



HAL
open science

Permanent Magnet Sources for Magnetic Refrigeration

Julien Roudaut, Jean-Paul Yonnet, Afef Kedous-Lebouc, Christian Muller

► **To cite this version:**

Julien Roudaut, Jean-Paul Yonnet, Afef Kedous-Lebouc, Christian Muller. Permanent Magnet Sources for Magnetic Refrigeration. 2010. hal-00516457

HAL Id: hal-00516457

<https://hal.science/hal-00516457>

Submitted on 9 Sep 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Permanent Magnet Sources for Magnetic Refrigeration

J. ROUDAUT¹, J.-P. YONNET¹, A. KEDOUS-LEBOUC¹, C. MULLER²

¹ Grenoble Electrical Engineering Laboratory, Grenoble-INP – UJF – CNRS UMR 5269, G2Elab, ENSE3, BP 46, 38402 St Martin d'Hères Cedex, France

² Cooltech Applications, 2 impasse Antoine Imbs, 67810 Holtzheim, France

Abstract: Several permanent magnet structures have been proposed for magnetic refrigeration but it remains difficult to compare their performance. To overcome this issue some recent studies have proposed different magnet performance criteria and calculated the design performance. This paper aims to define a new set of performance criteria taking into account the magnetic work and to perform an accurate comparison of some published designs of magnetic field sources. First a brief review of previously proposed performance criteria is given and their limitations are discussed. Then a set of performance criteria is defined. Magnetic coefficient of performance is introduced. The set is completed by cooling power density, price per unit of cooling power and maximum magnetic torque or force (respectively for rotary or reciprocating designs). Different published structures are compared, from simple C-shaped magnets to complex flux concentration multi-pole machine, including Halbach assemblies. Finally these structures are modelled using commercial Finite Element software, namely FLUX[®], and compared according to the set of performance criteria.

Key words: permanent magnets, magnetic refrigeration, magnetocaloric systems,

Address: Jean-Paul Yonnet, Tel: +33 (0) 476 82 62 97, Fax: +33 (0) 476 82 63 00, E-mail: Jean-Paul.Yonnet@grenoble-inp.fr, Julien.Roudaut@g2elab.grenoble-inp.fr (J. Roudaut)

1. Introduction

Magnetic Refrigeration (MR) at room temperature is a good alternative to gas compression refrigeration systems because it does not involve the use of greenhouse gases and is more efficient. MR is expected to lower energy consumption by 20-30% over conventional technology [1]. MR systems are complex and need better design to be competitive with conventional systems. One of the major difficulties is the field source design, as it constitutes a major part of the expense in MR systems and involves coupled magnetic, mechanic and thermal phenomena.

Recent studies have focussed on field source for MR. Bjørk *et al.* [2] ranked several published magnet design according a magnet efficiency parameter Λ_{cool} directly related to cooling power per unit of magnet mass. Bouchekara *et al.* [3] studied forces and torque occurring when the magnet structure is moved relative to the magnetocaloric materials.

However, the first study did not calculate magnetostatic forces and torque occurring in MR systems leading to mechanical power input requirement and mechanical breakage. The second study focussed on forces and torque, not considering cooling power.

The purpose of this paper is to perform an accurate comparison of several published MR magnet structures taking into account both cooling power, forces and torque and other criteria. First a set of performance criteria representative of the field source performance is defined.

Then six published MR systems are modelled and computed. Finally the structures are compared and guidelines given for the selection of magnetic field sources.

2. Method

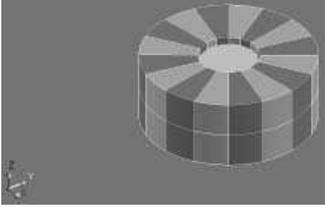
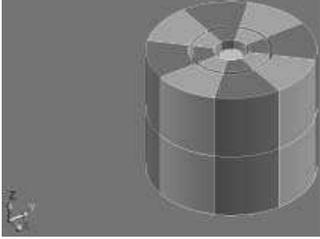
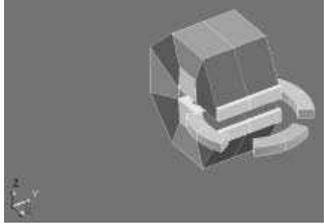
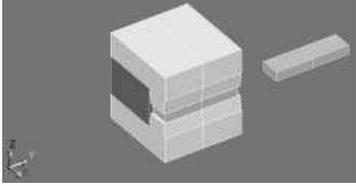
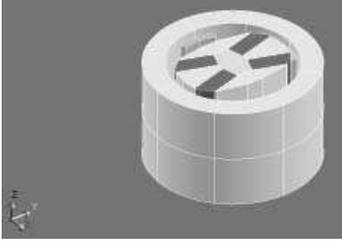
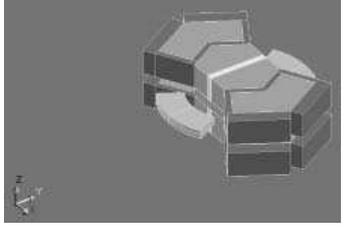
2.1. Magnet Structures of the Study

Six permanent magnet structures were studied and are presented in Table 1. All those structures have been used in magnetic refrigeration systems but in some cases information were lacking to model the exact structure, so that the design is only similar. Permanent magnets are depicted in magenta and pink, regenerators are in green and light green, soft magnetic materials are in white and non-magnetic materials are in yellow.

The first structure was used by Bjørk *et al.* [2]. It consists of a Halbach cylinder with a cylindrical Active Magnetic Regenerator (AMR) placed inside. AMR is subjected to a reciprocating motion so that it undergoes a variable magnetic field. The second structure is a rotating system proposed by Tura and Rowe [4, 5]. A cylindrical AMR is set inside two nested Halbach cylinder. The inner cylinder rotates to create a variable magnetic field in AMR. The third structure was designed by Lee *et al.* [6]. A slot was made in a Halbach cylinder to allow rotating motion of a circular AMR. FeCoV parts were added inside the cylinder to concentrate flux in the air gap. The fourth structure was built by Zheng *et al.* [7]. It is composed of a simple C-shaped magnet with two AMRs subjected to a dual reciprocating motion inside and outside the air gap region. Okamura *et al.* designed the fifth structure [8, 9;



Table 1. Magnet structures of the study

		
<i>Halbach cylinder</i> (Bjørk <i>et al.</i>)	<i>Two nested Halbach cylinders</i> (Tura and Rowe)	<i>Halbach cylinder with a slot</i> (Lee <i>et al.</i>)
		
<i>C-shaped magnet</i> (Zheng <i>et al.</i>)	<i>Bipolar motor</i> (Okamura <i>et al.</i>)	<i>Structure with 2 V-shaped air gap</i> (Zimm <i>et al.</i>)

10] which is very similar to a permanent magnet machine. The rotor consists of two flux concentration poles and the stator is composed of four AMRs placed on an iron yoke. The last structure was proposed by Zimm *et al.* [11]. It is a complex permanent magnet assembly which rotates to alternatively magnetize and demagnetize the four AMRs.

In order to perform an accurate comparison, gadolinium was used to model the magnetocaloric material even if a different material was used in the original design. The AMR is modelled as a bulk material (corresponding to a null porosity) because demagnetizing field is closely related to regenerator shape.

2.2. Selection of Performance Criteria

Several authors have proposed different performance criteria for magnetic refrigeration systems. For instance, Russek and Zimm [12] proposed the price per unit of power, Bjørk *et al.* [13] used the cooling power per unit of magnet mass and Rowe [14] suggested the cooling exergy. However it seems that a single criterion is not sufficient to describe AMR efficiency. If we focus on field source design, five criteria appear to be of interest. Indeed, a

magnetic refrigeration system is aimed to be efficient, cost effective and compact and have a long life time, which leads to the five following criteria: (1) Magnetic coefficient of performance, (2) Cost per unit of cooling power, (3) Specific power density, (4) Volumetric power density and (5) Forces or torque occurring during refrigeration cycle (responsible for mechanical breakage). The magnetic coefficient of performance is defined as:

$$COP_{mag} = \frac{\dot{Q}_{mcm}}{\dot{Q}_{mec}}$$

with \dot{Q}_{mcm} the power absorbed by the magnetocaloric material (MCM) during demagnetization and \dot{Q}_{mec} the mechanical power required to move the magnet structure relative to AMR. It is representative of the field source efficiency. For 2nd order materials as Gd, the magnetocaloric effect (MCE) is proportional to the magnetic field to the power 2/3 [15] so the power absorbed during magnetization is given by:

$$\dot{Q}_{mcm} = f \rho_s V_s c_{ps} \left(\frac{\partial T}{\partial H^{2/3}} \right) \left(\langle H_{hf}^{2/3} \rangle - \langle H_{lf}^{2/3} \rangle \right)$$

f symbolises the frequency of the cycle, T the temperature, H the magnetic field. ρ_s , V_s and c_{ps} are respectively

Table 2. Performances of the magnet structures

Design	COP_{mag} (-)	Cost (€/W)	Specific power density (W/kg)	Volumetric power density (W/m ³)	F_{max} (N)
Bjørk <i>et al.</i>	17.4	3.16	32.5	19.8×10 ⁴	-421
Tura and Rowe	15.3	16.4	6.12	4.24×10 ⁴	-348
Lee <i>et al.</i>	154	5.35	18.4	13.0×10 ⁴	-55
Zheng <i>et al.</i>	57.7	2.46	15.2	11.0×10 ⁴	-165
Okamura <i>et al.</i>	25.4	1.69	12.1	7.38×10 ⁴	-1291
Zimm <i>et al.</i>	85.9	4.56	21.9	8.24×10 ⁴	-508

the density, volume and specific heat capacity of the MCM. Subscripts hf and lf respectively mean in the high field region and in the low field region and operator $\langle \rangle$ is the volume average in the AMR. In reciprocating devices, the mechanical power required to overcome magnetostatic forces is calculated from:

$$\dot{Q}_{mec} = f \int F_x dx$$

with F_x the component of the force along displacement dx . In rotary systems, it becomes:

$$\dot{Q}_{mec} = f \int \Gamma_z d\theta$$

with Γ_z the torque about the z axis and $d\theta$ the angular displacement. For all calculations, frequency was set to 0.5 Hz which is a typical value for AMR systems. Results are closely related to this value but the dependence is the same for every structure. Systems are supposed not to recover work when forces or torque are driving so \dot{Q}_{mec} was calculated during demagnetization (*i.e.* when forces and torque are resistive).

2.3. Methodology

A multistatic 3D analysis was performed using the commercial Finite Element software FLUX®. Demagnetizing effects and permeability of the AMR were taken into account. Gadolinium heat capacity and MCE were respectively set to 230 J/kg/K and 3.8 K/T^{2/3}. Cost of materials include processing and shaping and are estimated from the USGS web site on commodities [16]. Cost of NdFeB magnets, Gadolinium, Fe and FeCoV are respectively set

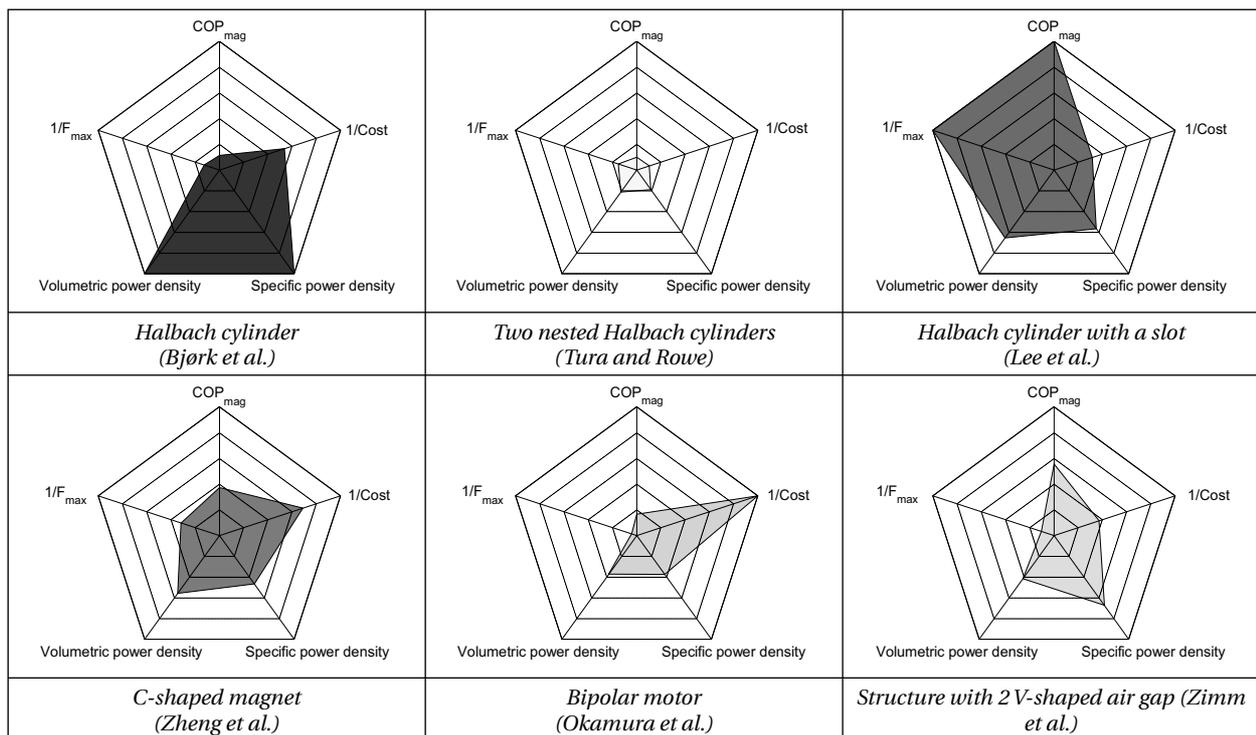
to 100 €/kg, 130 €/kg, 1 €/kg and 80 €/kg. The volumetric power density is the ratio of the AMR volume to the total volume of the system. The latter takes into account the volume required to displace the AMR but actuators are not considered.

3. Comparison of the Different Structures

Performance criteria were calculated for all the magnet structures and are given in Table 2. To compare rotary and reciprocating systems, maximum torques in rotary structures were reduced to forces by dividing them by their level arm (the average radius of the rotor). For an easier visual comparison Table 3 presents the performance criteria of magnet structures on radar charts. As forces and cost should be as low as possible, their inverses are plotted. Some structures set apart the others because of a high value for one performance criterion or more. Two criteria are easy to analyse, namely specific power density and volumetric power density. Specific power density is related to the ratio of AMR mass to total mass, and volumetric power density is related to the ratio of AMR volume to total volume. The most compact structure (for both criteria) is the Bjørk *et al.* design for it has the highest ratios.

The cost effectiveness first depends on iron relative mass in the structure. The most cost effective design is the one of Okamura *et al.* followed by the Zheng *et al.* design, both containing a high relative mass of iron parts. Then cost effectiveness is closely linked to the ratio of AMR mass to total mass, so the ranking of the remaining structures is the same as the one of the specific power density.

Table 3. Comparison of permanent magnet structures performances





The maximum force is both related to the magnitude of the magnetic field and to its spatial variation. The best designs are those using several AMRs arranged so that the resistive forces or torque (due to AMRs leaving the high field region) are partly balanced by driving forces or torque (due to AMRs entering the high field region). The structure undergoing the least force is the Lee *et al.* design, followed by the Zheng *et al.* design magnet because both have a suitable AMRs arrangement. All the other designs are subjected to relatively high forces or torque, but it is possible to use several AMRs to reduce the effect. The last criterion is the magnetic coefficient of performance. It is proportional to the cooling power and to the inverse of the mechanical power. An efficient structure requires a low mechanical power, a high AMR volume and a large magnetic field variation. The most efficient design is the one of Lee *et al.* because it fulfils these three conditions, mostly owing to its low mechanical power. The second most efficient design is the structure used by Zimm *et al.* followed by Zheng *et al.* design because both designs have a high AMR volume. The last three structures have relatively low COP_{mag} because of the high value of their mechanical power.

4. Discussion

If the results summarized in the previous section give some information about the potential of typical magnet structures for MR, it should be noted that all calculations were run on non-optimized geometries. Moreover, some information was lacking for some structures so the results may not reflect the potential of the original design. Ranking of structures do not seem appropriate since weighting of performance criterion is difficult and depends on the scope of application. For instance, specific (or volumetric) power density and COP_{mag} are key factors for on-board applications, whereas cost effectiveness seems to be the major criterion for domestic applications. The maximum value of force acting on the moving parts may be an all-or-none criterion, meaning that a force bigger than a given value would lead to unacceptable mechanical breakage. Future work will focus on designing a new field source for MR according to these five performance criteria.

References

- [1] Gschneidner Jr. KA, Pecharsky VK. 2008, Thirty years of near room temperature magnetic cooling: Where we are today and future prospects. *Int. J. Refrig.* 31(6): 945-961.
- [2] Bjørk R, Bahl CRH, Smith A, Pryds N. 2009, On the optimal magnet design for magnetic refrigeration, In Proc. *Third IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 473-480.
- [3] Bouchekara H, Kedous-Lebouc A, Dupuis C, Yonnet JP. 2009, Electromagnetic analysis of a multipole field source for a magnetic refrigeration system, In Proc. *Third IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 401-407.
- [4] Tura A, Rowe, A. 2007, Design and testing of a permanent magnet magnetic refrigerator, In Proc. *Second IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 363-370.
- [5] Rowe, A. 2009b, Private communication.
- [6] Lee SJ, Kenkel JM, Pecharsky VK, Jiles DC. 2002, Permanent magnet array for the magnetic refrigerator. *J. Appl. Phys.* 91(10): 8894-8896.
- [7] Zheng ZG, Yu HY, Zhong XC, Zeng DC, Liu ZW. 2009, Design and performance study of the active magnetic refrigerator for room-temperature application, *Int. J. Refrig.* 32(1): 78-86.
- [8] Okamura T, Yamada K, Hirano N, Nagaya S. 2006, Performance of a room-temperature rotary magnetic refrigerator, *Int. J. Refrig.* 29(8): 1327-1331.
- [9] Okamura T, Rachi R, Hirano N, Nagaya S. 2007, Improvement of 100W class room temperature magnetic refrigerator. In Proc. *Second IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 377-382.
- [10] Okamura T. 2009, Private communication.
- [11] Zimm C, Auringer J, Boeder A, Chell J, Russek S, Sternberg A. 2007, Design and initial performance of a magnetic refrigerator with a rotating permanent magnet, In Proc. *Second IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 341-347.
- [12] Russek SL, Zimm CB. 2006, Potential for cost effective magnetocaloric air conditioning systems, *Int. J. Refrig.* 29(8): 1366-1373.
- [13] Bjørk R, Bahl CRH, Smith A, Pryds N. 2008, Optimization and improvement of Halbach cylinder design, *J. Appl. Phys.* 104(1): 013910.1-013910.9.
- [14] Rowe A., 2009, Performance metrics for Active Magnetic Refrigerators, In Proc. *Third IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*: 195-204.
- [15] Oesterreicher H, Parker FT. 1984, Magnetic cooling near Curie temperatures above 300K, *J. Appl. Phys.* 55(12): 4334-4338.
- [16] U.S. Geological Survey, 2007 Minerals Yearbook, Rare Earths, March 2010 http://minerals.usgs.gov/minerals/pubs/commodity/rare_earth.