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Initial experimental results from a rotary permanent magnet magnetic refrigerator

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ABSTRACT

In this paper, a novel rotary magnetic refrigerator is described, and initial experimental results are presented. The prototype employs a two-pole magnetic system based on a double U configuration of permanent magnets with an air gap of 43 mm and 1.25 T. The magnetocaloric refrigerant is confined within eight static regenerator enclosures, which are alternatively magnetized and demagnetized with the rotation of the magnets. A rotary valve mechanically coupled with the field generator imparts the direction of heat transfer fluid through the regenerators. Using a total mass of 1.20 kg of gadolinium spheres (of 400–500 microns) as refrigerant and distilled water as regenerating fluid, the device produced a maximum temperature span of 13.5 K under zero applied thermal load with an utilization factor of 1.40 and a heat rejection temperature of 298 K.

Résultats expérimentaux initiaux pour un réfrigérateur magnétique à aimants rotatifs permanents

Mots clés : Froid magnétique ; Prototype ; Conception ; Expérimental ; Aimant permanent

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Nomenclature

Acronyms

AMR	active magnetic regenerator
CF	cold flow: from hot end to cold end
CV	cold sub-valve
FEA	finite element analysis
FFR	fluid flow rate
HMF	high magnetic field
HF	hot flow: from cold to hot end
HV	hot sub-valve
LMF	low magnetic field
PID	proportional integrative differential logic
MCE	magnetocaloric effect
MCM	magnetocaloric material
MR	magnetic refrigeration
RPMMR	rotary permanent magnet magnetic refrigerator

Symbols

A0	cross section of the regenerator [m^2]
B	magnetic flux density [T]
$\overline{B}$	average magnetic flux density [T]
$\overline{B}_{High}$	average magnetic flux density in the volume of a high magnetic field [T]
$\overline{B}_{Low}$	average magnetic flux density in the volume of a low magnetic field [T]
B_r	magnetic remanence [T]
δ_r	regeneration factor [-]
d_p	diameter of the particle [m]
ΔT_{loss}	ΔT_{AMR}-ΔT_{span} [K]
Δp	pressure drop [Pa]
Δp_{Ergun}	pressure drop calculated by means of Ergun's equation [Pa]
ΔT_{ad}	adiabatic temperature change [K]
ΔT_{AMR}	operating temperature span of the AMR [K]
ΔT_{span}	temperature span [K]
$\overline{\Delta T}_{span}$	mean temperature span [K]
$\varepsilon_{\Delta Tspan}$	temperature span error [K]
ε	mean porosity [–]
F_{add}	additional factor [Pa]
f_{AMR}	AMR cycle frequency [Hz]
Φ	utilization factor [–]
θ	rotation angle [rad]
θ_{closed}	rotation angle for which the hole is fully closed [rad]
$\theta_{opening}$	rotation angle for which the hole is opening [rad]
Λ_{cool}	magnet performance parameter [T$^{2/3}$]
M_f	mass of regenerating fluid [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
μ	fluid viscosity [Pa s^{-1}]
P_{field}	fraction of an AMR cycle [–]
Q_c	cooling power [W]
R	regenerator [–]
ρ_f	density of the regenerating fluid [kg m^{-3}]
τ	time constant defined as the time required to reach 63.2% of an instantaneous temperature change [s]
V_0	undisturbed velocity of the fluid [m s^{-1}]
V_{field}	volume with a high magnetic flux density equal to $\overline{B}_{High}$ [l]
V_{mag}	volume of the magnets [l]
$\dot{V}$	fluid flow rate [l min^{-1}]

1. Introduction

Magnetic refrigeration (MR) is an emerging environmentally friendly technology that uses a solid as a refrigerant and exploits the magneto-caloric effect (MCE), which is characterized by a change in temperature with magnetization. The MCE originates from the interaction of the magnetic field with the molecular magnetic moments of the substance.

In general, the magnetocaloric effect is associated with warming as the magnetic moments of the atoms align by the application of a magnetic field and corresponding cooling upon removal of the magnetic field. Therefore, MCE can be defined as an adiabatic temperature change due to magnetization/demagnetization.

Magnetic refrigeration technology has the potential to achieve higher energetic efficiencies than conventional vapor compression in more compact devices (Zimm et al., 1998; Yu et al., 2003; Rowe and Tura, 2006; Aprea et al., 2011). Indeed, in general, with vapor compression refrigeration systems, the work of compression is lost through a throttling valve, whereas magnetic refrigerators can be designed in such a way that most of the magnetization–demagnetization work is recovered (Kotani et al., 2013). Furthermore, this technology has no direct impact on ozone depletion or greenhouse effects because of the solid-state nature of the refrigerant.

Given the small temperature rise due to magnetization, a regenerative cycle is required to produce a useful temperature lift. Barclay (1982) suggested the use of active magnetic regenerators, or AMRs, which consist of thermal regenerators coupled with a magnetocaloric cycle. The secondary fluid can be a liquid or a gas.

For a magnetic refrigerator, the magnetic field can be supplied by an electromagnet, superconducting coil, or a permanent magnet. Although an electromagnet can generate a magnetic flux density of 8 T, this is not a commercially viable solution because of the power required to maintain the active field (Allab et al., 2006). A superconducting magnet is a better option because no power is lost by ohmic resistance. Even if a superconducting magnet can create magnetic flux density on the order of 15–20 T, it needs to be cryogenically cooled (Nishijima et al., 2006; Watanabe et al., 2013). This can be expensive, energy intensive, and impractically cumbersome. For large-scale central cooling systems (e.g., large refrigerators for warehouses) a superconducting magnet might be a plausible solution (Evans, 2012). However, for commercial household refrigeration and air conditioning, superconducting