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Influence of the flow rate waveform and mass imbalance on the performance of active magnetic regenerators. Part II: Numerical simulation☆

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ABSTRACT

In this part of the paper, an existing regenerator model was extended to predict the experimental data generated in Part I on the influence of the blow time fraction on the performance of a Gd packed bed AMR. The effect of mass imbalance between the hot and cold blows was evaluated numerically, and a significant improvement of the model predictions was obtained when the numerical and experimental mass imbalance set points were equal. A numerical assessment of the system performance beyond the conditions of Part I indicated optimal utilization factors and blow time fractions for temperature spans of 10 and 20 K, and operating frequencies of 0.25 and 0.5 Hz. For an operating point specified by fixed values of cooling capacity (20 W), temperature span (10 K) and frequency (0.5 Hz), the maximum COP was generated for a blow time fraction of 31% and a utilization factor of approximately 0.6.

Influence du déséquilibre de la courbe de débit et de la masse sur la performance des régénérateurs magnétiques actifs. Partie II : Simulation numérique

Mots-clés: Froid magnétique; Réfrigérateur magnétique actif; Déséquilibre du débit; Simulation numérique; Performance thermodynamique

1. Introduction

In the first part of this two-part paper, an experimental analysis was presented on the synchronization between the magnetic and fluid flow waveforms in an active magnetic regenerator (AMR) apparatus. Blow time fractions, F_B, between 50% and 32.5% were evaluated and a thermodynamically optimum value of 45% was clearly identified. Flow imbalance issues were also experimentally assessed and solved by defining a mass imbalance parameter set point for the test rig. Even though the heat transfer rate results agreed with the trends previously reported by other authors (Eriksen et al., 2016; Teyber et al., 2016), the flow distribution valve system was a major obstacle to further reducing the blow time fraction.

In the present (second) part of the paper, we explore a wider range of blow time fractions using the AMR mathematical model developed by Trevizoli et al. (2016a). Numerical models of different types and features have been proposed in the literature. A review of earlier models was presented by Nielsen et al. (2011), but since 2012 new models have been proposed for evaluating, designing and optimizing AMR systems (Aprea et al., 2012; 2018; Bouchekara et al., 2014; Burdyny et al., 2014; Lei et al., 2017; Monfared, 2018; Teyber et al., 2018; Trevizoli and Barbosa Jr., 2017a). Numerical work has been carried out specifically on the effect of synchronization parameters. For example, the influence of the duration of the magnetization step on the maximum cooling capac-

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Nomenclature

Roman letters

A_c	Cross section area, m^2
A_t	Pressure drop amplitude, Pa, bar
c_E	Ergun constant
COP	Coefficient of Performance
$c_{p,f}$	Fluid specific heat capacity, J kg^{-1} K^{-1}
c_s	Solid specific heat capacity, J kg^{-1} K^{-1}
d_p	Particle diameter, m
$D_{\|\|}$	Longitudinal thermal dispersion, m^2 s^{-1}
e	Thickness, m
F_B	Blow time fraction
f	Cycle frequency, Hz
$g(t^*)$	Pressure gradient waveform
h	Interstitial heat transfer coefficient, W m^{-2} K^{-1}
K	Permeability, m^2
k^{eff}	Effective thermal conductivity, W m^{-1} K^{-1}
k_f	Fluid thermal conductivity, W m^{-1} K^{-1}
L	Length, m
$\dot{m}_B$	Mass flow rate, kg s^{-1}
N_D	Demagnetization factor
NTU	Number of transfer units
P	Pressure, bar, Pa
Pr	Prandtl number
$\dot{Q}_C$	Cooling capacity, W
$\dot{q}_{csg}$	Casing heat transfer loss, W m^{-3}
$\dot{Q}_H$	Heat rejection rate, W
s	Specific entropy, J kg^{-1} K^{-1}
T	Temperature, K
t	Time, s
t^*	Reduced time, rad
$t^*_{o,a}$	Initial reduced time of the acceleration ramp, rad
$t^*_{o,d}$	initial reduced time of the deceleration ramp, rad
u	Darcy velocity, m s^{-1}
u_m	Mass imbalance parameter
V	Volume, m^3
$\dot{W}_{flow}$	Hydraulic power, W
$\dot{W}_{mag}$	Magnetic power, W
$\dot{W}_{valve}$	Valve power, W
z	Axial distance, m
z^*	Dimensionless length

Greek letters

β	Interstitial heat transfer area to matrix volume ratio, m^{-1}
$\overline{\Delta B}$	Average magnetic field variation during fluid flow steps, T
ΔT_{ad}	Adiabatic temperature change, K
ΔT_{span}	Temperature span, K
ε	Porosity
μ_f	Dynamic viscosity, kg m^{-1} s^{-1}
ϕ	Utilization factor
ρ	Density, kg m^{-3}
τ	Period, s
τ_{ramp}	Ramp period, s

Subscripts

air	Air gap
C	Cold regenerator end
CB	Cold blow
CHEX	Cold heat exchanger
f	Fluid
H	Hot regenerator end
HB	Hot blow
HHEX	Hot heat exchanger
Reg	Regenerator
s	Solid
wall	Casing wall

Abbreviations

AMR	Active magnetic regenerator
MCE	Magnetocaloric effect

ity developed by parallel plate and packed bed AMRs was presented by Bjørk and Engelbrecht (2011). The results indicated the existence of an optimum magnetization period associated with the highest cooling capacity. A comparison between different magnetic field waveforms was presented in a previous work from our group (Trevizoli et al., 2014), where it was found that the instantaneous field change (i.e., square wave) outperformed the sinusoidal and rectified sinusoidal waveforms in both temperature span and cooling capacity. The magnetic field ramp was numerically investigated by Plaznik et al. (2013), who showed that fast ramps could be used to increase the cooling capacity. In their work, an experimental evaluation of three thermodynamic cycles (Ericsson, Brayton and a hybrid cycle) was also carried out, revealing that the Brayton and the hybrid cycles gave better results in terms of cooling capacity.

Since all of the aforementioned numerical works on the synchronization effects focused on the influence of variations in the magnetic field, the experimental validation of such models could be challenging due to material cost and intrinsic complexity of magnetic circuits developed for AMRs. Oppositely, the present work focuses on changing parameters related to the hydraulic circuit, thus allowing a more extensive comparison between experimental data and the model, which solves balance equations for fluid flow and energy in the solid and fluid phases of the regenerative matrix. Flow imbalance and waveform synchronization parameters were included as inputs to the model in order to be consistent with the experimental setup described in detail in Part I and elsewhere (Trevizoli et al., 2016b). Furthermore, a systematic evaluation of the performance of the model for balanced and unbalanced flow conditions generated in the experimental apparatus strenghtens our confidence in using it to simulate smaller values of blow fraction that are currently not feasible in the experimental apparatus. The model also enables a more in-depth analysis of the time-dependent temperature profiles, thus helping to consolidate the numerical investigations of the fluid flow and magnetic field synchronization performed in the open literature so far.

2. Mathematical Model

A schematic representation of the problem geometry is presented in Fig. 1, which includes the regenerator porous matrix, as well as regenerator casing and the air gap, whose energy balance equations are solved to simulate heat gain/loss from/to the surroundings.

As previously mentioned, a numerical evaluation of the problem was performed using the 1-D AMR model developed by and thoroughly described by Trevizoli et al. (2016a). Equations for the fluid momentum (Brinkman–Forchheimer equation) and energy balances in the solid matrix and working fluid were solved using the Finite Volume Method. The MCE was implemented as a finite adiabatic temperature change, ΔT_{ad}, in the solid phase in between consecutive time steps of the numerical solution (the discrete approach) (Nielsen et al., 2011). The model also accounted for flow imbalance and synchronization effects by allowing the selection of different mass flow rates and blow time fractions for the hot