INTERNATIONAL JOURNAL OF REFRIGERATION 43 (2014) 143–153

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

Modelling of a magnetocaloric system for cooling in the kilowatt range

V.R. Govindaraju [a], D.M. Vilathgamuwa [b], R.V. Ramanujan [a,*]

[a] School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore
[b] School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 12 December 2013
Received in revised form
6 March 2014
Accepted 10 March 2014
Available online 21 March 2014

Keywords:
Magnetic refrigerator
Modelling
Gadolinium
COP
Brayton cycle

ABSTRACT

A numerical time-dependent model of an active magnetic regenerator (AMR) was developed for cooling in the kilowatt range. Earlier numerical models have been mostly developed for cooling power in the 0.4 kW range. In contrast, this paper reports the applicability of magnetic refrigeration to the 50 kW range. A packed bed active magnetic regenerator was modelled and the influence of parameters such as geometry and operating parameters were studied for different geometries. The pressure drop for AMR bed length and particle diameter was also studied.

High cooling power and coefficient of performance (COP) were achieved by optimization of the diameter of the magnetocaloric powder particles and operating frequency. The optimum operating conditions of the AMR for a cooling capacity of 50 kW was determined for a temperature span of 15 K. The predicted coefficient of performance (COP) was found to be ~6, making it an attractive alternative to vapour compression systems.

Modélisation d'un système magnétocalorique pour le refroidissement à l'échelle des kilowatts

Mots clés : Réfrigérateur magnétique ; Modélisation ; Gadolinium ; COP ; Cycle de Brayton

1. Introduction

Near room temperature magnetic cooling is an emerging technology that bridges several research areas. Magnetic cooling is a promising alternative for cooling near room temperature due to the following advantages; high energy efficiency compared to conventional vapour compression cooling, absence of ozone layer depleting refrigerants and high value of coefficient of performance.

Vapour compression systems are the foundation of most conventional cooling systems. They use refrigerants like chlorofluorocarbon (CFC) and other harmful gases which damage the ozone layer (Gschneidner and Pecharsky, 2008). On the other hand, magnetic refrigeration has many attractive features like higher efficiency compared to vapour

* *Corresponding author.*
E-mail address: ramanujan@ntu.edu.sg (R.V. Ramanujan).
http://dx.doi.org/10.1016/j.ijrefrig.2014.03.007
0140-7007/

Nomenclature

Variables

A_c	regenerator cross section, m^2
a_{surf}	contact surface per unit volume, m^2
a	absorption coefficient, m^{-2}
B	magnetic flux density
C	specific heat capacity J $(kg\ K)^{-1}$
c	diffusion coefficient
$\bar{c}_s$	maximum specific heat capacity of the MCM
d_a	damping coefficient, sm^{-2}
d_h	hydraulic diameter, m
d_p	particle diameter, m
E	electric field
e_a	mass coefficient, s^2m^{-2}
f	frequency, Hz
H	external magnetic field
h	convective heat transfer coefficient, W m^{-2} K^{-1}
L	length of the regenerator bed, m
M	magnetization, Am^{-1}
m	mass, kg
$\dot{m}_f$	fluid mass flow rate, kgs^{-1}
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
$\dot{Q}_{ref}$	averaged cooling power, W
$\dot{Q}_{rej}$	averaged rejected power, W
Re	Reynolds number
T	temperature, K
T_c	Curie temperature, K
T_h	hot reservoir temperature, K
T_c	cold reservoir temperature, K
t	time, s
t_c	period of the AMR cycle, s
U	internal energy, W
x	distance to the origin of the bed, m
V_D	Darcy velocity, ms^{-1}
υ	interstitial velocity, ms^{-1}
W	work, J
W_{Mag}	magnetic work, J
W_{Pump}	pump work, J

Greek

ε	porosity
α	conservative flux convection coefficient, m^{-1}
β	convection coefficient, m^{-1}
λ	thermal conductivity, W $(m\ K)^{-1}$
γ	conservative flux source, m^{-1}
ρ	density, kgm^{-3}
μ_0	permeability of the vacuum equal to $4\pi 10^{-7}$ NA^{-2}
ϕ	utilization factor

Subscripts

fl	fluid
sl	solid
H_0	constant magnetic field
T	constant temperature
ΔT_{ad}	adiabatic temperature change

Acronym

AMR	active magnetic regenerator
FOMT	first order magnetic transition
MCE	magnetocaloric effect
MCM	magnetocaloric material
MFT	mean-field theory
SOMT	second order magnetic transition

compression refrigeration, no CFC's used, fewer moving parts, low noise, and low vibration (Yu et al., 2010). The thermodynamics of magnetic cooling is based on the magnetocaloric effect (MCE). Magnetic materials will experience a temperature change, especially near the Curie temperature, in response to an external magnetic field. This adiabatic temperature change is a function of temperature and magnetic field. Rare ΔT_{ad} earth materials are suitable for magnetocaloric applications near room temperature. At present, the rare earth element gadolinium and selected compounds of Gd are used for magnetic cooling devices.

Magnetic cooling generally uses active magnetic regenerator (AMR), which employs a regenerator which operates on the principle of the MCE. The AMR operates as a regenerator as well as a magnetic refrigerant and works in the inverse Brayton refrigeration cycle (Fig. 1).

The entropy change of a magnetocaloric material as a function of temperature, T and magnetic field, H can be expressed (Kitanovski and Egolf, 2006) as:

$$ds = \frac{c_H}{T}dT + \left(\frac{\partial s}{\partial H}\right)_T dH \tag{1}$$

where c_H is the specific heat at constant magnetic field. The spin entropy of MCM decreases with increasing magnetic field.

Since 1976, several researchers have studied the performance and operation of AMR cooling systems (Gschneidner and Pecharsky, 2008). A one dimensional time dependent model is developed and their predictions were compared with experimental results to optimize the AMR cycle is the work performed by (Roudaut et al., 2011). A practical model for predicting the efficiency and performance of AMR has been developed by (Li et al., 2006). A two dimensional time dependent mathematical model of an AMR has been proposed by (Petersen et al., 2008) which exhibited significant temperature difference between the regenerator and the heat transfer fluid cycle. Rowe (Rowe and Tura, 2006) compared their model with experimental results using single and multilayer regenerators of Gd, $Gd_{0.74}Tb_{0.26}$ and $Gd_{0.85}Er_{0.15}$. In recent publication (Law et al., 2013), Law demonstrated enhanced cooling rate of a heated resistor, of upto 85%, for active cooling by MCE compared to passive cooling.

There are also several numerical models for the AMR (Engelbrecht, 2008; Ivan, 2012; Li et al., 2011; Risser et al., 2013;