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Critical parameters in design of active magnetocaloric regenerators for magnetic refrigeration applications

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ABSTRACT

A new way to evaluate the performance of the active magnetocaloric regenerator (AMR) was developed based on a few critical parameters proposed in this study. The critical parameters were derived from the energy equations that have been used to describe the transient energy transfer processes in the AMR for both the magnetocaloric materials and the heat transfer fluid. Each parameter is corresponding to a specific energy transfer mechanism in the AMR and can be easily implemented to evaluate the contribution from each term, including axial conduction and remnant energy storage in the magnetocaloric materials, axial conduction, remnant energy storage and fluid dissipation in the heat transfer fluid, and internally regenerated energy. Parametric studies were carried out to explore the impact of geometric and operating parameters and to determine whether or not a certain heat transfer mechanism is significant to the overall system performance.

Paramètres critiques dans la conception de régénérateurs magnétocaloriques pour les applications de froid magnétique

Mots clés : Effet magnétocalorique ; Refroidissement magnétocalorique ; Simulation ; Gadolinium ; Refroidissement à l'état solide

1. Introduction

Magnetocaloric cooling for near room temperature refrigeration and heat pump applications has attracted significant research attentions globally since 1976 (Brown, 1976; Gschneidner and Pecharsky, 2008; Yu et al., 2010). Magnetocaloric cooling technology does not rely on any environmental harmful conventional refrigerants, which have been used in vapor compression systems and has either ozone depletion potential or global warming potential. Therefore, magnetocaloric cooling has been considered as an environmentally friendly alternative

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Nomenclature

AMR	active magnetocaloric regenerator
c	specific heat [J·kg^{-1}·K^{-1}]
fr	cycling frequency [s^{-1}]
HTF	heat transfer fluid
h	convective heat transfer coefficient [W·m^{-2}·K^{-1}]
k	thermal conductivity [W·m^{-1}·K^{-1}]
MCE	magnetocaloric effect term [W·m^{-3}]
MCM	magnetocaloric cooling materials
LHT	left hand term
L	length of AMR [m]
P	fluid pressure [Pa]
$P_{MCMcond}$	proposed parameter measuring the conduction loss in MCM [-]
$P_{HTFcond}$	proposed parameter measuring the conduction loss in HTF [-]
P_{dsp}	proposed parameter measuring the dissipation loss in HTF [-]
$P_{MCMstorage}$	proposed parameter measuring the energy storage in MCM [-]
$P_{HTFstorage}$	proposed parameter measuring the energy storage in HTF [-]
$P_{usefulcooling}$	proposed parameter measuring the useful cooling carried out of AMR [-]
P_{regen}	proposed parameter measuring the internal regeneration energy [-]
RHT	right hand term
T_c	heat source temperature (low temperature side of heat pump) [K]
T_f	heat transfer fluid temperature [K]
T_h	heat sink temperature (high temperature side of heat pump) [K]
ΔT_{lift}	temperature span of the system [K]
ΔT_{ad}	material adiabatic temperature span [K]
t	time [s]
t_f	fluid flowing time in each half cycle [s]
U^*	utilization factor [-]
u	heat transfer fluid velocity [m·s^{-1}]
x	spatial coordinate [m]
α	thermal diffusivity [m^2·s^{-1}]
β	specific heat transfer area [m^2·m^{-3}]
ε	porosity [-]
ρ	density [kg·m^{-3}]
$\mu_0 H$	magnetic field intensity [T]

cooling technology since 1990s. Recently, magnetocaloric cooling technology was recognized as one of the most promising alternative to substitute the vapor compression technology due to advances in its efficiency and technical maturity (Goetzler et al., 2014; Qian et al., 2016). Furthermore, a few demonstration commercial prototypes has been developed by Astronautics US (Jacobs et al., 2014), General Electric (Benedict et al., 2016), and CoolTech in the past few years with performance close to realistic product requirements, which indicates exciting application prospects for the future market.

Modern magnetocaloric cooling technology is based on the so-called active magnetocaloric regenerator (AMR) (Barclay and Steyert, 1982), in which the magnetic field induced first order or second order magnetic phase transformation drives periodic heat rejection and heat absorption from the magnetocaloric materials (MCMs) to the heat transfer fluid (HTF). AMR can be categorized based on the MCM configuration and its motion type (Trevizoli et al., 2016a). Rotary magnetocaloric prototypes with packed-bed AMRs and Gadolinium as refrigerant were the most widely adopted type in the past few years (Aprea et al., 2016; Arnold et al., 2014; Bahl et al., 2014; Balli et al., 2012; Engelbrecht et al., 2012; Eriksen et al., 2015; Lozano et al., 2013, 2016; Trevizoli et al., 2016c; Tura and Rowe, 2011), with 0.1~0.6 W/g specific cooling power and up to 33 K maximum system temperature lift reported so far. There are many factors contributing to the performance of the AMR and the entire magnetocaloric cooling system. The magnetocaloric materials' properties are the first group of parameters and have been explored in literature (Benedict et al., 2017; Silva et al., 2016). Other than properties, AMR's geometries, operating frequency, mass-flow rate and magnetic field change were identified as major parameters affecting an AMR's performance (Tušek et al., 2011, 2013). Among them, a non-dimensional number called utilization factor was identified as a comprehensive and crucial parameter determining the performance of both the AMR and the entire system (Engelbrecht, 2008; Engelbrecht et al., 2011; Tušek et al., 2011), which has been used in the porous regenerative type heat exchanger performance evaluation as a tradition (Shah and Sekulic, 2002). Recently, the effect of utilization factor on thermal performance of three AMRs with three different configurations, including square pin, parallel plates, packed-bed of spheres was extensively studied by comprehensive experiments (Trevizoli et al., 2017). A comprehensive review discussing the thermodynamic cycle, numerical modeling, detailed parametric impacts and fabrication techniques regarding the AMR and magnetocaloric cooling technology can be found in a recently published book (Kitanovski et al., 2015). From literature, the most common two approaches to study the performance of an AMR and associated magnetocaloric cooling system are simulation and experiment. However, there are also a few analytical works that are much simpler to use than numerical models to conduct performance prediction. The analytical model developed by University of Victoria are convenient to implement and study the basic cooling power, power consumption and coefficient of performance, wherein the analytical results agreed relatively well with experimental data (Burdyny et al., 2014; Rowe, 2012).

Despite the extensive studies carried out in literature, most focused on how the geometric parameters, operating parameters and materials properties contribute to the system level performance indices, such as cooling capacity and coefficient of performance, with little attention about the detailed heat transfer characteristics in an AMR. In fact, the transient heat transfer characteristics in the porous MCM that operated under cyclic magnetic field variation and oscillating flow