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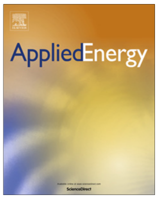

Performance assessment of different porous matrix geometries for active magnetic regenerators

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HIGHLIGHTS

- Evaluation of parallel-plate, pin array and packed-sphere regenerative geometries.
- Thermal and viscous losses were quantified with (passive) stainless steel matrices.
- Magnetic losses were quantified with (active magnetic) gadolinium matrices.
- Matrices had the same porosity, volume and interstitial area.
- Packed spheres had the highest cooling capacity and pin arrays the highest COP.

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ABSTRACT

The development of efficient active magnetic regenerators (AMR) is highly dependent on the regenerative matrix thermal performance. Matrix geometries should have a high thermal effectiveness and small thermal and viscous losses. In this study, we present a systematic experimental evaluation of three different regenerator geometries: parallel-plate, pin array and packed bed of spheres. All matrices were fabricated with approximately the same porosity (between 0.36 and 0.37). The cross sectional area and length of the regenerator beds are identical, resulting in the same interstitial area. Hence, any difference in performance between the matrices is due to interstitial heat transfer between the solid and the fluid and losses related to thermal, viscous and magnetic effects. As a means to quantify these losses individually, experiments were first conducted using stainless steel matrices without the application of a magnetic field (passive regenerator mode). Later, gadolinium matrices made with the same characteristics as the stainless steel ones were evaluated in an AMR test apparatus for which experimental results of cooling capacity, temperature span between the thermal reservoirs, coefficient of performance and second-law efficiency were generated as a function of utilization for different operating frequencies. Parallel plates had the poorest performance, while the packed bed of spheres presented the highest cooling capacity. On the other hand, the packed bed also had the highest viscous losses. For this reason, the pin array exhibited the highest COP and second-law efficiency.

1. Introduction

Almost all of the so-called *active caloric* technologies [1–4] make use of thermal regeneration for internal energy conversion. In magnetocaloric refrigeration — the most widely studied active cooling technology — an active magnetic regenerator (AMR) is responsible for building up a temperature span between the hot and cold reservoirs, thereby amplifying the magnetocaloric effect of the regenerative matrix, which is of the order of 2–3 K/T for gadolinium (the reference material for near-room temperature applications) [5].

Unlike passive regenerators, whose only function in regenerative cooling cycles is thermal storage [6], active regenerators are also responsible for providing the refrigerating effect [7–9]. In AMRs, this is achieved by subjecting the solid refrigerant to successive magnetization-demagnetization cycles. While it is relatively easy to increase the AMR cooling capacity and improve its performance by using bigger AMR beds, one should always consider performance penalties associated with pressure drop, matrix volume, applied magnetic fields intensities and thermal losses [10,11].

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Nomenclature

Roman

A_c	cross-section area [m^2]
A_{HT}	interstitial heat transfer area [m^2]
c	specific heat capacity [J/kg K]
COP	coefficient of performance [–]
D_{Reg}	regenerator housing diameter (for spheres) [mm]
d_p	particle diameter [mm]
e	thickness [mm]
f	cycle frequency [Hz]
h	convective heat transfer coefficient [W/m^2 K]
H	magnetic field [T]
H_{Reg}	regenerator housing height (for pins and plates) [mm]
L_{Reg}	regenerator length [mm]
m	regenerative matrix mass [kg]
$\dot{m}$	mass flow rate [kg/h]
N_D	demagnetizing factor [–]
NTU	number of heat transfer units [–]
P	pressure [kPa]
$\dot{Q}_C$	cooling capacity [W]
Re_{dp}	Reynolds number based on the particle diameter = ud_p/ν_f [–]
t	time [s]
T	temperature [K]
W_{Reg}	regenerator housing width (for pins and plates) [mm]
$\dot{W}$	power [W]

Greek

ΔP	pressure drop [Pa]
ΔT_{HEX}	(=$T_H - T_C$) reservoir temperature difference [K]
ϵ	effectiveness
ε	porosity [–]
ϕ	utilization factor [–]
η_{2nd}	second-law efficiency [–]
ρ	density [kg/m^3]
τ	cycle period [s]
Γ	torque [N m]
ϑ	total void volume size [cm^3]
ϑ^*	void volume fraction [–]

Subscripts and superscripts

app	applied magnetic field
C	cold reservoir or cold side
CB	cold blow
CE	cold end
ch	channel
csg	casing
dp	based on particle diameter
eff	effective magnetic field
f	fluid phase
g	solid piece
geo	geometry
H	hot reservoir or hot side
HB	hot blow
HE	hot end
id	ideal
in	inlet flow
M	stepper motor
mag	magnetic
out	outlet flow
pump	pumping
Reg	regenerator
s	solid phase
tot	total
tub	tubing
$\bar{x}$	average value
*	dimensionless variables

In order to understand the individual contributions of different loss mechanisms in AMRs, several authors have studied the thermal-hydraulic behavior of passive regenerators [12–15]. The convenience of this approach is the uncoupling of the magnetocaloric phenomena from the analysis, so that the matrix can be manufactured with more conventional and inexpensive materials. As a result, valuable information to the overall system performance can be generated regarding the heat transfer and viscous losses, effectiveness imbalance and carryover (dead volume) and axial conduction losses [16,17]. For example, Sarlah et al. [14] proposed a hybrid procedure in which experiments were conducted to compare the thermal-hydraulic characteristics of six regenerative geometries made from copper. The Colburn *j*-factor and the friction factor data were incorporated in a numerical model to predict the performance of AMRs with those geometries. Parallel-plate AMRs had the best coefficient of performance (COP), while the spheres AMR presented the highest temperature span, but the lowest COP.

In the context of AMRs, reciprocating liquid flows through stacks of parallel plates and beds of packed spheres have been studied experimentally [9,18] and numerically [19–21]. Other geometries have been evaluated mainly by numerical modeling. Tusek et al. [22] studied six different AMR geometries, including parallel plates, packed beds of spheres, powder and cylinders. They concluded that parallel plates with a large heat transfer area and refrigerant mass outperformed the remaining geometries, including the sphere packed beds. However, parameters such as the total heat transfer area, mass of magnetocaloric material and porosity were not kept constant in the comparison between the different geometries.

Trevizoli and co-workers [23,24] compared the performances of different matrix geometries (parallel plates, pin arrays and packed beds of spheres) by combining a fixed-geometry (FG) performance evaluation criterion [25] with a minimum entropy generation calculation for the AMR. Depending on the operating conditions, optimal length scales (e.g., plate thickness, sphere diameter) were found to be outside practical ranges associated with manufacturing or operating conditions. Lei et al. [26] also compared different matrix geometries using entropy generation minimization. Sphere packed beds, parallel plates, micro-channels and screen packed beds were evaluated. Simulations were performed considering different geometric parameters, while the flow rate and frequency were adjusted to achieve the maximum COP or the minimum entropy production. The specific cooling capacity (in W/kg) was a constraint. The parallel-plate, microchannel and screen packed bed matrices performed better than packed beds of spheres in terms of maximum coefficient of performance. Other second-law based optimization approaches to regenerator performance evaluation and design have been pursued in Refs. [27,28]. However, in none of them the cooling capacity was kept fixed during the analysis, thus complicating the assessment of the effect of each parameter, such as the hydraulic diameter or aspect ratio of the AMR bed.

Kitanovsky et al. [9] performed an extensive review of AMR systems, comparing the different types of regenerator embodiment. Compacted powder and irregular particles have been used in