system due to the change in the magnetic field can be defined as

$$\Delta T_{ad}(T, \Delta H) = -\int_{H_1}^{H_2} \left(\frac{T}{C(T,H)} \right)_H \cdot \left(\frac{\partial M(T,H)}{\partial T} \right)_H \cdot dH \tag{5}$$

where C is the already defined heat capacity of the solid and it depends on both the temperature, T and the magnetic field, H. Equation 5 is the temperature change that can be archived under adiabatic circumstances due to the magnetocaloric effect.

Magnetic refrigeration

Researcher Carl Zimm made a successful proof of principle in near room temperature magnetic refrigeration. It was achieved using a magnetic field between 1.5 and 5 T and a temperature span of 38°C was observed when ΔH=5T. This was done by using roughly 3 kg of Gd spheres in two different magnetocaloric beds and using water as the heat transfer medium [3]. He used two piston two push the fluid around the system as a superconducting magnet was reciprocated over the beds. This machine was able to produce 600 W in a 5 T magnetic field and 300 W in a 1.5 T magnetic field [4].

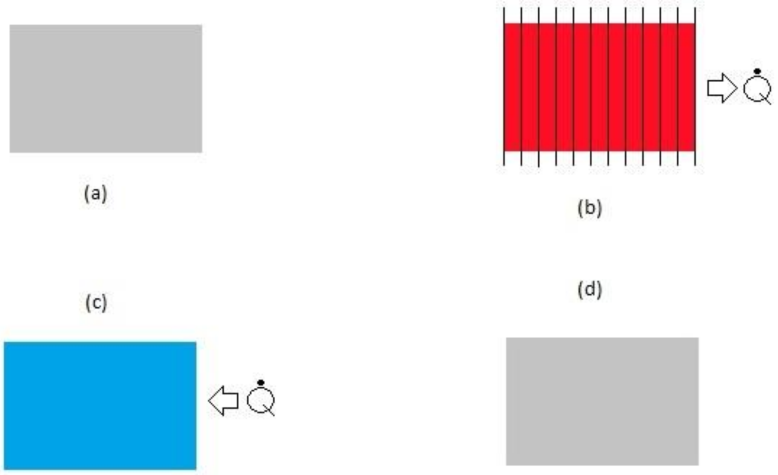

Figure 1: Shows a extremely simplified schematic for magnetic cooling solely in the purpose of understanding the refrigeration cycle from a basic point of view. a) implies to the solid before any MCE. b) shows the solid as a magnetic field is applied over it and the excess heat is transferred away using an appropriate method. c) when the magnetic field is turned off and the solid cools and heat can be absorbed from the volume that needs to be cooled. d) the process goes back to the start.

The giant magnetocaloric effect

A giant magnetocaloric effect is theoretically possible when the change in magnetic field due to the temperature change is infinitely large causing the magnetic entropy to become large. This giant magnetocaloric effect has been experimentally observed in FeRh as it undergoes a phase transition from antiferromagnetic to ferromagnetic around 308 K. A MCE as large as roughly -13 K for a $\Delta H=H_2-H_1=2$ T makes it a giant although the MCE in FeRh is only observable on a virgin sample, meaning a sample that has never been subjected to a magnetic field before. Therefore the process is irreversible [5].

Discussion

For a commercial point of view I think magnetic refrigeration has enormous potential. Magnetic refrigeration in Gadolinium has a theoretical limit of 60% versus the best vapor-compression cycle that has around 40% [6]. Due to the sheer number of operating refrigerators and air conditioning systems in the world gives a good perspective on the amount of savings that can be achieved from a 20% efficiency boost. You also have to take in to account that these numbers are about 5 years old, and better materials and more effective cycles could have been found.

As magnetic cooling is free from any compression there is no noise from a compressor while the cooling cycle is active. This adds to the sturdiness in the cycle, the fewer moving parts the better. If it was possible to get the heat transfer medium to flow through the system using only the temperature difference as the driving force. This would furthermore increase the efficiency of the cycle and making it sturdier and therefore would work for a longer period of time.

Research today seems to be about finding new magnetic materials with a high magnetocaloric effect and especially one with a giant magnetocaloric effect near room temperature for use in refrigerators or air conditioning systems. Personally I find a bit odd since it seem to have the potential to beat the vapor-compression cycle but I haven’t heard of any refrigerators that’s being sold today that uses this technique. There might be that the research hasn’t made the necessary progress needed for a commercial market or they have trouble with incorporating it or to comply with today’s safety regulations. I believe that we will see magnetic refrigerators in the near future and that it will outrival its competitor the vapor-compression cycle.

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