International Journal of Fluid Mechanics & Thermal Sciences
2015; 1(3): 49-53
Published online June 22, 2015 (http://www.sciencepublishinggroup.com/j/ijfmts)
doi: 10.11648/j.ijfmts.20150103.12

Thermodynamic Study of the Active Magnetic Regenerative Refrigeration in Transitional Regime

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To cite this article:
Zina Meddeb, Rabaa Ben Sidhom, Khouloud Azaeiz, M. Razak Jeday. Thermodynamic Study of the Active Magnetic Regenerative Refrigeration in Transitional Regime. *International Journal of Fluid Mechanics & Thermal Sciences*. Vol. 1, No. 3, 2015, pp. 49-53.
doi: 10.11648/j.ijfmts.20150103.12

Abstract: Magnetic refrigeration is an emerging technology based on the magnetocaloric effect. In this paper, the magnetocaloric effect is remembered. The components of magnetic refrigeration system are described. An analogy between magnetic refrigeration and conventional refrigeration is done concerning the steps and the original work received by the system. A regenerator positioned between the hot source and the cold source increases the efficiency of the refrigeration system, from which the active magnetic regenerative refrigeration (AMRR) is studied. Thus a thermodynamic study is developed and thermal regenerator study transitional regime is done. From the results obtained by the numerical calculation, the difference of temperature between hot and cold sides reaches a limit after a certain number of cycles. This number of cycles (*Nc*) necessary to wait for the permanent regime depends on the difference in temperature hot side and cold side (ΔT), the flow regime and the magnetocaloric effect (MCE) of the regenerator. Moreover this work allowed us to study the thermal and fluidic behavior of the magnetic regenerative refrigeration, as well as to determine the flux exchanged during magnetization and demagnetization.

Keywords: Magnetic Refrigeration, Magnetocaloric Effect, Heat Transfer, Regenerator

1. Introduction

Magnetic refrigeration is a cooling technology based on the magnetocaloric effect (MCE). The MCE describes the resulting change in temperature of a material due to the application of an external magnetic field. From an environmental point of view, this technology is very attractive because it does not involve the use of greenhouse gases. The study of magnetic refrigeration was started with the discovery of MCE [1]. Then it has been used in cryogenic refrigeration. It is maturely used in liquefaction of hydrogen and helium. Since Brown first applied rare-earth metal gadolinium (Gd) in the room temperature magnetic refrigerator, the research range for magnetic refrigeration working materials has been greatly expanded. Based on the concept of the active magnetic regenerator (AMR), Zimm at American Astronautics Technology Center developed a magnetic refrigerator, which used approximately 3 kg of Gd as working material and generated up to 500–600 W cooling power in a 5 T magnetic field [2]. To be competitive with conventional systems, magnetic refrigeration requires efficient designs for both the magnetic field source and the active magnetic regenerator. Models are necessary in order to design and size prototypes. Also efficient to investigate the influence of several parameters on an AMRR. The effects of parameters are given for a specific working point.

2. Magnetic Refrigeration Principle

Magneocaloric effect (MCE) is an intrinsic propriety of magnetic materials. It consists on absorbing or emitting heat by the action of an external magnetic field. In addition, the term MCE can be considered more widely by its application not only to the temperature variation of the material, but also to the variation of the entropy of its magnetic subsystem under the effect of the magnetic field [3-7].

The entropy of such a system can be considered a combination of the magnetic entropy ΔS_m, the lattice subsystem entropy ΔS_{lat} and the entropy of the conduction electrons ΔS_{el}.

It follows that:

$$\Delta S = \Delta S_m + \Delta S_{lat} + \Delta S_{el} \quad (1)$$

If a magnetic field is applied under adiabatic conditions when any heat exchange with the surroundings is absent, then the entropy related to the temperature should increase in order to preserve the total entropy of the system constant. Increasing of this entropy implies the system heating up, and an increase in its temperature. The opposite process adiabatic removal of the magnetic field (demagnetization) will cause cooling of the magnetic system under consideration. The described temperature change is the manifestation of the MCE." [8]

This process is described in "Fig 1**".**

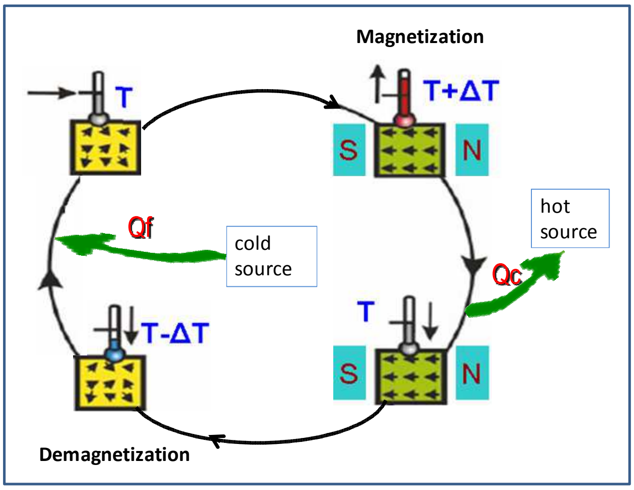

Figure 1*. Magnetocaloric effect (the arrows symbolize the direction of the magnetic moments).*

3. Analogy

3.1. Analogy with Conventional Refrigeration

The response of a magnetocaloric material to a magnetic field (magnetization / demagnetization) is similar to the response of a gas to a compression or a detention. An analogy between the magnetic refrigeration with conventional refrigerationboils downby : compression is replaced by magnetization and expansion is replaced by demagnetization.

The magnetic refrigeration cycle is composed of four steps [9].

1.Magnetization: magnetocaloric material is adiabatically magnetized.

2.Hot blow: heat transfer fluid flows from the cold end to the hot end of the regenerator.

3.Demagnetization: magnetocaloric material is adiabatically demagnetized.

4. Cold blow: heat transfer fluid flows from the hot end to the cold end of the regenerator.

In the Active Magnetic Regenerative Refrigeration this cycle is repeated n times and the magnetocaloric effect ΔT induced is amplified at each cycle to achieve temperatures of hot and cold source limits (Steady state).

3.2. Analogy with Stirling Refrigerator

The free-piston Stirling refrigerator is a completely closed system.

Q_c: the heat exchanged with the heat source.

Q_f: heat exchanged with the cold source.

Q_a: the heat stored in the regenerator in one direction and in the other recovered.

W: mechanical work.

In the magnetic refrigeration system, the mechanical work is replaced by the magnetic work and Q_a is replaced by heat transferred between the fluid and the regenerator (stored after demagnetization and recovered after magnetization).

"Fig.2"shows the diagram of refrigerator.

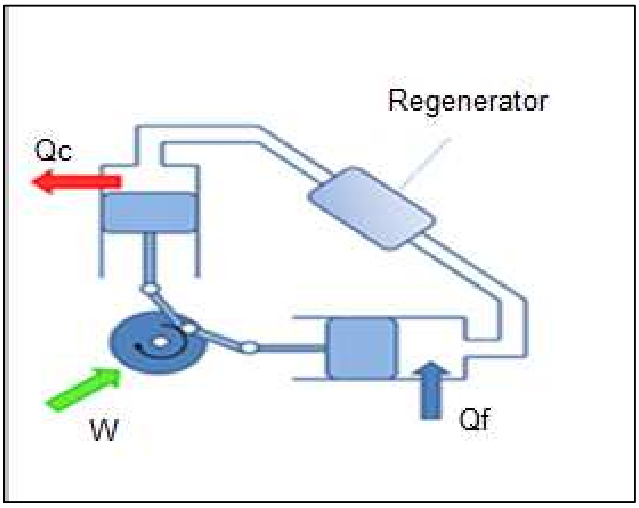

Figure 2*. Stirling refrigerator.*

The Stirling regenerator is passive but in the magnetic refrigeration the regenerator is active.

4. Thermodynamic Study

4.1. Regenerator Design and Working Cycle

The regenerator design is shown in ''fig 3". It consists of parallel plates equally spaced between which flows a heat transfer fluid.

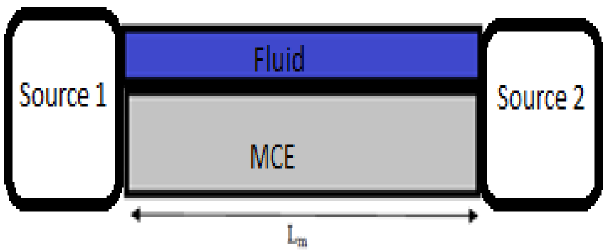

Figure 3*. Parallel plates regenerator.*

By applying the energy balance on a differential fluid segment, the following equation is obtained:

$$\frac{\partial}{\partial x}\left(Dc_f T_f\right) = h\frac{S}{L}\left(T_f - T_m\right)dx - \frac{\partial}{\partial t}\left(\rho_f c_f S T_f\right)dx \quad (2)$$

4.2. Energy Balance on the Magnetocaloric Material

By applying the energy balance on a differential segment of the magnetocaloric material, we obtain the following equation:

$$\frac{\partial}{\partial t}(\rho_m c_m S\, T_m)dx + \lambda_m S\frac{\partial^2 T_m}{\partial x^2}dx - h\frac{S}{L}(T_f - T_m)dx = \lambda_m S\frac{\partial T_m}{\partial x} \quad (3)$$

Where λ_m is the conductivity of the magnetocaloric material.

Only convection exchanges between the regenerator and the fluid are considered. Axial conduction is neglected; this can be verified in several cases if parameters are correctly chosen: thin MCE material, spheres, stacked bed perpendicularly to the flow direction, etc[10].

By combining the two equations obtained on the fluid and the magnetocaloric material, a final system of equations is obtained as follows

$$m_f c_f\left(\frac{\partial T_f}{\partial t} + d\frac{\partial T_f}{\partial x}\right) = hS(T_m - T_f)$$

$$m_m c_m\frac{\partial T_m}{\partial t} + \lambda_m v\frac{\partial^2 T_m}{\partial x^2}dx = hS(T_m - T_f)$$

$$Q = hS(T_m - T_f)$$

$$\text{With } d = \frac{Dv}{m_f S} \quad (4)$$

5. Numerical Study

To solve the previous system of equations we use finite difference method. Therefore, after discretization, and some developments, the final system can be written as follows:

$$T_{f(i+1,j)} = A_{f1}T_{f(i,j)} + A_{f2}T_{f(i,j-1)} + A_{f3}T_{m(i,j)}$$

$$T_{m(i+1,j)} = A_{m1}T_{m(i,j)} + A_{m2}T_{f(i,j)}$$

$$Q_{(i+1,j)} = hS\left(T_{m(i+1,j)} - T_{f(i+1,j)}\right) \quad (5)$$

Where

$$A_{f1} = \left(1 - \left(d(t)\frac{\Delta t}{\Delta x} + \frac{hS}{m_f c_f}\right)\Delta t\right) \quad (6)$$

$$A_{f2} = d(t)\frac{\Delta t}{\Delta x} \quad (7)$$

$$A_{f3} = \frac{hS}{m_m c_m}\Delta t \quad (8)$$

$$A_{m1} = \left(1 - \frac{hS}{m_m c_m}\Delta t\right) \quad (9)$$

$$A_{m2} = \frac{hS}{m_m c_m}\Delta t \quad (10)$$

The equations system is solved numerically by finite difference scheme. Two boundary conditions are imposed on the regenerator: the fluid enters the bed at temperature of the Cold reservoir during the hot flow period and at the temperature of the hot reservoir at the cold flow period [11].

The following flowchart illustrates the different stages of the modeling code, in a simplified manner:

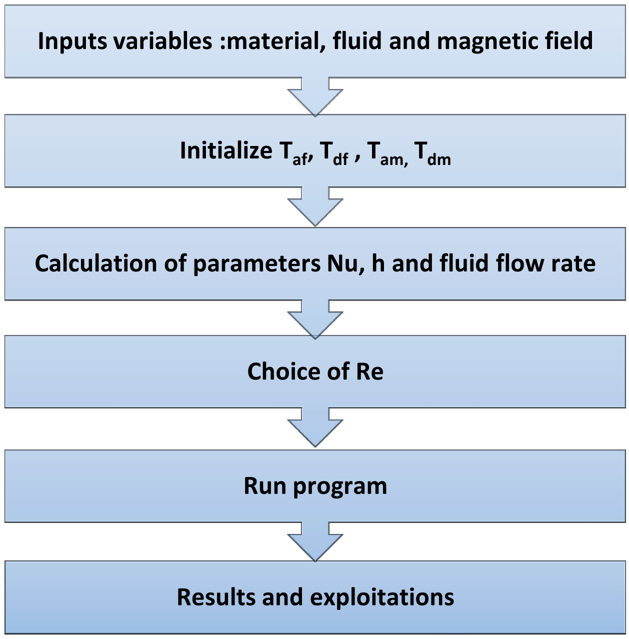

Figure 4. *Simulation flowcharts.*

6. Results and Discussion

The problem is solved considering a gadolinium MCE material as regenerator and a water as heat transfer fluid. The flow rate is fixed to $5.10^{-6} m^3 s^{-1}$.

The temperature profiles in the two sides (hot and cold) of the material are shown in "Fig.5". We note that after a transient phase the two curves reach their steady state.

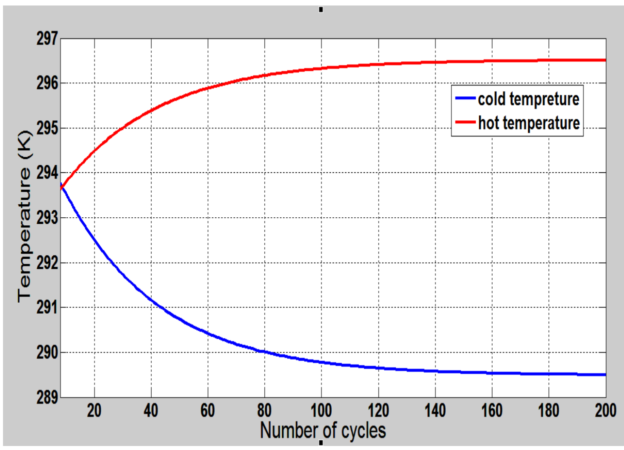

Figure 5. *Temperature profile in two sides hot and cold of material.*

The variation of temperature with position on the magnetocaloric material is shown in "Fig.6". We note that, after small number of cycles the temperature in every point of the material is almost constant and equal to the room temperature T_0=293K but while increasing the number of cycles, the difference of temperature between the two sides of the plate increases and keep increasing with increasing number of cycle till $T_{max} = T_{hot}$ and $T_{min} = T_{cold}$.

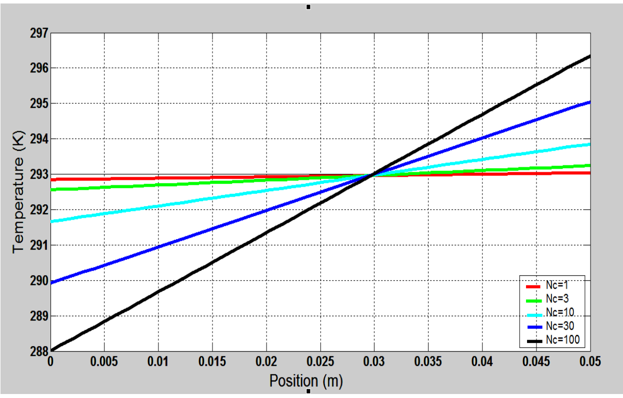

Figure 6. *Temperature profile through plate length after different number of cycle.*

In the graph below "Fig.8",we present different profiles of temperature with different values of $\Delta T = (T_h - T_c)$ between cold and hot sources. This graph shows the evolution of the temperature with number of cycles. The values number of cycles necessary to reach steady state increases with ΔT between hot source and cold source.

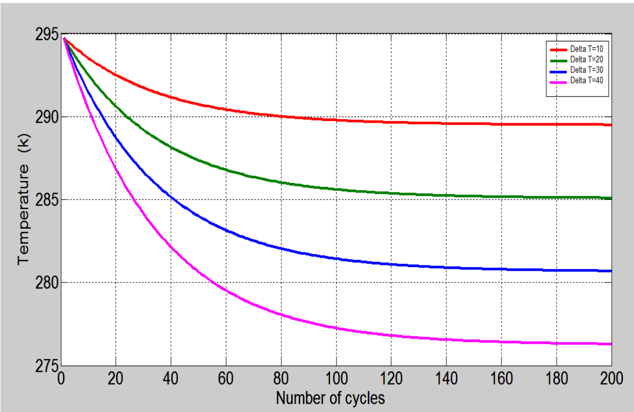

Figure 7. *Temperature profiles for different* ΔT *between hot and cold sources.*

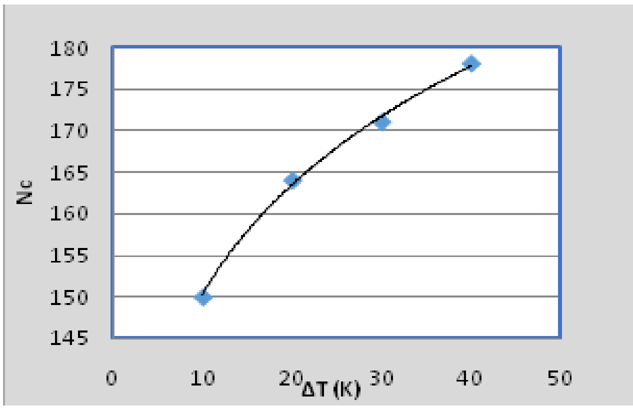

Figure 8. *Variation of number of cycles with Tempreture range between cold and hot reservoir.*

The varation of the number of cycles with ΔT is shown in ''Fig.8''. Curve smoothing allow us to obtain an approximative expression engendring this variation.

$$N_c = 113.4\ \Delta T^{0.121} \tag{11}$$

In figure "Fig.9''we present four temperature profiles for four different volumetric flow rates , we note that the flow rate is inversely proportional to the number of cycle necessary to reach the steady state ,This can be explained by the fact that increasing the flow rate increases heat transfer coefficient so the system reach steady state faster .

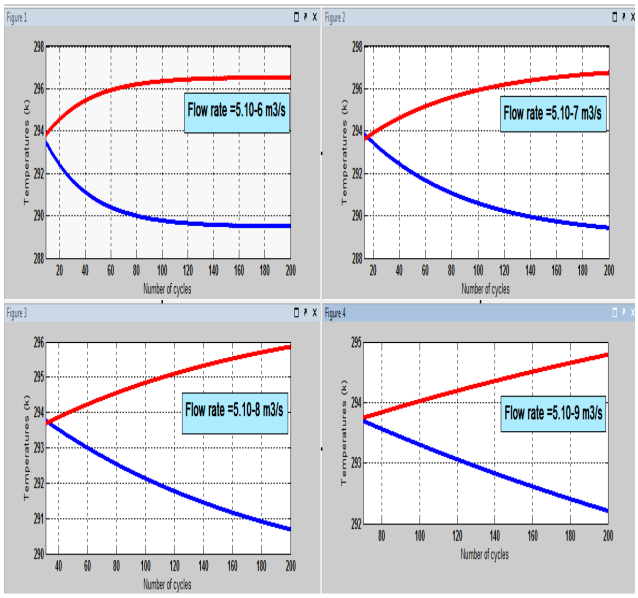

Figure 9. *Tempreture profiles fordifferent flow rates.*

"Fig.10"presents the variation of the energy exchanged between the EMC material and the fluid during magnetization, with the number of cycles. The curve given shows that after a transient phase the energy reach a limit. This can be justified by the fact that the temperature becomes constant and the regime becomes stable.

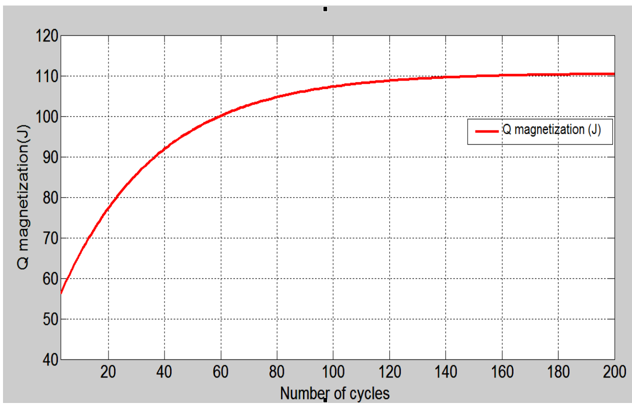

Figure 10. *Energy profile during magnetization.*

7. Conclusions

In this paper, we recalled the magnetocaloric effect and we made an analogy between classical and magnetic refrigeration.In particular the system with regenerator. This regenerator will increase the temperature difference between the two sources. We can achieve significant ΔT but a longer transitory regime.

We study a model of AMRR, results reveals that the temperature profile reach the steady state after a specific number of cycles, this number changes with the fluid rate flow, and the difference of temperature between cold and hot sources. This study help us to predict AMRR system performance and it helps us to size a magnetic refrigeration system. The model can be easily used to study more complicated magnetic refrigerant systems like multi-layered beds which can be the aim of future works.

Nomenclature

T	temperature [K]
T_h	temperature of the hot reservoir [K]
T_c	temperature of the cold reservoir [K]
T_0	ambient temperature [K]
S	cross-sectional area of regenerator bed [m^2]
h	convection heat transfer coefficient [W/(m^2K)]
C	specific heat of either fluid or material [J/(kg K)]
L	the length of theplate of the material[m]
Q	energy [J]
D	fluid flow rate[kg/s]
m	mass [kg]
v	volume [m3]
t	time [s]
x	position on the bed
N_c	number of cycles
λ_m	Thermal conductivity of material[W/mK]
Subscripts	
f	fluid
m	material

References

[1] B.F. Yu, Q. Gao, B. Zhang, X.Z. Meng, Z. Chen; Review on research of room temperature magnetic refrigeration; International Journal of Refrigeration 26 (2003) 622–636

[2] Zimm C, Jastrab A, Sternberg A, Pecharsky VK, Gschneidner Jr KA, Osborne M, Anderson I. Description and performance of a near-room temperature magnetic refrigerator. Adv Cryog Eng 1998;43:1759–66.

[3] Tishin, A.M. “Hand Book of Magnetic Material”, Vol.12, Ed. Buschow K.H.J., North Holland, Amsterdam, 1999.

[4] AfefLebouc, Morgan Almanza, Jean Paul Yonnet, Ulrich Legait, Julien Roudaut. Réfrigération magnétique Etat de l'art et développements récents. Symposium de Génie Electrique 2014, July 2014, Cachan, France.

[5] K. K. Nielsen, J. Tusek, K. Engelbrecht, S. Schopfer, A. Kitanovski, C.R. H. Bahl, A. Smith, N.Pryds, et A. Poredos, « Review on numerical modeling of active magnetic regenerators for room temperature applications », Int. J. Refrig., vol. 34, no 3, p. 603-616, mai 2011.

[6] U. Legait, F. Guillou, A. Kedous-Lebouc, V. Hardy, et M. Almanza, « An experimental comparison of four magnetocaloric regenerators using three different materials », Int. J. Refrig., vol. 37, p. 147‑155,janv 2014.

[7] O. Sari et M. Balli, « From conventional to magnetic refrigeratortechnology », Int. J. Refrig., vol. 37, p. 8‑15, janv. 2014.

[8] A. M. Tishin and Y. I. Spichkin,Themagnetocaloric effect and its applications, 2003.

[9] Barclay, J. A., Steyert Jr., W. A., 1982.Active magnetic regenerator. U.S. Patent No. 4,332,135

[10] H.R.Bouchekara (2008), thèse “Recherche sur les systèmes de réfrigération magnétique. Modélisation numerique, conception et optimisation ‘’,G2Elab Grenoble .

[11] F. Allab, A. Kedous-Lebouc, J. M. Fournier and J. P. Yonnet, “Numerical Modeling for Active Magnetic Regenerative Refrigeration,” IEEE Transaction on magnetic, vol. 41, pp. 3757.