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Development of a novel rotary magnetic refrigerator [†]

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ABSTRACT

A novel rotary magnetic refrigerator was designed and built at the Federal University of Santa Catarina (UFSC). The optimized magnetic circuit is a two-pole system in a rotor-stator configuration with high flux density regions of approximately 1 T. Eight pairs of stationary regenerator beds filled with approximately 1.7 kg of gadolinium spheres (425–600 μm diameter) were placed in the magnetic gap. Two low-friction rotary valves were developed to synchronize the hydraulic and magnetic cycles. The valves were positioned at the hot end to avoid heat generation in the cold end. In this work, experimental results are presented as a function of the operating frequency, fluid flow rate, hot reservoir temperature and thermal load. The performance of the device was evaluated in terms of the coefficient of performance (COP) and overall second-law efficiency (η_{2nd}). The maximum no-load temperature span was 12 K at 1.5 Hz and 150 L h^{-1}, and the maximum zero-span cooling power was 150 W at 0.8 Hz and 200 L h^{-1}. For a thermal load of 80.4 W, at 0.8 Hz and 200 L h^{-1}, the device generated a temperature span of 7.1 K, with a COP of 0.54 and η_{2nd} of 1.16%.

Développement d'un nouveau réfrigérateur magnétique rotatif

Mots-clés : Froid magnétique ; Effet magnétocalorique ; Aimant permanent ; Régénérateur ; Gadolinium ; Coefficient de performance

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Nomenclature

Roman

A	area [m^2]
B	magnetic induction [T]
c	specific heat [J kg^{-1} K^{-1}]
f	frequency [Hz]
H	magnetic field [A m^{-1}]
L	length [mm]
m	mass [kg]
N	number
p	pressure [bar]
R	radius [mm]
T	temperature [K]
V	volume [m^3]
w	width [mm]

Greek

Δ	change
η	efficiency
Λ_{cool}	figure of merit for magnetic circuits for M.R. [T$^{2/3}$]
ϕ	utilization factor
ε	porosity
σ	standard deviation
τ	cycle time

Composed and constants

A_c	cross sectional area [m^2]
BH	energy product [kJ m^{-3}]
HC	magnetic coercivity [kA m^{-1}]
μ_0	magnetic permeability of vacuum [$4\pi \times 10^{-7}$ N A^{-2}]
μ_r	relative magnetic permeability
$\dot{W}$	power [W]
Δp_{sys}	system pressure drop [bar]
$\dot{Q}_C$	cooling capacity [W]
T_C	Curie temperature [K]
T_R	room temperature [K]
ΔT_{reg}	regenerator temperature span [K]
$\dot{V}$	volumetric flow rate

Subscript

2nd	second-law
C	cold
f	fluid
H	hot
id	ideal cycle
in	inlet of the pump
M	electric motor
max	maximum value
out	outlet of the pump
OP	overall pumping
P	pumping
R	room
reg	regenerator
rem	remanence
s	solid
sys	system
visc	viscous

Abbreviation

AMR	active magnetic regenerator
COP	coefficient of performance
Gd	gadolinium
MCE	magnetocaloric effect
PFA	perfluoroalkoxy alkane
PMMA	polymethyl methacrylate
POM	polyacetal
RTD	resistance temperature detector
UFSC	Federal University of Santa Catarina

1. Introduction

The magnetocaloric effect (MCE) is the thermal response of a magnetic material when subjected to a changing magnetic field. Magnetocaloric refrigeration harvests the MCE in a regenerative thermodynamic cycle to transfer heat from a low-temperature environment to a high-temperature one by means of magnetic work. The main advantage of magnetocaloric refrigeration compared to well-established vapor compression technologies is that the former is based on internally reversible thermodynamic cycles (i.e., Brayton, Stirling, Ericsson), while the latter are based on an internally irreversible cycle (i.e., Reversed Rankine). The MCE is also reversible in most of the known materials used as solid refrigerants in magnetic cooling cycles, including the benchmark material, gadolinium (Gd), and other alloys, especially those exhibiting the second-order phase transition (Nielsen et al., 2010).

Despite the potential benefits of magnetic refrigeration as an emerging cooling technology, its true gains are yet to be fully verified for near room temperature applications. Commercial devices are yet to be developed, and some of the challenges associated with the technology involve (i) the investigation of new magnetocaloric working materials, (ii) new permanent magnet configurations and (iii) the development of new active magnetic regenerator (AMR) geometries for which a substantial knowledge of the conjugate heat transfer and fluid flow in a porous matrix is essential for achieving an optimum design of the cooling system.

A state-of-the-art magnetic refrigeration system is composed basically of an AMR, a magnetic circuit to promote the change in magnetic field and a hydraulic system synchronized with the magnetic field profile. Magnetic refrigerators are classified as reciprocating or rotary. Reciprocating AMRs have fewer moving components, but limitations in the operating frequency due to higher inertia. On the other hand, rotary AMRs are able to perform at higher frequencies with multiple regenerators (larger magnetocaloric mass), but at the expense of more complex flow distribution systems. Magnetic refrigerators are also classified according to the magnetic field change generation, which can be performed by three different configurations: a stationary regenerator with a moving magnetic