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The performance of a large-scale rotary magnetic refrigerator

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ABSTRACT

Astronautics has constructed a large-scale rotary magnetic refrigerator which was designed to provide 2 kW of cooling power over a temperature span of 12 K with Electrical Coefficient Of Performance (COPe) > 2. The system uses a NdFeB magnet assembly with peak field of 1.44 T which rotates over twelve beds arranged circumferentially. Each bed was packed with six layers of LaFeSiH of different Curie temperatures, chosen to optimize system performance over the desired span. We report here on the performance of this system at flow rates ranging from 12.5 to 21.2 L min^{-1}. At the largest flow rate, the system produced 3042 W of cooling power at zero span and peak performance of 2502 W over a span of 11 K. To our knowledge, this represents the largest cooling power yet observed for a magnetic refrigeration system. We show that the measured performance is in good agreement with theoretical prediction.

Performance d'un réfrigérateur magnétique rotatif de grande échelle

Mots clés : Froid magnétique ; Coefficient de performance ; Froid magnétique actif ; Matériau magnétocalorique

1. Introduction

With the development of powerful NdFeB magnets and the discovery of materials with a so-called giant magnetocaloric effect, room temperature magnetic refrigeration (MR) has the potential to supplant vapor compression for many typical cooling applications (Gschneidner and Pecharsky, 2008). Magnetic cooling systems, in theory, provide a significant increase in energy efficiency relative to vapor compression systems (Engelbrecht et al., 2007), which would lead to reduced operating costs and energy consumption. In addition, unlike vapor compression, MR uses no greenhouse or ozone-depleting gases, making it a truly green technology. Finally, the (typically) aqueous heat transfer fluid used in an MR system is much less likely to leak than the gases used in vapor compression, and the leaks can be readily identified and corrected if they should occur. Modern room-temperature MR systems implement the so-called Active Magnetic

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Nomenclature

Acronyms

AMR	Active Magnetic Regenerator
COPe	Electrical Coefficient of Performance
DSC	Differential Scanning Calorimetry
MCM	Magnetocaloric Material
MR	Magnetic Refrigeration

Symbols

A	bed cross-sectional area (cm^2)
a	linear coefficient for temperature-dependent fluid viscosity (Pa s)
b	quadratic coefficient for temperature-dependent fluid viscosity (Pa s)
B_0	peak magnetic flux density (Tesla)
C_e	heat capacity of epoxy (J kg^{-1} K^{-1})
C_{es}	effective solid-phase heat capacity (J kg^{-1} K^{-1})
C_f	fluid heat capacity (J kg^{-1} K^{-1})
C_{MCM}	heat capacity of the magnetocaloric material
D_p	particle diameter (μm)
h	fluid-particle surface heat transfer coefficient (W m^{-2} K^{-1})
k_f	static fluid thermal conductivity (W m^{-1} K^{-1})
k_{ef}	effective fluid-phase thermal conductivity (W m^{-1} K^{-1})
Pr	Prandtl number
Q_C	cooling power (W)
Q_H	heat exhaust (W)
r	epoxy:magnetocaloric material mass ratio
Re	Reynolds number
V_B	total bed volume (liter)
T	temperature (K)
T_{Ci}	cold inlet fluid temperature (°C)
T_{Co}	cold outlet fluid temperature (°C)
T_{Hi}	hot inlet fluid temperature (°C)
T_{Ho}	hot outlet fluid temperature (°C)
ε	bed porosity
μ	specific exergetic cooling power (W T^{-1} L^{-1})
μ_0	reference fluid viscosity (Pa s)
μ_f	fluid viscosity (Pa s)
ω	angular velocity of magnet assembly (degrees s^{-1})
ρ_f	fluid density (kg m^{-3})
Φ	system flow rate (L min^{-1})
Φ_b	bed flow rate (L min^{-1})

Regenerator (AMR) cycle to perform cooling (Barclay and Steyert, 1982). The AMR used in this cycle consists of a porous bed of magnetocaloric material (MCM). A heat transfer fluid exchanges heat with the MCM as it flows through the bed. The cycle has four stages. In the first stage ("magnetization"), while the fluid in the bed is stagnant, a magnetic field is applied to the MCM, causing it to heat. In the next stage (the "hot blow"), while the magnetic field over the bed is maintained, fluid at a temperature T_{Ci} (the cold inlet temperature) is pumped through the bed from the cold side to the hot side. This fluid pulls heat from the MCM and rises in temperature as it passes through the bed. During the hot blow, the fluid exits the bed at the temperature T_{Ho} (the hot outlet temperature) and is circulated through a heat exchanger, where it gives up heat to the ambient environment and returns to the temperature T_{Hi} (the hot inlet temperature) $< T_{Ho}$. In the next stage ("demagnetization"), the fluid flow is terminated and the magnetic field is removed. This causes the bed to cool further. In the final stage (the "cold blow"), fluid at a temperature T_{Hi} is pumped through the bed from the hot side to the cold side in the continued absence of the magnetic field. The fluid is cooled as it passes through the MCM, reaching a temperature T_{Co} (the cold outlet temperature) $\leq T_{Ci}$. The colder fluid exiting the bed during the cold blow may be circulated through a cold-side heat exchanger, picking up heat from a refrigerated environment, allowing it to maintain its colder temperature. The fluid exits the cold-side heat exchanger at temperature T_{Ci} and completes the AMR cycle. A number of prototype magnetic refrigeration systems, all implementing the AMR cycle, have been reported in the literature (see, for example, Engelbrecht et al., 2012; Tura and Rowe, 2011; Zimm et al., 2007) and demonstrate that the magnetic refrigeration process is capable of providing cooling power (50 W–1000 W) comparable to that delivered by common household appliances. However, to justify the significant investment that will be required to bring this technology to the marketplace, ever higher performance in cooling power, span, and efficiency must be demonstrated, with systems of reasonable size. To this end, Astronautics Corporation of America has constructed a large-scale MR system designed to provide at least 2 kW of cooling power over a temperature span of 12 K with COP of at least 2. The system, constructed with funding provided by the US Office of Naval Research, is intended to meet the preliminary performance specifications of a supplemental electronics cooler, a compact ship-board cooling system that provides additional localized cooling to critical electronics on a naval vessel during operation in warm-water environments. The system is intended for operation above room temperature, with a hot inlet fluid temperature of 44 °C and cold inlet fluid temperature of 32 °C.

2. System description

The Astronautics MR system uses a rotating magnet architecture where a magnet assembly producing a peak field of 1.44 T rotates over twelve fixed beds arranged circumferentially. Each bed is separated by an angle of 360°/12 = 30° from its neighbors. The magnet assembly, in the form of a modified Halbach array (Chell and Zimm, 2006), was designed by Astronautics and fabricated by Vacuumschmelze GmbH & Co. KG. Beds in the system fit into a gap in this assembly. Each bed has four ports: the hot inlet, hot outlet, cold inlet, and cold outlet. Flow through the beds is controlled by four rotary disk valves referred to as the hot inlet valve, cold outlet valve, cold inlet valve, and hot outlet valve, which are mechanically coupled to the rotation of the magnet. Each bed in the system undergoes the same AMR cycle, with a hot blow duration of 1/