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A flexible numerical model of a multistage active magnetocaloric regenerator

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ABSTRACT

A flexible one-dimensional model was created in Python to determine the periodic steady state cooling power of an active magnetocaloric regenerator. Several features of the model provide advantages when performing large parametric studies. Geometry, material properties, and operation parameters are read in as input. Fluid flow and magnetization profiles are parameterized, and thermodynamic consistency is forced in magnetocaloric material properties. A dynamic time step is used, and three associated model constants are set to work over a wide range of input parameter combinations. Derivative gain is adjusted to minimize convergence time resulting in an average convergence time reduction of approximately 50%.

Un modèle numérique flexible d'un régénérateur multiétagé actif magnéto calorique

Mots clés : Magnéto calorique ; AMR ; Froid magnétique ; Modèle numérique ; Accélération de convergence ; Pas de temps

1. Introduction

Magnetic heating and cooling at near room temperature is an emerging technology, which has the potential to replace vapor compression in many applications. Continued development of magnetic refrigeration technology is driven by efficiency, which may exceed that of vapor compression (Engelbrecht, 2008).

Magnetic cooling relies fundamentally on the magnetocaloric effect (MCE); an adiabatic temperature change due to a change in magnetic field strength. The magnitude of temperature change due to the MCE is a function of temperature and magnetic field strength, and is largest near a material's Curie temperature. An example of a magnetocaloric material (MCM) is gadolinium, which has a maximum effect near room temperature.

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Nomenclature

Abbreviations

MCE	magnetocaloric effect
MCM	magnetocaloric material
AMR	active magnetocaloric regenerator

Variables

A	Area $[\mathrm{m}^2]$
α	Thermal diffusivity $[\mathrm{m}^2/\mathrm{s}]$
C	Specific heat capacity [J/kgK]
D	Diameter [m]
E	Energy [J]
ε	Fluid fraction of the packed bed
H	Magnetic field strength [H]
k	Thermal conductivity or thermal dispersion coefficient [W/mK]
L	Length [m]
M	Ratio of volumetric heat capacities of fluid and MCM
m	Mass [kg]
N	Number or count
P	Pressure [Pa]
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
ρ	Density $[\mathrm{kg/m}^3]$
S	Entropy [J/kgK]
T	Temperature [K]
t	Time [s]
U	Heat transfer coefficient $[\mathrm{W/m}^2\mathrm{K}]$
V	Volume $[\mathrm{m}^3]$
v	Velocity [m/s]

In order to harness the magnetocaloric effect, a secondary material is often introduced as a heat carrier. Because the MCE is only a few degrees per K per Tesla of applied field, most magnetic refrigeration machines employ a regenerative cycle to increase temperature span. The interface between MCM and heat carrier in regenerative machines is referred to as an active magnetocaloric regenerator (AMR). Many reviews summarize the operating principles as well as details of constructed machines (Yu et al., 2010), (Gomez et al., 2013), (Kitanovski et al., 2014). The simplified AMR cycle as described by (Brown, 1976) consists of four segments:

1. Adiabatic magnetization; MCM temperature raises to high level.
2. Constant magnetization heat transfer; fluid is displaced. Fluid enters from the cold side, and heated fluid exits the hot-side.
3. Adiabatic demagnetization; MCM temperature falls to lower level than step 1.
4. Constant magnetization heat transfer; fluid is displaced in the opposite direction. Ambient temperature fluid enters from the hot side, and cooled fluid exits the cold side.

There have been many studies performed on AMR systems since 1976, and magnetocaloric technology continues to develop (Gschneider and Pecharsky, 2008). A major branch of the magnetocaloric field of study is machine and cycle simulation. An accurate model can allow for much better understanding of the complex challenges in achieving cooling power and efficiency in a real machine. Many numerical models have been published, utilizing similar fundamental equations: Engelbrecht (2008), Roudaut et al. (2011), Aprea and Maiorino (2010), Li et al. (2011), Ivan(2012), Risser et al. (2013), Tagliafico et al. (2013), and Govindaraju et al. (2014). Most of these place an emphasis on modeled physics, which are extremely important for model accuracy.

Previous numerical models typically utilize either a constant MCE or MCE as a function of temperature at the simulation field strength. Data for the MCE come either from direct MCE measurements or analytical material models for second order materials such as Gadolinium. Accurate mathematical models of first order materials are not readily available. There is also a lack of measured MCE at multiple field strengths. One objective of the presented model is to scale measured MCE by magnetic field strength and force thermodynamic consistency, eliminating the need for measured data at multiple field strengths. A thermodynamically consistent model helps eliminate physically impossible solutions that come about from MCE measurement error. The presented model also seeks to facilitate large design studies by reducing computation time and maximizing model robustness to large parameter ranges by using convergence acceleration and a variable time step. AMR models often break the cycle into four basic segments, while the presented model treats the cycle as a continuous process subjected to magnetic and fluid flow profiles. Because of this the model is able to represent non-ideal cycles that occur in real machines, where cycles may not be symmetric or have clearly defined segments. If a cycle is treated as separate segments with various simplifications explicit solutions can be made to further speed up a model (Torregrosa-Jaime et al., 2015). This is not the case in the presented model, as flexibility is a primary concern.

2. One-dimensional AMR model

2.1. *Model inputs and outputs*

Fluid cycles are defined in the model input file by event start times, ramp times, and peak durations and magnitudes. Magnetic profiles are defined as a square profile with a start and stop time. An example flow profile can be observed in Fig. 1. Cycles are defined this way to enable parameterization of flow and magnetic profiles. Flow can be modeled as anything from step profiles to fully triangular profiles to any custom profile input into the model via a read-in file. The decision was made to use a square magnetic profile in order to reduce overall calculations required for the simulation to complete. Non-square profiles can be estimated be using an average amplitude. MCM thermal conductivity and density are considered constant, as are fluid thermal conductivity, density, viscosity, and heat capacity. Geometry parameters such as cross sectional area, regenerator length, fluid fraction, and characteristic length are also included in the input file. Finally, the input file provides the location of MCE data file(s) to be read into the program.