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Static and rotating active magnetic regenerators with porous heat exchangers for magnetic cooling

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Abstract

The operation behaviour of an active magnetic regenerator (AMR) with a wavy-structure, or a honeycomb-like regenerator bed was numerically investigated. The thermodynamic model was applied to a static regenerator and – in a generalized version – to a rotary type. The models take two-dimensional unsteady heat conduction in the magnetic material during the four basic processes of the AMR cycle into account. The numerical results were used to determine optimal arrangements of different magnetic materials in order to obtain larger temperature spans between both ends of the porous beds. Furthermore, a first study of magnetic flux lines in a porous rotary heat exchanger was performed.
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Keywords: Magnetic refrigerator; Heat exchanger; Regenerator; Material; Porous medium; Modelling; Performance; COP

Réfrigérateurs magnétiques statiques ou actifs munis d'échangeurs de chaleur poreux, pour le refroidissement magnétique

Mots clés : Réfrigérateur magnétique ; Échangeur de chaleur ; Régénérateur ; Matériau ; Milieu poreux ; Modélisation ; Performance ; COP

1. Introduction

Presentations of first magnetic refrigerators working at or near room temperature caused a real outburst of scientific research work in the field of magnetic materials, magnetic refrigeration technology and also have positively influenced the development of permanent magnets. Some research institutes located all over the world, in the last few years, have discovered new or improved magnetic materials suitable for room temperature refrigeration (e.g. [1,2]), while others have successfully demonstrated the operation of magnetic refrigerators at room temperature (e.g. [3]). This indicates that magnetic refrigeration is a prospective technology, which

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Nomenclature

Symbols	
A_p	face area of channel [m^2]
a_r	length of a wave [m]
B	magnetic induction [T]
c_p	specific heat at const. pressure [J kg^{-1} K^{-1}]
c_H	specific heat at const. field [J kg^{-1} K^{-1}]
d_h	hydraulic diameter [m]
D	diameter rotor [m]
f	frequency [Hz]
h	height of structure [m]
H	magnetic field strength [A m^{-1}]
L	length [m]
M	magnetization [A m^{-1}]
P_c	channel perimeter [m]
P_f	fluid flow period [s]
$\dot{Q}$	heat flux [W]
T	temperature [K]
t	time [s]
v	specific volume [m^3 kg^{-1}]
v_f	velocity [m s^{-1}]
x	mass fraction [kg kg^{-1}]
x, y	position [m]
Subscripts	
c	cold
cin	cold in
f	fluid
h	hot
hin	hot in
ri	room initial
s	solid
w	wall
Greek	
α	heat transfer coefficient [W m^{-2} K^{-1}]
δ	thickness of sheet [m]
ε	porosity
λ	conductivity [W m^{-1} K^{-1}]
μ_0	vacuum magn. perm. [Vs A^{-1} m^{-1}]
ρ	density [kg m^{-3}]
τ	characteristic time [s]

could be a rival to the vapour-compression refrigeration technology one day, at least in certain applications or niche markets. It is known from basic physical principles that magnetic refrigeration machines should be more efficient than the conventional refrigeration systems. And the difficulties of conventional refrigeration – with its harmful substances – gives further hope to a positive development of the environmental friendly magnetic refrigeration technology.

Magnetic refrigeration is based on the magnetocaloric effect (MCE) of magnetic materials. In the case of ferromagnetic materials, the MCE manifests itself by a heating-up of the material when it is moved into a magnetic field and with a cooling effect when the magnetocaloric material is removed from it. The effectiveness of the MCE mainly depends on the applied magnetic field and is fairly small (in Gd in low fields it is ~ 3 *K/T*, while in higher fields it decreases to ~ 2.2 *K/T* [3], which results in limited temperature spans occurring in one-stage magnetic refrigerators. Another obstacle is that magnetic materials are solid and cannot be easily pumped through the cycle as refrigerants in classical vapour-compression systems. In order to overcome these two barriers the regeneration principle and external heat transport fluids can be applied. Regeneration can be achieved with reciprocating flows of heat exchanging fluids through the magnetic material, which results in a temperature gradient in the material along the flow [4].

In an active magnetic regenerator (AMR) the magnetic material has a double function: on one hand it acts as a refrigerant and on the other hand as a regenerator. The AMR cycle usually consists of four processes: (a) adiabatic magnetization, (b) isofield cooling, (c) adiabatic demagnetization and (d) isofield heating. Each particle in the regenerator undergoes a unique Brayton cycle (see review article, Ref. [5]). If the regenerator works according to a cascade Brayton cycle [4], the temperature span can greatly exceed the adiabatic temperature change of the MCE.

Most of the theoretical and experimental work on room temperature refrigeration was performed with regenerators in a shape of packed beds [6,15]. According to Tishin and Spichkin [4] a regenerator with a stack of solid plates has a higher thermal efficiency than a regenerator with a packed bed. Furthermore, it has a lower pressure drop, resulting in a lower energy consumption of the fluid pumps. On the other hand the heat transfer coefficients and the heat transfer areas are higher in packed bed regenerators [7,8]. In order to obtain higher NTU (number of heat transfer units), stacked plane solid plates may be exchanged by corrugated sheets, which increase the heat transfer surface area. Such realizations are common in air-conditioning, process technique applications, and waste-air regenerative units.

Peksoy and Rowe [9] and Dai et al. [10] discussed demagnetizing effects inside magnetic materials of different shapes. They concluded that demagnetizing effects are strongest in bulk pieces while they are weaker in long and thin magnetic materials, oriented along the applied magnetic field (such as in a honeycomb-like regenerator).

2. The thermodynamic model for the steady regenerator

The geometry of a honeycomb regenerator is shown in Fig. 1(a). It is made of alternating flat and corrugated sheets

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