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A numerical study on the unsteady heat transfer in active regenerator with multi-layer refrigerants of rotary magnetic refrigerator near room temperature

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ABSTRACT

As the temperature span($\triangle T$) of a refrigerator with an active magnetic regenerator(AMR) of single magneto-caloric material is limited, in the current investigation, the multi-layer AMR consisting of Gd and $Gd_{0.73}Tb_{0.27}$ is studied to improve the refrigeration performance at a larger $\triangle T$ with the numerical method, where the experimental magneto-caloric properties are adopted for a better precision. Effects of $Gd_{0.73}Tb_{0.27}$ content (φ) and fluid flowrate (q_V) on refrigeration capacity ($q_{ref,V}$) and coefficient of performance (COP), together with those of hot and cold reservoir temperatures (T_c and T_h), are investigated. Besides, temperature contours of fluid and solid matrix are presented for discussions. The present study demonstrates that compared with AMR of pure Gd, the multi-layer AMR improves the $q_{ref,V}$ and COP by ~167% and 57% at $\triangle T = 28K$, respectively. Moreover, it is observed that $q_{ref,V}$ of multi-layer AMR has a convex variation tendency with φ, and the maximum at T_c of 268K equals 874.7 kW/m^3. As a contrast, COP has two peaks, and the optimal φ is almost independent of T_c, while it decreases with a rising T_h. In addition, current investigation indicates that $q_{ref,V}$ takes a lager value at a larger q_V, while a smaller q_V facilitates a good COP.

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Une étude numérique du transfert de chaleur transitoire dans un régénérateur actif avec des frigorigènes multi-couches d'un réfrigérateur magnétique rotatif proche de la température ambiante

Mots clés : Simulation numérique ; Transfert de chaleur transitoire ; Performances frigorifiques ; Régénérateur actif multi-couches ; Réfrigérateur magnétique rotatif ; Proche de la température ambiante

1. Introduction

Magnetic refrigeration (MR), based on the significant magneto-caloric effects (MCE) of magneto-caloric materials (MCMs), represents an attractive alternative to the vapor compression one near room temperature. However, the lattice entropy variations of MCMs are significant near room temperature, which consume some cooling capacities and decrease the adiabatic temperature drops of demagnetization, resulting in finite temperature spans (Yu et al., 2003). To crack the nut, various MR cycles were proposed and investigated (Aprea et al., 2011a; Gomez et al., 2013; Kitanovski et al., 2014; Plaznik et al., 2013), and the active magnetic regenerator (AMR), where MCMs also act as the regenerative medium and each part runs with an individual MR cycle, behaves the best except the Carnot cycle. For the past two decades, dozens of MR prototypes near room temperature have been built and experimented all over the world, and most of them adopted the designs with AMR (Aprea et al., 2014; Gschneidner and Pecharsky, 2008; Kitanovski et al., 2015; Lozano et al., 2014; Rowe and Tura, 2006; Yu et al., 2006; Zimm et al., 2006).

As the key parts of magnetic refrigerators, AMRs were extensively investigated with the experimental method (Tušek et al., 2013; 2014; Richard et al., 2004; Yu et al., 2006); meanwhile, the complicated convection heat transfer in AMRs, coupled with the non-linear MCEs of solid refrigerants, was numerically studied widely. Compared with steady models, the unsteady ones could capture the physical mechanisms in AMRs more accurately and thus have higher precisions. Besides, the spatially one-dimensional AMR models behave well in the balance between computation load and prediction precision,

Nomenclature

Variables

A_s	specific surface area [m^2 m^{-3})
c	specific heat capacity [J kg^{-1} K^{-1}]
COP	coefficient of performance
d	particle diameter of regenerator [mm]
k_f	fluid molecular thermal conductivity [W m^{-1} K^{-1}]
k_{eff}	effective static thermal conductivity of regenerator with particles and fluid [W m^{-1} K^{-1}]
D_d	thermal dispersion coefficient
H	magnetic field [Tesla]
L	length [m]
M	magnetization intensity [A m^{-1}]
MCM	magneto-caloric material
MCE	magneto-caloric effect
Nt	amount of time step in a cycle
Nx	amount of longitudinal computation cell
$\partial p/\partial x$	longitudinal pressure gradient [Pa m^{-1}]
q_V	volumetric flowrate [L min^{-1}]
Q_{ref}	refrigeration capacity[W]
q_{ref}	volumetric refrigeration capacity [W m^{-3}]
q_{rej}	volumetric heat rejection [W m^{-3}]
s	specific entropy [J kg^{-1} K^{-1}]
t	time [s]
T	temperature [K]
u_D	Darcy velocity [m s^{-1}]
U	specific internal energy [J kg^{-1}]
W_r	volumetric revolution work [W m^{-3}]
W_p	volumetric pump power [W m^{-3}]
x	longitudinal position [m]
α	convection heat transfer coefficient [W m^{-2} K]
ε	regenerator porosity; allowable relative error
ρ	density [kg m^{-3}]
τ	cycle duration [s]
φ	content of Gd alloy in multi-layer regenerator, $\varphi = L_{alloy}/L_{reg}$

Superscript

j	temporal index

Subscripts

Alloy	occupied by Gd alloy
c	cold reservoir
f	fluid
h	hot reservoir
H	constant magnetic field
i	spatial index
s	magneto-caloric material
V	per unit volume of refrigerant
Gd	occupied by Gd particles
reg	occupied by whole regenerator