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ROOM TEMPERATURE MAGNETIC REFRIGERATION: AN AIR CONDITIONING APPLICATION

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Abstract

In the last years magnetic refrigeration is been promoted also for near-room-temperature applications (RTMR), promising to be a quite interesting alternative to vapor-compression refrigeration systems.

In this work, a thermodynamic steady-state model is employed to investigate the behavior of a rotary Steyert-like magnetic refrigerator device, operating near room temperature, in which a gadolinium magneto-caloric porous matrix is used. Despite the simplicity of its thermal and fluid dynamic modelling, the Steyert configuration keeps all the main issues of magnetic refrigerators regarding the sensitivity analysis of the system performance to changes in design and operating condition data. The possibilities to apply this technology to air conditioning applications is highlighted and some performance parameters are presented.

1. Introduction

Magnetic Refrigeration is a technology that exploits an intrinsic property of the magneto sensitive materials that is called magneto caloric effect (MCE). The MCE is the ability of the material to increase (or decrease) its bulk temperature when undergoing increases (or decreases) in the applied external magnetic field B, in adiabatic conditions (a qualitative sketch of such effect is shown in Figure 1, with reference to two constant magnetic field B lines in the T-S diagram).

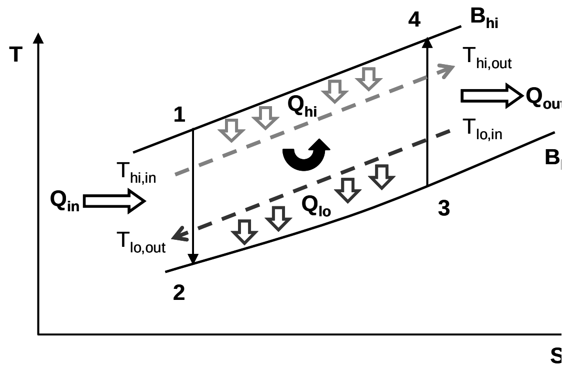

Figure 1 – Brayton cycle in the T-S plane, along iso-B curves. Qualitative fluid temperatures are reported (dashed lines) with no reference to the entropy axis.

Discovered by P. Weiss and A. Piccard in 1917 [1], this adiabatic temperature change ΔT_{ad} got its early proof of concept applications at room temperature in 1976 by Brown [2] who realized the first proof of principle active magnetic regenerator (AMR). The regenerative process is the core of the magnetic refrigeration technology, because it increases by several times the magnitude of the MCE showed by the actually known and employed materials (~ 3 K per applied Tesla variations, showed for instance by Gadolinium).

Arranging a proper sequence of magnetic field changes and heat transfer processes, the magnetic refrigerator will perform continuous cooling of a thermal sink, over temperature spans of several degrees, as shown in Figure 1. Literature shows many RTMR prototypes developed and built both with proof of principle purposes and with performance oriented purposes. Very different embodiments and arrangements can be conceived, operating with similar or identical conceptual behavior. A wide set of prototypes and test sections known in literature is reported in Scarpa et al. (2012) [3].

A magnetic refrigerator employs a solid refrigerant coupled to a common fluid like water as fluid medium, with no need to use HCFC refrigerant fluids and no need to realize high pressure plants, such as those with ammonia or carbon dioxide. This results in an almost no Ozone Depletion Potential and zero direct Global Warming Potential. Furthermore, the low noise behavior and the simple control system can be added to the favorable features of this new refrigeration technique. Nevertheless, the challenge to realize an effective magnetic refrigerator with performances and costs competitive with the traditional refrigeration techniques is not simple at all, and still to be achieved so far.

In this work a thermodynamic steady-state model is employed to investigate the behavior of a rotary Steyert-like magnetic refrigerator device, operating near room temperature, in which a gadolinium magneto caloric porous matrix is used.

Despite the simplicity of its thermal and fluid dynamic modelling, the Steyert configuration keeps all the main issues of magnetic refrigerators linked to the sensitivity of the system performance to changes in design and operating condition data.

The investigation focuses on the influence that the design parameters of the model have on the global performances of the device, the magnetic and constrained variables being constant.

The possibilities to apply RTMR technology to air conditioning applications is highlighted and some performance parameters are calculated.

2. Steyert-Like Magnetic Refrigerator

In the Steyert-like rotary configuration [4] the rotation of the magneto caloric medium is continuous and the heat transfer fluid flows steadily in a counter flow arrangement, as shown in Figure 2. This embodiment develop a continuous active magnetic regeneration (AMR), giving rise to high efficiency regenerated Ericsson thermodynamic cycles such as the one reported in Figure 1. The use of effective AMR leads to high values of the temperature difference (usually known as ΔT_{span}) between hot and cold sources of the refrigeration cycle, even with magneto caloric effects (ΔT_{AD}) of few degrees.

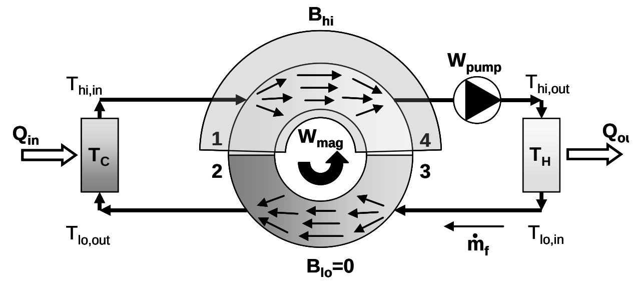

Figure 2 – Schematic drawing of the Steyert-like magnetic refrigerator configuration. The external fluid loop exploits the MCE of the central rotating gadolinium disk assembly.

A detailed model of the entire system is reported in [5], evidencing the dependency of the performance variables (cooling capacity Qin, energy consumption Wtot=Wpum+Wth, COP=Qin/Wtot) from the operative variables (ΔT_{span};;ΔT_{AD}; magnetic field, and so on).

One of the most crucial operating parameters resulted to be the Thermal Capacity Ratio, TCR. The magnitude of the mass flow rate of the medium fluid depends on the nature of the fluid employed, and on the mass flow rate of the solid. As the regenerator is modeled as a counter flow heat exchanger, the best efficiency is obtained if the heat capacity flow rates of the circulating fluids are well balanced: the TCR is therefore defined in the form: $TCR = \frac{\dot{m}_f \cdot c_f}{\dot{m}_{MCM} \cdot c_{MCM}}$ to derive the proper mass flow rate for a given solid mass flow rate. If TCR equals the unit, a perfectly balanced heat transfer inside the regenerator will take place.

As an example if the solid mass flow rate is 0.2 kg/s (depending on the gadolinium mass and rotation speed of the regenerator), the corresponding mass flow rate of the fluid should be about 0.01 kg/s if water is used as heat exchanger medium, or about 0.5 kg/s if air is used instead. The mutual influence of TCR and ΔT_{span} (for given materials, ΔT_{AD}, magnetic field and geometry of the system) is evidenced in Figure 3, in the case of water, where the strong effect on the cooling capacity Q_{in} is highlighted, when TCR and ΔT_{span} are varied.

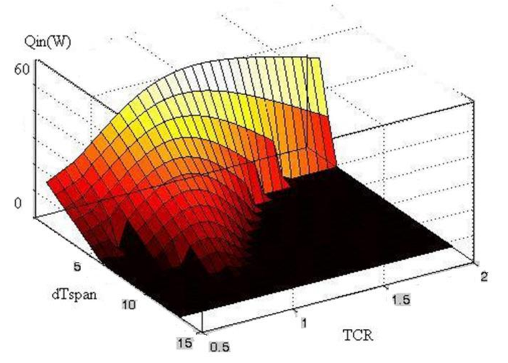

Figure 3 – Refrigeration capacity Q_{in}(W) for a MR using water, as a function of ΔT_{span} and TCR.

3. Application To Air Conditioning

The heat transfer conditions inside the AMR regenerator are crucial. A great heat transfer rate between the fluid and the solid is required (the ratio between the regenerative heat flux and the cooling capacity reaches values up to 20 times for a ΔT_{span} of 10°C, operating with water), but a well balanced heat exchanger is also needed, to obtain great temperature gradients in very short distances. To fulfill these requirements a closed loop configuration like the one shown in Figure 4 can be good for air conditioning applications. The Magnetic Refrigerator RTMR develop the inverse cycle, while the heat exchangers reject heat to the surrounding on the hot side and absorb heat from the refrigerated environment on the other side (the ATU, Air Treatment Unit).

In the arrangement defined by Figure 5 (on the left), the RTMR acts like a chiller. It is a very simple plant for air conditioning, which employs only a cooling heat exchanger in the Air Treatment Unit (ATU). Air in the conditioned ambient flows in part outdoors to the surrounding and in part circulates again into the cooling loop. After mixing with the new air introduced from the surrounding total mass flow rate is treated in the ATU, to reach the desired state at the inlet of the ambient. Just to make an example of a possible application, in this case there is only one single cooling unit. This cooling ATU could be connected to the RTMR, which could play the role of the cold heat exchanger, as shown in Figure 5 on the left. As an example the transformations of air in the previous described plant are reported in the psychometric chart in Figure 5 on the right. The desired condition for the ambient is located in point A in the psychometric chart. The surrounding condition is identified by the point E. The condition of the mixture at the ATU inlet lies on the line linking points A and E and is identified by point M. The condition of the air entering the ambient is identified by point B that lies on the load line (defined by the ratio between the sensible and the total heat load) and has a temperature T_B = 6÷10 °C less that the ambient temperature T_A. The cooling coil (that is the RTMR) forces the air to cool from point M to point B. It has to absorb the heat flux calculated as the product of the mass flow rate of air crossing the ATU and the enthalpy difference of points M and B. For example a typical summer application should have an ambient temperature T_A= 26 °C, a surrounding temperature T_E= 33°C and the

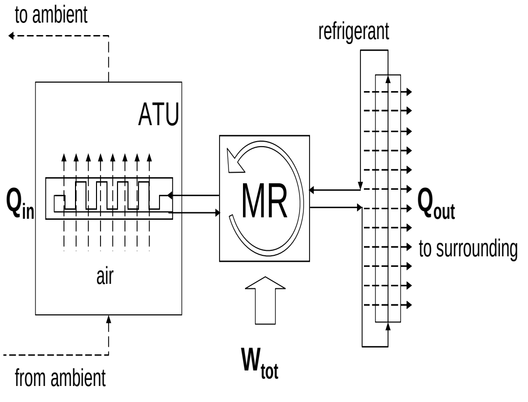

Figure 4 – Schematic drawing of a MR applied to air conditioning. Dashed lines and arrows indicates the air flows,

temperature of the air entering the ambient T_B= 18 °C.

Looking at the psychometric chart, these data ask the RTMR to operate over a $\Delta T_{span}=T_M-T_B$, which reaches as a minimum $\Delta T_{span}=T_A-T_B=12°C$ (with no air recirculation).

To calculate the performance of the Steyert-like RTMR the already mentioned calculation program [5] is used, assuming given gadolinium mass and operating conditions, assuming and using air or water as an intermediate fluid. The results in terms of cooling capacity and ΔT_{span} are reported in figure 6.

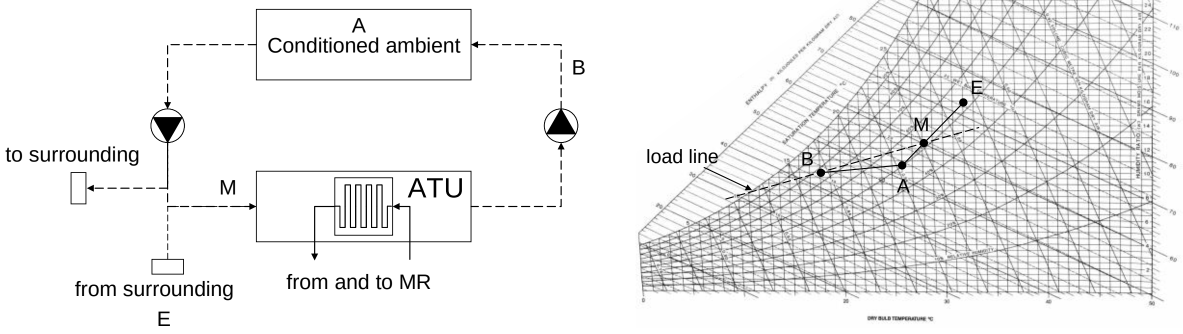

Figure 5 – Sketch of the simplest air conditioning loop coupled to the MR (left) and corresponding thermodynamic points in the humid air ASHRAE diagram (right).

It is easy to identify two significant points in the plot reported by Figure 6: a no-load working condition (Q_{in}=0, ΔT_{span} MAX) and a zero-span working condition (ΔT_{span}=0°C, Q_{in} MAX). These two points briefly summarize the operating limits and describe the potential of a RTMR, as they are connected by an almost straight line.

The performance using water or air almost lie on two parallel straight lines, with the water line showing a refrigeration capacity about six times greater than air. This is due to the more heat transfer effectiveness of water if compared to air, inside the AMR regenerator. Both the lines show that the capacity Q_{in} strongly decreases if the temperature span ΔT_{span} increases.

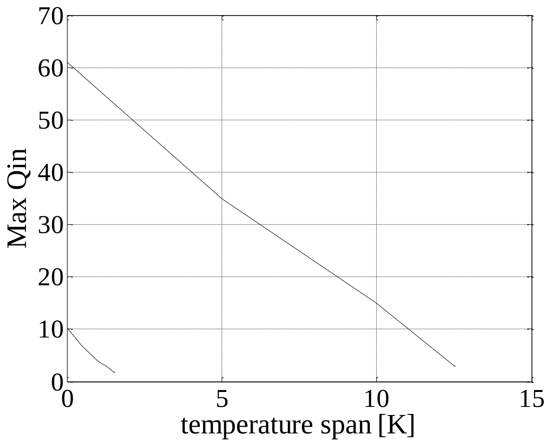

Figure 6 – Maximum calculated refrigeration capacity Q_{in} vs ΔT_{span} for different fluids: water (upper line) and air (lower line). Maximum value means that it is the best performance expected when all the MR design parameters are optimized and maximum COP is achieved.

In particular in the case of air a temperature span of less than 2°C makes the RTMR completely useless. Using water instead, the RTMR can reach a maximum temperature span of about 13°C, which is however still definitely too low for the given application.

In conclusion the simple air conditioning application presented in this paper (figure 5) cannot be performed by means of the simple rotary magnetic refrigerator here studied, irrespective of the required heat loads. Indeed the required temperature (of the order of ΔT_{span} =20°C) is too high for the chosen magnetic field (B=0.8T) applied to the chosen gadolinium compound. The simple solution to increase the mass of the MCM is not useful to overcome this bottleneck, due to the temperature constraints.

The potential solutions to improve the predicted performances of this Steyert-like RTMR are:

- enhancement of the heat transfer process inside the regenerator (changing the geometry, for example a MCM porous bed or a roughened plate arrangement);
- choice (or discovery) of better MCMs with larger MCE, also with different Curie temperatures (such as perovskites) to be used in series inside the AMR;
- increase of the available magnetic field (better design in permanent magnets and better rare earths magnets).

Obviously the possibilities to change the RTMR configuration are quite different from each other, looking for more efficient ones: this has been the work of researchers in the last decade, with a great number of new prototypes proposed and developed [3, 6].

4. Conclusions

A steady-state model of a Steyert-like magnetic refrigerator (RTMR) has been used to predict the maximum performance that a RTMR can guarantee over its whole field of application, with particular reference to a simple air conditioning refrigeration system.

Even if the predicted performances were optimized with respect to both design parameters and to operating parameters, in order to get maximum performances (cooling capacity Q_{in} and ΔT_{span}) the best performances predicted by the model gives 60 W of cooling power in the zero ΔT_{span} condition, and a ΔT_{span} of about 13 °C in the no-load condition.

The above performance is however not sufficient for the typical summer application of an air conditioning problem , which ask for a temperature span of at least 20°C.

The improvement in any one of the aspects involved in RTMR (magnets, materials, heat transfer) ensures an enlargement of the field of application of a magnetic refrigerator.

In conclusion magnetic refrigeration technology at room temperature is an actually growing research area and there are many different interdisciplinary aspects that can let it move towards improved performances, making future applications feasible also in the field of air conditioning.

Aknowledgement

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