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Validation of an active magnetic regenerator test apparatus model

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ABSTRACT

This work focuses on the development and validation of a transient one-dimensional numerical model of an active magnetic regenerator (AMR) test apparatus. Simulation results are validated by comparison to room temperature experiments for varying hot heat sink temperature, system pressure, and applied heat load. Three different second-order magnetocaloric materials are used. In addition to external heat leaks, parameters such as thermal conductivity, Curie temperature, and peak magnetocaloric effect are adjusted to obtain better fits to experimental results. In the case of gadolinium, where material properties are well-characterized, the inclusion of parasitic heat leaks as well as an increase in diffusivity resulted in good fits across a broad range of operating conditions. Adjustments to Curie temperature and peak magnetocaloric effect produced good matches with experimental data for $Gd_{0.85}Er_{0.15}$. Predictive simulations of a Gd − $Gd_{0.85}Er_{0.15}$ two-layer regenerator are briefly discussed.

Validation d’un modèle de banc d’essai utilisé pour tester les régénérateurs actifs magnétiques

Mots clés : froid magnétique ; simulation ; effet magnétocalorique ; régénérateur actif magnétique ; gadolinium

1. Introduction

Magnetic cycles are being considered for room-temperature refrigeration, heat pumps, and gas liquefaction systems. These devices employ the magnetocaloric effect (MCE), a reversible temperature change that can be induced in a magnetic material through the application or removal of a magnetic field. The MCE is generally a strong non-linear function of temperature and is largest in magnitude when a material is near its magnetic ordering temperature, also known as its Curie temperature. Gadolinium, Gd, a rare-earth metal, is the most thoroughly studied material for its MCE and the standard by which other materials are compared for room-temperature applications (Pecharsky and Gschneidner, 2002). However, the maximum value of the MCE is limited to about 2 K T^{-1} at the Curie point and decreases as temperature changes. For temperatures above ∼20 K, temperature spans are improved by implementation of the active magnetic

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Nomenclature

AMR	Active Magnetic Regenerator
AMRTA	Active Magnetic Regenerator Test Apparatus
FEM	Finite Element Modeling
MCE	Magnetocaloric Effect
A_f	Fluid flow area (m^2)
A_d	Displacer piston surface area (m^2)
A_p	Particle surface area (m^2)
B	Applied magnetic field intensity (T)
c_f	Fluid heat capacity ($J\ kg^{-1}\ K^{-1}$)
c_s	Solid heat capacity ($J\ kg^{-1}\ K^{-1}$)
$c_{s,ref}$	Reference solid heat capacity ($J\ kg^{-1}\ K^{-1}$)
D	Tube diameter (m)
D^d	Dispersion coefficient
D_h	Hydraulic diameter (m)
D_{eq}	Equivalent spherical diameter (m)
f_o	Effective conductivity constant
G	Mass velocity ($kg\ m^{-2}\ s^{-1}$)
h	Convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_p	Particle height (m)
j_H	Colburn j-factor
k	Conductivity ($W\ m^{-1}\ K^{-1}$)
K_s	Dimensionless solid conductivity parameter
k_{eff}	Effective conductivity ($W\ m^{-1}\ K^{-1}$)
k_{static}	Static conductivity ($W\ m^{-1}\ K^{-1}$)
L	Sub-domain length (m)
l_p	Particle length (m)
m	Mass (kg)
$\dot{m}$	Fluid mass flow rate ($kg\ s^{-1}$)
NTU	Number of Transfer Units
Pe	Peclet number
Pr	Prandtl number
$\dot{Q}_{load}$	Rate of heat load input ($W\ s^{-1}$)
$\dot{Q}_{rad}$	Rate of radiative heat input ($W\ s^{-1}$)
r	Radius (m)
Re	Reynolds number
T	Temperature (K)
T_C	Cold temperature (K)
T_H	Hot heat sink temperature (K)
T_∞	Temperature of surroundings (K)
t^*	Non-dimensionalized time
V_p	Particle volume (m^3)
v	Velocity ($m\ s^{-1}$)
w_p	Particle width (m)
x	Space (m)
x^*	Non-dimensionalized space
α	Porosity
α_o	Effective conductivity constant
ΔT_{ad}	Adiabatic temperature change due to magnetocaloric effect (K)
ε	Emissivity
κ	Thermal capacity ratio
μ	Dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
σ	Stefan–Boltzmann constant
τ	Blow duration/period (s)
ϕ	Utilization
ϕ_{ref}	Reference utilization
ϕ_s	Sphericity
ψ	Symmetry

regenerator (AMR) concept. An AMR acts as both the working material (or refrigerant) and the heat transfer medium. A temperature gradient is developed along the length of the AMR bed such that each location within the bed undergoes a slightly different cycle.

For high efficiency to be realized, optimum materials, regenerator design, and cycle parameters must be determined. Due to the broad range of variables impacting AMR performance, simulation tools with predictive capabilities are needed. One area where simulations can be particularly useful is with the optimization of multi-material AMRs. Varying the amount of each material experimentally can be tedious and is an area where a validated modeling tool would be useful. A reliable modeling tool will help optimize parameters such as system mass flow rate, operating frequency, AMR geometry, aspect ratio, and material composition. The purpose of this work is to develop a model that can accurately simulate the operation of an AMR test apparatus (AMRTA) developed at the University of Victoria (Rowe, 2002). An important step in developing a predictive tool is validation of simulation results with experimental results.

2. Model background

As summarized in by Nielsen et al. (2011), a number of simulation tools to model AMR refrigeration systems have been developed (Trevizoli et al., 2012; Li et al.,2008; Engelbrecht et al., 2005; Rowe, 2002; Smaïli and Chahine, 1998; Carpetis, 1994; Spearing, 1994; DeGregoria, 1992; Matsumoto and Hashimoto, 1990). To reduce computational time, simulations of this type are often one-dimensional analyses. Further, except for a small number of models (Spearing, 1994), the model domain typically encompasses only one AMR. In this case a temperature span is imposed across the AMR and the resulting cooling power is calculated. Other simulations approximate the operation of an AMR refrigerator with a simplified model such as a magnetic Brayton cycle. Stepping and ramping functions are typically used to model the application of fluid blow and magnetization. Furthermore, all models make simplifications to reduce numerical complexity and computational time. These may include neglecting axial conductivity, dispersion effects, and void space thermal mass in addition to simplified properties. Few works have been thoroughly validated with experimental results from a magnetic refrigeration apparatus using multiple alloys over a broad range of operating conditions.

Although the model presented in this paper is also based on a one-dimensional analysis, it differs from previous work in several ways. The model domain encompasses two AMRs and a cold space between them. This mimics the operation of a magnetic refrigeration apparatus since it requires only the hot heat sink boundary temperature and allows for a temperature span to develop across each of the regenerators based on the magnitude of heat absorbed in the cold section. Heat loads