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Space- and time-resolved interferometric measurements of the thermal boundary layer at a periodically magnetized gadolinium plate

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ABSTRACT

By means of a Mach-Zehnder interferometer we examine the transient dynamics of heat transfer from two periodically magnetized gadolinium (Gd) plates into a heat transfer fluid (n-decane). We demonstrate that the propagation of the thermal fronts emanating from the Gd plates after magnetization or demagnetization obeys a $\sqrt{t}$-dependence. A finite time required for magnetization and demagnetization causes a spatially delayed propagation of the thermal fronts. The diffusive heat flux, derived from the temperature profiles, experiences a drop down by about 80% after first 3 s while the percentage of thermal energy transferred into n-decane experiences a maximum there. Although limited to heat transfer into a stagnant fluid, the present works provides reasons for lower bounds of geometry and operation frequency of a simplified parallel-plate structure in the diffusive limit. In this way, the results are instructive for an efficient design of a parallel-plate magnetic regenerator with forced convection.

Mesures interférométriques à résolution spatiale et temporelle de la couche limite thermique d'une plaque de gadolinium magnétisée périodiquement

Mots clés : Froid magnétique ; Gadolinium ; Interféromètre de Mach-Zehnder ; Régénérateur magnétique à plaques parallèles

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Nomenclature

Variables

B_{ext}	magnetic field applied [T]
Bi	Biot number [–]
C_p	specific heat capacity [J (gK)$^{-1}$]
H_{ext}	external magnetic field [A m^{-1}]
H_{dem}	demagnetization field [A m^{-1}]
H_{int}	internal magnetic field [A m^{-1}]
h	heat transfer coefficient [W (m^2 K)$^{-1}$]
I	grey scale of the interferogram
k	heat conductivity [W (mK)$^{-1}$]
l	depth of the cell [m]
m	mass [kg]
Δn	refractive index change [–]
ΔQ	energy change in substance compared to room temperature (J)
$T(x, y)$	temperature field [K]
ΔT_{ad}	adiabatic temperature change [K]
κ_f	thermal diffusivity of the fluid [m^2 s^{-1}]
λ	wavelength of the laser [nm]
μ_0	permeability of free space [Vs Am^{-1}]
$\phi(\mathbf{x})$	overall phase information
$\varphi(\mathbf{x})$	unwrapped phase
$\Psi(x)$	Morlet wavelet
$\Psi_{a,b}(x)$	daughter wavelet
ω_0	control peak frequency [Hz]
τ	control width of the wave [–]

1. Introduction

Magnetic cooling (MC) is an emerging cooling technology which offers certain advantages (Gschneidner Jr and Pecharsky (2008); Tishin and Spichkin (2014)) compared to conventional cooling based on gas compression. It has the potential of high efficiency, compact design and silent operation, and promises the use of non-toxic solid cooling material and an environmentally friendly heat transfer fluid. MC is based on the magnetocaloric effect (MCE), which refers to the adiabatic temperature change ΔT_{ad} of a magnetocaloric material (MCM) when exposed to a changing magnetic field. Since ΔT_{ad} is not large enough to allow MCM to be used directly in cooling devices, the concept of the active magnetic regenerator (AMR) was developed by Barclay and Steyert (1982). The core of the AMR is a porous structure made up of MCM, frequently realized as a packed sphere bed or as an ensemble of flat parallel plates, and the heat transfer fluid. Using the AMR, a larger temperature span than just the adiabatic temperature change ΔT_{ad} can be obtained. This forms the basis of near-room-temperature refrigeration, as was first demonstrated by Barclay (1983). The development of a rotating magnetic refrigerator by Zimm et al. (2003) and further advances as reviewed in Bahl et al. (2011) render the technology closer to a commercialized state. A general review of near-room-temperature MC prototypes can be found in Yu et al. (2010); Gschneidner Jr and Pecharsky (2008); Engelbrecht et al. (2007).

In contrast to gas compression refrigerators where the refrigerant and the heat transfer fluid are identical, a challenge of magnetic cooling machines is the additional heat transfer from the refrigerant (MCM) to the heat transfer fluid in the AMR. Hence, the optimization of the performance of the AMR is of primary importance. Precondition for this is an efficient heat transfer at small viscous losses. Numerical modeling was already performed both for parallel-plate AMR (Tušek et al. (2013a); Petersen et al. (2008a, b); Roudaut et al. (2011); Tura et al. (2012)) and for packed sphere-bed AMR (Shir et al. (2005); Tušek et al. (2011); Aprea et al. (2012); Sarlah et al. (2006)). Main objectives consist in the prediction of the temperature span between hot and cold end of the AMR and its cooling capacity e.g. as a function of the time (Shir et al. (2005); Sarlah et al. (2006); Roudaut et al. (2011)), the frequency of operation (Tura et al. (2012); Tušek et al. (2011); Li et al. (2006)), the utilization (Tura et al. (2012); Nielsen et al. (2011); Li et al. (2006)) or the thermal losses (Nielsen et al. (2009)). Experimental approaches to determine the temperature span and cooling capacity in different MCM geometries are discussed in Tušek et al. (2013b). Geometrical aspects of the AMR have been studied in Tušek et al. (2013a) to identify optimum lengths, sphere diameters or plate spacings for different operation frequencies and cooling loads, or in Jensen et al. (2010) to understand how a non-uniform plate spacing affects the heat transfer.

The foregoing works worked out that optimum values for mass-flow rate and operating frequency exist for a particular AMR which are in turn functions of heat–transfer coefficient in the AMR. This optimum depends on the delicate coupling between geometry offered to the fluid flow, the viscous losses, the timing of mag-/demagnetization and the resulting formation of the thermal boundary layers. At present these issues are not fully resolved. Only a very few number of works provide space-resolved temperature data inside the AMR (e.g. see Sarlah et al. (2006); Petersen et al. (2008b); Christensen et al. (2010)) while the majority of the works is focused onto global quantities such as the temperature span between hot and cold end of the AMR.

Thus it make sense to study the dynamics of the heat transfer in the simplest case, namely from a periodically magnetized and demagnetized plane gadolinium plate into the stagnant heat transfer fluid, first without any natural or forced convection. By means of a Mach-Zehnder interferometer we are able to provide for the first time the space- and time-resolved temperature field inside the heat transfer fluid during the magnetization and the demagnetization phases.

2. Experimental setup and supporting numerical simulations

Gadolinium (Gd) plates (99.5% pure, Jiangxi South Rare Earth Hi-Tech Co., Ltd.) were used as the MCM. Each Gd plate has an