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Influence of the flow rate waveform and mass imbalance on the performance of active magnetic regenerators. Part I: Experimental analysis☆

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This is the first part of a two-part paper on the synchronization between the applied magnetic field and fluid displacement waveforms in a gadolinium packed sphere active magnetic regenerator (AMR) apparatus. For a rectified cosine magnetic field waveform, new rotary valves were developed to assess the influence of the duration of the fluid flow steps on the AMR performance. In order to correct flow imbalance effects caused by torque oscillations in the magnetic circuit and guarantee thermodynamically consistent conditions, a new criterion based on a mass imbalance parameter has been proposed. By keeping the displaced fluid mass fixed for a given utilization, the cooling capacity increased significantly with shorter blow times due to the higher fluid velocity and larger average magnetic field change. However, because of the associated increase in power consumption, an optimal blow time fraction of 45% was identified for operating frequencies of 0.25 and 0.5 Hz.

Influence du déséquilibre de la courbe de débit et de la masse sur la performance des régénérateurs magnétiques actifs. Partie I : Analyse expérimentale

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1. Introduction

Most devices and prototypes developed for room temperature magnetic refrigeration are based on the Active Magnetic Regenerator (AMR) cycle (Barclay and Steyert, 1982; Franco et al., 2018; Kitanovski et al., 2015). AMRs are thermal storage devices composed of a porous medium matrix made of a single or multi-layered magnetocaloric material (MCM). In addition to the regular cold and hot blow periods characteristic of thermal regenerators (Nellis and Klein, 2009; Schmidt and Willmott, 1981), AMRs are subjected to magnetic field changes. These changes generate a temperature variation in the MCM due to the magnetocaloric effect (MCE) (Pecharsky et al., 2001). In order to produce a cooling effect, the magnetic field changes can be performed simultaneously with the hot or cold blows, or during a different period of the cycle.

From a practical standpoint, a magnetic refrigerator combines three main subsystems (Kitanovski et al., 2015; Trevizoli et al., 2016a): (i) the regenerator matrix; (ii) the magnetic field source, composed in general of permanent magnets in relative motion with respect to the AMR; and (iii) a fluid management system which generates the oscillatory flow through the AMR. Several technical solutions for each subsystem have been proposed in state-of-the-art magnetic refrigeration prototypes (Kitanovski et al.,

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Nomenclature

Roman letters

A_{HT}	Interstitial heat transfer area, m^2
B	Magnetic field, T
COP	Coefficient of Performance
c_{Gd}	Solid matrix specific heat capacity, J kg^{-1} K^{-1}
$c_{p,f}$	Fluid specific heat capacity, J kg^{-1} K^{-1}
F_B	Blow time fraction
F_R	Ramp time fraction
f	Cycle frequency, Hz
f_M	Motor frequency, Hz
h	Interstitial heat transfer coefficient, W m^{-2} K^{-1}
m_B	Displaced mass during blows, kg
m_{avg}	Average displaced mass between hot and cold blows, kg
$\overline{\dot{m}}_B$	Blow average mass flow rate, kg s^{-1}
m_{Gd}	Solid matrix mass, kg
NTU	Number of transfer units
P	Pressure, Pa, bar
$\dot{Q}_C$	Cooling capacity, W
$\dot{Q}_H$	Heat rejection rate, W
T	Temperature, K
t	Time, s
t^*	Reduced time, rad
U_{avg}	Average expanded uncertainties
u_m	Mass imbalance parameter
$\dot{W}$	Power, W
$\dot{W}_P$	Pumping power, W
$\dot{W}_{RV}$	Rotary valve power, W

Greek letters

$\overline{\Delta B}$	Average magnetic field variation during fluid flow steps, T
ΔP_P	Pump pressure difference, Pa, bar
ΔT_{span}	Temperature span, K
η_{2nd}	Second-law efficiency
Γ	Torque, N m
ω	Angular frequency, rad s^{-1}
ϕ	Utilization factor
ρ_f	Fluid density, kg m^{-3}
τ	Period, s

Subscripts

C	Cold regenerator end
CB	Cold blow
CHEX	Cold heat exchanger
H	Hot regenerator end
HB	Hot blow
HHEX	Hot heat exchanger

Abbreviations

AMR	Active magnetic regenerator
BV	Balancing valve
HPV	High pressure valve
LPV	Low pressure valve
MCE	Magnetocaloric effect
MCM	Magnetocaloric material
NHC	Nested Halbach cylinder

2016; Yu et al., 2010). For instance, regarding the regenerative matrix, the use of multiple layers of materials of different compositions and magnetic transition temperatures have been evaluated experimentally and numerically (Govindappa et al., 2017; Kamran et al., 2016; Legait et al., 2014; Teyber et al., 2016b). As for the fluid management system, which is the main focus of the present work, two pumping configurations are commonly applied: (i) double-effect displacement pumps coupled with check or cam-actuated valves (Arnold et al., 2014; Teyber et al., 2016a; Trevizoli et al., 2016c); (ii) or a rotodynamic pump and valves, which can be rotary (Engelbrecht et al., 2012; Jacobs et al., 2014; Lozano et al., 2016), cam-actuated (Eriksen et al., 2015b; Fortkamp et al., 2018), or electronic (Cardoso et al., 2016; Dall'Olio et al., 2017). Current magnetic field generators (Bjørk et al., 2010) apply a geometric array of permanent magnets in which the relative motion with respect to the AMR generates the desired magnetic field variation (Arnold et al., 2014; Dall'Olio et al., 2017; Lozano et al., 2016; Trevizoli et al., 2015).

While some works focus on analyzing and optimizing individual subsystems, such as the AMR (Trevizoli et al., 2017; Tusek et al., 2013), or the magnetic circuit (Bjork et al., 2010; Teyber et al., 2017), more comprehensive analyses combining two or more subsystems and their integrated optimization are still an open research area. For example, as proposed by several works (Bjørk and Engelbrecht, 2011; Plaznik et al., 2013; Teyber et al., 2016a; Trevizoli et al., 2014a), the synchronization between the magnetic and fluid flow waveforms poses some interesting design challenges, with promising results regarding the increase in AMR performance.

Teyber et al. (2016a) proposed a cam-actuated valve system that diverted the flow from the AMR. The magnetic field, kept fixed in their study, was a sinusoidal waveform generated by nested Halbach cylinders. The fluid flow waveform was varied by controlling the duration of the blow steps using different cam profiles to change the *diversion ratio*. The authors defined this parameter as the ratio of fluid volume which is diverted from the regenerator (therefore bypassing it) to the total volume displaced by the piston pump during one cycle. Teyber et al. (2016a) evaluated the AMR performance for diversion ratios ranging from 0 to 0.74. Improvements were reported when the ratio was increased up to the point where the regenerator effectiveness started to decrease as a result of the higher mass flow rates required to maintain a constant displaced volume in the shorter blow periods.

In the first part of this two-part paper, we advance an experimental analysis of the synchronization between the magnetic and fluid flow waveforms in an AMR apparatus. The mathematical modeling of the problem will be presented in Part II. The experimental setup presented by Trevizoli et al. (2016c) was adapted to accommodate a rotary valve system in which different sealing faces enabled modifying the blow time fraction, F_B, in the interval between 50% and 32.5%. Here, F_B is defined as the ratio of the blow and total cycle periods. F_B is related to the diversion ratio of Teyber et al. (2016a) in such a way that higher values of the latter represent lower values of the former. During operation of the apparatus, flow imbalance effects (Eriksen et al., 2016) were observed, and a procedure to correct them was implemented. Results for cooling capacity, power input and coefficient of performance indicated the existence of an optimal flow waveform (blow fraction) for the present apparatus.

2. Experimental apparatus

Fig. 1 presents a schematic diagram of the experimental apparatus. A complementary description of the apparatus is available in Trevizoli et al. (2016c). The magnetic circuit is a nested Halbach cylinder (NHC) array driven by a stepper motor. Counter rotation of the two cylinders generates a rectified sinusoidal magnetic field waveform between 0.04 T (minimum) and 1.69 T (maximum) in the core of the NHC. A single AMR matrix composed of 194.8 g of commercial grade Gd spheres (0.55-mm average diameter) is placed in the core. The regenerator dimensions and porosity are 22.2 mm (internal diameter), 100 mm (length) and