INTERNATIONAL JOURNAL OF REFRIGERATION 63 (2016) 14–24

Available online at www.sciencedirect.com

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A comprehensive study of a versatile magnetic refrigeration demonstrator

D. Velázquez [*], *C. Estepa, E. Palacios, R. Burriel*

Instituto de Ciencia de Materiales de Aragón (ICMA), CSIC – Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 2 October 2015
Accepted 3 October 2015
Available online 12 November 2015

Keywords:
Magnetic refrigerator
Prototype
Experimentation
Thermodynamic cycle
Gadolinium

ABSTRACT

A versatile room temperature reciprocating magnetic refrigeration demonstrator has been designed, built and tested in order to evaluate the influence of different running parameters and to check suitable magnetocaloric materials for cooling at room temperature. A comprehensive study has been done with Gd spheres of 0.2–0.4 mm diameter arranged as a double regenerator with 15 g each. A Halbach $Nd_2e_{14}B$ permanent magnet with a slot of 10 mm width has been used to generate the magnetic field with a maximum value of 1.4 T. The heat transfer fluid is a mixture of water and ethylene glycol in a 75–25 percentage. The demonstrator achieves a maximum no-load temperature span close to 20 K, with a regeneration ratio of $\xi = 4.1$, and a maximum cooling power $\dot{Q}_c = 6$ W at zero temperature span. COP values have been shown and different thermodynamic AMR cycles have been studied looking for the best parameters.

Une étude exhaustive d'un démonstrateur de froid magnétique modulable

Mots clés : Réfrigérateur magnétique ; Prototype ; Expérimentation ; Cycle thermodynamique ; Gadolinium

1. Introduction

Magnetic refrigeration is a novel technology which is trying to be an alternative to conventional gas compression–expansion cooling systems at room temperature. This technology is more environmental friendly because it does not use CFC gases, which are partially responsible for the ozone layer depletion and the enhancement of the greenhouse effect. In addition, it has the potential to lower the energy consumption by 20–30%, as reported by Gschneidner and Pecharsky (2008).

Many prototypes have already been built and tested successfully. Most of them are composed of plates or spheres of gadolinium as an active refrigerant because it is a well known benchmark material. They have been widely reported by Yu et al. (2010) and Gschneidner and Pecharsky (2008). Some of

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[*] *Corresponding author.* Instituto de Ciencia de Materiales de Aragón (ICMA), CSIC – Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain. Tel.: +34 976 762467; Fax: +34 976 761229.

E-mail address: davelazq@unizar.es (D. Velázquez).

http://dx.doi.org/10.1016/j.ijrefrig.2015.10.006

Nomenclature

Standard

COP	coefficient of performance [–]
c_f	fluid specific heat [J kg^{-1} K^{-1}]
c_s	solid specific heat [J kg^{-1} K^{-1}]
ΔT	temperature span of the regenerator [K]
ΔT_{MCE}	adiabatic temperature change [K]
f	frequency [Hz]
g	gravitational acceleration [m s^{-2}]
H_0	zero magnetic field [T]
H_{max}	maximum magnetic field [T]
L	length of the regenerator [mm]
m_f	fluid mass [kg]
m_s	solid mass [kg]
$\dot{m}$	mass flow rate [g s^{-1}]
$\dot{Q}_c$	cooling power [W]
R_{vd}	dead volume ratio [–]
R_{vf}	pushed fluid volume ratio [–]
t	time [s]
U	utilisation factor [–]
V_d	dead volume of the regenerator [cm^3]
V_f	pushed fluid volume [cm^3]
V_i	interstitial volume of the regenerator [cm^3]
ξ	regeneration ratio [–]

Abbreviations

AMR	active magnetic regenerator
CB	cold blow
D	demagnetisation process
HB	hot blow
M	magnetisation process
PF	programming the positions of the pistons
PM	programming the position of the magnet

Indices

f	final
i	initial

them are test devices to check magnetocaloric materials and operation parameters, and others are closer to commercial machines to achieve useful temperature spans and cooling powers for applications at room temperature. According to the simple classification given by Gschneidner and Pecharsky (2008), test devices are from the type of the first generation systems and were the first to be built. The magnetisation–demagnetisation steps are reciprocating and versatile in order to test and optimise the operation parameters. The main limitation is the frequency because of the reciprocating motion, so, low cooling power is achieved. Second and third generation systems are rotary and achieve higher frequencies, thus higher cooling power. Second generation systems rotate the magnetic beds and third generation rotate the permanent magnet assembly. More elaborated classifications of systems have been reported, as seen in a recent publication by Scarpa et al. (2012), that take into account many different parameters of the refrigeration device.

Several results have been presented from test devices, showing varying success. Some of the systems show only a proof of concept of magnetic refrigeration without optimising parameters or doing any further study, as presented by Lu et al. (2005), Bour et al. (2009), and Chiba et al. (2014). Other publications as Plaznik et al. (2013) and Tušek et al. (2013) show not only successful results but also a comprehensive experimental and simulation study regarding the influence of different thermodynamic cycles and geometries of the active magnetic regenerator. In general, a more advanced study is required for a deeper understanding of the technology.

In this paper a versatile reciprocating magnetic refrigeration machine to test active refrigerants is presented. A comprehensive study of the parameters has been done with gadolinium as the active material, optimising the temperature span and the cooling capacity of the system. Also the *COP* has been measured, although this optimisation has not been the aim of this system. Finally, several thermodynamic cycles have been tested and compared.

2. Active magnetic regenerator design

There are many parameters to be taken into account in the design of a magnetic refrigerator system. The type of system should be chosen according to the required performance and the aim of the project. The performance is mainly defined by the temperature span reached between cold and hot sides, the cooling power and the coefficient of performance. The *COP* is an industry standard, defined as the ratio between the cooling power and the total power consumption to achieve it. A reciprocating system should be suitable for a comprehensive study of the operation parameters, whereas a rotary system, that allows reaching higher frequencies and then higher cooling powers, should be suitable to fulfil some of the performance requirements of a specific application or even all of them.

An efficient design of the permanent magnet by simulations is needed. Bjørk et al. (2008) defined a performance parameter to optimise it. The magnetic field in the high field region, the available volume to place magnetocaloric material and the fraction of the cycle in which the magnet is being used have to be maximised, while the magnetic field in the low field region and the magnet volume have to be minimised. Moreover, the work related to the motion for applying the high and zero magnetic field should be included in the simulations and minimised considering also the *COP*.

The active magnetic regenerator should also be simulated. The optimisation of its geometry and porosity allows the maximisation of the solid–liquid heat transfer and therefore the performance of the system. As a result of the simulation, the range of the operation parameters, such as frequency and pushed fluid volume, is defined. In general, effective heat transfer configurations lead to higher pressure drop through the regenerator, and therefore higher input work, so a compromise should be achieved if the *COP* is considered.

Finally, there are a few technical issues related to the regenerator to be followed. These define the range of the operation parameters for a given regenerator.

The utilisation factor is an important parameter, defined in Eq. (1), and represents the ratio between the thermal capacities