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Review

Review and comparison of magnet designs for magnetic refrigeration

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ARTICLE INFO

Article history:
Received 11 July 2009
Received in revised form
8 December 2009
Accepted 12 December 2009
Available online 28 December 2009

Keywords:
Magnetic refrigerator Review
Design
Technology
Magnetic

ABSTRACT

One of the key issues in magnetic refrigeration is generating the magnetic field that the magnetocaloric material must be subjected to. The magnet constitutes a major part of the expense of a complete magnetic refrigeration system and a large effort should therefore be invested in improving the magnet design. A detailed analysis of the efficiency of different published permanent magnet designs used in magnetic refrigeration applications is presented in this paper. Each design is analyzed based on the generated magnetic flux density, the volume of the region where this flux is generated and the amount of magnet material used. This is done by characterizing each design by a figure of merit magnet design efficiency parameter, Λ_{cool}. The designs are then compared and the best design found. Finally recommendations for designing the ideal magnet design are presented based on the analysis of the reviewed designs.

Tour d'horizon et comparaison des conceptions d'aimants pour le froid magnétique

Mots clés : Réfrigérateur magnétique ; Enquête ; Conception ; Technologie ; Aimant

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0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2009.12.012

Nomenclature

Variables

ΔT_{ad}	Adiabatic temperature change (K)
T_c	Curie temperature (K)
I	Current (A)
B	Magnetic flux density (T)
N	Number of winding turns (–)
L_{core}	Length of soft magnetic material (m)
L_{gap}	Length of air gap (m)
B_{rem}	Magnetic remanence (T)
V_{mag}	Volume of magnet(s) (m^3)
V_{field}	Volume of high flux density region (m^3)
M^*	Magnet figure of merit from Jensen and Abele (1996) (–)
K	Strength of magnetic field from Coey and Ni Mhiochain (2003) (–)
A_{field}	Area of the high flux density region (m^2)
A_{mag}	Area of the magnet (m^2)
B_{out}	Flux density of low flux density region (T)
P_{field}	Fraction of AMR cycle where magnet is in use (–)
H	Magnetic field ($A\,m^{-1}$)
H_C	Intrinsic Coercivity ($A\,m^{-1}$)

Greek

μ_r	Relative permeability (–)
μ_0	Permeability of free space ($N\,A^{-2}$)
Λ_{cool}	Magnet characterization parameter ($T^{2/3}$)

1. Introduction

Magnetic refrigeration is an evolving cooling technology that has the potential of high energy efficiency using environmentally friendly refrigerants. Magnetic refrigeration utilizes the magnetocaloric effect (MCE), which is the temperature change that most magnetic materials exhibit when subjected to a changing magnetic field. This temperature change is called the adiabatic temperature change, ΔT_{ad}, and is a function of temperature and magnetic field. The temperature change is greatest near the Curie temperature, T_c, which is different for different magnetocaloric materials (Pecharsky and Gschneidner, 2006). Because the MCE in the best magnetocaloric materials currently available exhibit a temperature change of no more than 4 K in a magnetic field of 1 T, a magnetic refrigeration device must utilize a regenerative process to produce a large enough temperature span to be useful for refrigeration purposes. The most utilized process for this is called active magnetic regeneration (AMR).

At present, a great number of magnetic refrigeration test devices have been built and examined in some detail, with focus on the produced temperature span and cooling power of the devices (Barclay, 1988; Yu et al., 2003; Gschneidner and Pecharsky, 2008). So far the magnet, a key component in the magnetic refrigeration system, has been largely overlooked, even though it is often the single most expensive part of a magnetic refrigerator. Also little effort has been made to compare existing magnet designs in order to learn to design more efficient magnetic structures.

In general, a magnet design that generates a high magnetic flux density over as large a volume as possible while using a minimum amount of magnet material is to be preferred. Since the magnet is expensive it is also important that the magnetic refrigerator itself is designed to continuously utilize the magnetic flux density generated by the magnet.

1.1. *Magnetic refrigeration magnets*

As previously stated a substantial number of magnetic refrigeration devices have been built. In all devices, one of three types of magnets has been used to generate the magnetic field. The first magnetic refrigeration device used a superconducting electromagnet (Brown, 1976), and other systems also using a superconducting electromagnet have since been built (Zimm et al., 1998; Blumenfeld et al., 2002; Rowe and Barclay, 2002). Devices using a non-superconducting electromagnet have also been constructed (Bahl et al., 2008; Coelho et al., 2009), but the greater majority of devices built in recent years have used permanent magnets to generate the magnetic field (Bohigas et al., 2000; Lee et al., 2002; Lu et al., 2005; Vasile and Muller, 2006; Okamura et al., 2007; Tura and Rowe, 2007; Zimm et al., 2007; Zheng et al., 2009; Engelbrecht et al., 2009).

The reason permanent magnets are preferred is that they do not require power to generate a magnetic field. This is not the case for an the electromagnet where a large amount of power is needed to generate, e.g. a 1 T magnetic flux density in a reasonable volume. This can be seen from the relation between the current, I, and the generated flux density, B, for an electromagnet in a single magnetic circuit consisting of a soft magnetic material with relative permeability, μ_r, and where the core has roughly the same cross sectional area throughout its length and the air gap is small compared with the cross sectional dimensions of the core,

$$NI = B\left(\frac{L_{core}}{\mu_r\mu_0} + \frac{L_{gap}}{\mu_0}\right), \tag{1}$$

where N is the number of turns in the winding, L_{core} is the length of the soft magnetic material, μ_0 is the permeability of free space and L_{gap} is the length of the air gap. In order to generate a 1.0 T magnetic flux density over e.g. a 30 mm air gap, which is typical for a magnetic refrigeration device, an iron cored solenoid with $\mu_r = 4000$ would need to have 24,000 ampere windings. The length of the soft magnetic material is irrelevant as the expression is dominated by the second term. Such an electromagnet with 24,000 ampere windings would need a massive power supply and an equally massive cooler to prevent the solenoid from overheating. Based on this simple calculation, it can be seen why an electromagnet is not preferred in most magnetic refrigeration devices.

A superconducting electromagnet is a better option than the traditional electromagnet because it requires little power