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Heat transfer enhancement in magnetic cooling by means of magnetohydrodynamic convection

Z. Lei [a], *Ch. Haberstroh* [b], *S. Odenbach* [a], *K. Eckert* [a,*]

[a] *Institute of Fluid Mechanics, Chair of Magnetofluiddynamics, Measuring and Automation Technology,*
Technische Universität Dresden, D-01062 Dresden, Germany
[b] *Bitzer Chair of Refrigeration, Cryogenics and Compressor Technology, Technische Universität Dresden, 01062 Dresden, Germany*

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ABSTRACT

In this work, we analyze the potential of magnetohydrodynamic (MHD) convection to increase heat transfer during magnetic cooling. To do this, we consider a section of an active magnetic regenerator, namely a flat gadolinium plate, immersed in an initially stagnant heat transfer fluid (NaOH) which is placed in a cuboid glass cell. To create the MHD flow, a small electric current is injected by means of two electrodes and interacts with the already present magnetic field. As a result, a Lorentz force is generated, which drives a swirling flow in the present model configuration. By means of particle image velocimetry and Mach–Zehnder interferometry, the flow field and its impact on the heat transfer at the gadolinium plate are analyzed. For the magnetization stage, we show that a heat transfer enhancement by about 40% can be achieved even with low currents of 3 mA.

Amélioration du transfert de chaleur en froid magnétique grâce à la convection magnétohydrodynamique

Mots clés : Froid magnétique ; Convection magnétohydrodynamique transfert de chaleur ; Interférométrie Mach-Zehnder ; Vélocimétrie à images de particule

1. Introduction

Magnetic cooling (MC) is an alternative cooling technology (Brown and Domanski, 2014) that possesses several advantages, such as the usage of an environmentally friendly heat transfer fluid and a non-toxic solid cooling material. The latter allows a compact design and a more silent operation as the compressor is replaced with the magnet. Principally, this is realized by the magnetocaloric effect (MCE), employing a magnetocaloric material (MCM) (Pecharsky and Gschneidner, 1999; Tishin and Spichkin, 2014). Since the introduction of the

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[*] *Corresponding author.* Institute of Fluid Mechanics, Chair of Magnetofluiddynamics, Measuring and Automation Technology, Technische Universität Dresden, D-01069 Dresden, Germany. Tel.: +49 0 351 46334636; Fax: +49 0 351 46333384.

E-mail address: kerstin.eckert@tu-dresden.de (K. Eckert).

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Nomenclature

$\vec{B}$	magnetic field applied [T]
$\vec{B}_r$	remanence of the NdFeB permanent magnet [T]
C_p	specific heat capacity [J (kg K)$^{-1}$]
E_{enh}	enhancement factor of heat transfer [–]
$\bar{E}_{enh}$	mean enhancement factor of heat transfer [–]
$G(x,y)$	frequency domain Gaussian filter
I	electric current applied [mA]
$I(x)$	intensity of the interferogram [–]
$I_0(x)$	slowly varying inhomogeneities of the illumination [–]
I_a	amplitude of the fringe contrast [–]
Re	Reynolds number [–]
$\vec{f}_L$	Lorentz force density [N m^{-3}]
$\vec{j}$	electric current density [A m^{-2}]
l	depth of the cell [mm]
v_c	characteristic velocity [mm s^{-1}]
Δn	refractive index change [–]
ΔQ_f	change of thermal energy in NaOH [J]
ΔT	difference between the local temperature in the cell and the ambient temperature [K]
Δt	time delay of electric current injection [s]
λ	wavelength of the laser [nm]
μ	dynamic viscosity [mPa·s]
μ_r	relative permeability of the NdFeB permanent magnet [–]
μ_x,μ_y	mean of the Gaussian distribution in x and y directions
ρ_f	density of the fluid (NaOH) [kg m^{-3}]
σ	standard deviation of the Gaussian distribution
$\phi(x)$	overall phase information
$\varphi(x)$	unwrapped phase

active magnetic regenerator (AMR) principle, based on the work of Brown (1976), more than 62 magnetic cooling prototype devices have been built; for a detailed review we refer to Gschneidner and Pecharsky (2008), Kitanovski et al. (2015), Romero Gómez et al. (2013), and Yu et al. (2010).

Comparing the current efficiency of magnetic cooling with conventional refrigeration (Sari and Balli, 2014), room-temperature MC is still far from being competitive. This is partly due to the fact that the efficiency of active regeneration is strongly coupled to the efficiency of the convective heat transfer in the regenerator. Hence, optimizing the performance of the AMR is of primary importance. Numerical AMR modeling has already been performed both for parallel-plate AMR (Petersen et al., 2008; Roudaut et al., 2011; Tura et al., 2012; Tušek et al., 2013a) and for packed sphere-bed AMR (e.g. Aprea et al., 2012; Shir et al., 2005). The main objectives consist in predicting the temperature span between hot and cold ends of the AMR and its cooling capacity e.g. as a function of the time (e.g. Roudaut et al., 2011; Shir et al., 2005), the frequency of operation (Tura et al., 2012; Tušek et al., 2011), the utilization (Nielsen et al., 2011; Tura et al., 2012) 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). Despite these efforts, insufficient heat transfer is currently one major bottleneck of the AMR. This is in particular true at the desired high power density to achieve compact and economic MC devices, because the fluid flow through the active regenerator is oscillatory.

Therefore, this work introduces a new heat transfer enhancement method by means of magnetohydrodynamic (MHD) convection. This type of convection is driven by the action of the Lorentz force density, $\vec{f}_L = \vec{j} \times \vec{B}$, generated by the interaction between an electric current density $\vec{j}$ and a magnetic flux density $\vec{B}$. The realization of this idea during MC is relatively cheap, especially during the magnetization phase, as the electric energy required is small and the magnetic field is already available. MHD flows have already been studied intensively in the context of magnetoelectrochemistry (e.g. Mühlenhoff et al., 2012; Yang et al., 2008). They can be used to significantly enhance the mass transfer in electrolytic cells which, for example, speeds up the rate of electrodeposition and its quality (Mühlenhoff et al., 2013). The objective of the present work is to transfer this concept to MC. For this purpose we applied an experimental setup sufficiently simplified with respect to the magnetic field and current injection such that it is still possible to measure both the velocity and temperature field. By means of particle image velocimetry and Mach–Zehnder interferometery we are able to deliver for the first time a proof-of-principle for heat transfer enhancement in MC by MHD flows.

2. Setup and data processing algorithm

2.1. Experimental setup

Gadolinium (Gd 99.5% pure, Jiangxi South Rare Earth Hi-Tech Co., Ltd.) is employed as a magnetocaloric material; this was machined to a flat plate with an area of 9.6 × 9.6 mm^2 and a thickness of 0.72 mm. After polishing the surface to create a roughness of less than 0.01 mm, the plate was glued to one side of a cuboid quartz glass cuvette with an inner side length of 10 mm as shown in Fig. 1b. Two NdFeB permanent magnets were combined to form an inhomogeneous magnetic field to generate the MHD flow and to trigger the magnetocaloric effect of the Gd plate. For this purpose, the two rectangular block magnets (50 × 30 × 12 mm^3) were juxtaposed with opposite magnetization directions so that their smallest sides touched at the outer side of the glass cell at the middle of the Gd plate, cf. Fig. 1a. A 3D finite element method is used to simulate the magnetic field with Ampere's law. The relative permeability of the permanent magnets is 1.07 and the remanence of the two magnets are regarded the same; both are $B_r = 0.7$ T. Simulation results in Fig. 2 show the expected quasi 2D magnetic field distribution in the entire cell region. The simulated results are verified by directly measuring the magnetic flux density using a Gaussmeter (SYPRIS Test & Measurement Model 5180), cf. Fig. 2b. A fair agreement between the simulated and measured magnetic flux density is seen in Fig. 2c. The largest error, at around $x = 2$ mm, is less than 20%. It is mainly caused