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Research articles

Permanent magnet design for magnetic heat pumps using total cost minimization

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ABSTRACT

The active magnetic regenerator (AMR) is an attractive technology for efficient heat pumps and cooling systems. The costs associated with a permanent magnet for near room temperature applications are a central issue which must be solved for broad market implementation. To address this problem, we present a permanent magnet topology optimization to minimize the total cost of cooling using a thermoeconomic cost-rate balance coupled with an AMR model. A genetic algorithm identifies cost-minimizing magnet topologies. For a fixed temperature span of 15 K and 4.2 kg of gadolinium, the optimal magnet configuration provides 3.3 kW of cooling power with a second law efficiency (η_{II}) of 0.33 using 16.3 kg of permanent magnet material.

1. Introduction

Energy conversion devices using solid-state magnetocaloric materials (MCM) have the potential to reduce energy consumption and mitigate environmental pollutants [1–4]. Although permanent magnet based active magnetic regenerator (AMR) devices have demonstrated commercially relevant temperatures spans, cooling powers and efficiencies [5–10], magnetic field generator and refrigerant costs must be reduced for broad market penetration.

A previous assessment of an AMR cooling device showed that the permanent magnet cost is of greatest importance to be competitive with existing air conditioning technologies [11]. The evaluation was based on the cost of cooling in $/kW, where the device performance was evaluated from the material T-S diagram and the magnetic field was generated using a theoretical Halbach cylinder. Compared with the permanent magnet, the refrigerant cost was found to be almost insignificant when using $La(Fe_{1-x}Si_x)_{13}$ with a cost of 8 $/kg. Using a similar methodology, Vuarnoz et al. (2012) [12] investigated a magnetocaloric heat engine and found the technology to be economically feasible for electricity prices between 0.1 and 0.2 CHF/kWh.

Bjørk et al. (2011) [13] investigated the regenerator configuration, magnetic field source and operating parameters that minimize the capital costs of a refrigerator using a one-dimensional AMR model. A device is optimized for both a theoretical Halbach cylinder and a theoretical magnet with maximum energy efficiency ($M^* = 0.25$) [14].

$$M^* \equiv \frac{V_{\text{bore}}}{V_{\text{mag}}}\left(\frac{B_{\text{bore}}}{B_{\text{rem}}}\right)^2 \tag{1}$$

Tura and Rowe (2014) [15] considered both the capital and operating costs of a dual-regenerator AMR with theoretical concentric Halbach arrays. An optimization routine determines the geometry and operating conditions that minimize the total cost of cooling using analytical expressions describing an AMR [16,17]. With a temperature span of 50 K and a cooling power of 100 W, the optimized design has magnet and refrigerant capital costs of $100 and $40, respectively, using an ideal refrigerant with an assumed cost of 150 $/kg.

More recently, Bjørk et al. (2016) [18] designed an operating scheme based on EU-directive 1060/2010 and European A^{+++} standards to minimize both the capital and operating costs of a magnetic refrigerator. A Halbach cylinder is used and the effects of a finite length magnet are included. The simulated lifetime cost of $150—$400 is shown to be competitive with comparable vapor compression devices.

These works couple AMR models with economic assessment tools to optimize the geometry and operating parameters of an AMR. Of the various magnetic circuits available [19,20], each study uses a Halbach cylinder [21–24] and concludes that the permanent magnet material (PMM) dominates the capital cost of an AMR.

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Nomenclature

Roman

B	magnetic flux density [T]
$\dot{C}$	cost rate [$/h]
c	cost per unit exergy [$/kWh]
c	specific heat [J/kgK]
cf	capacity factor [–]
$\dot{Ex}_Q$	exergetic cooling power [W]
f	frequency [Hz]
g	air gap between cylinders [m]
H	magnetic field strength [A/m]
i_d	discount rate[–]
L	length [m]
m	mass [kg]
M^*	magnet efficiency [–]
N_D	demagnetization factor [–]
$2p$	magnet poles [–]
P	magnet utilization [–]
$\dot{Q}_c$	cooling capacity [W]
r	radius [m]
R	thermal mass ratio [–]
R_{HC}	heat leak thermal resistance [K/W]
T	temperature [K]
t	time [s]
V	Volume [m^3]
$\dot{V}$	volumetric flow rate [$m^3\ s^{-1}$]
V_D	displaced volume [cm^3]
V_M	Magnetic scalar potential [A]
x	coordinate of regenerator length
$\dot{Z}$	ammortized capital costs [$/h]

Greek

γ	cost per unit mass [$/kg]
ε	porosity [–]
μ	magnetic permeability [H/m]
κ	effective thermal conductivity [–]
Λ_{cool}	magnet figure of merit [$T^{2/3}$]
η_{II}	second law efficiency [–]
Φ	utilization [–]
Ψ	topology design vector [–]
σ	specific magnetization [Am^2/kg]
τ	cycle period [s]
θ	angular coordinate [rad]
χ	domain material [–]
ζ	reduced magnetocaloric effect [–]

Subscripts and Superscripts

ad	adiabatic
app	applied field
C	cold reservoir or cold side
cj	intrinsic coercivity
csg	regenerator casing
D	displaced
f	fluid
FWA	flow weighted average
geo	geometry
H	hot reservoir or hot side
int	internal field
M	magnetic work
MCM	magnetocaloric material
PMM	permanent magnet material
p	constant pressure
reg	regenerator
rem	remanence
s	solid
SMM	soft magnetic material
span	temperature span

While optimization methods have been proposed for permanent magnet structures [25–29], none minimize the lifetime cost of an AMR. Instead, the most widely used objective function for magnetic refrigeration field generators is the Λ_{cool} parameter proposed by Bjørk et al. (2008) [22].

$$\Lambda_{cool} = (B_{high}^{2/3} - B_{Low}^{2/3})\frac{V_{bore}}{V_{mag}}P_{field} \tag{2}$$

Λ_{cool} resembles Eq. (1), but reflects the scaling of the magnetocaloric effect with applied field and the importance of minimizing the low field strength (B_{low}). Although Λ_{cool} encapsulates important design parameters, it is not suitable as an objective function for design optimization: for a theoretical Halbach cylinder, $\Lambda_{cool} = \frac{r_{in}^2}{r_{out}^2 - r_{in}^2}(B_{rem} \ln \frac{r_{out}}{r_{in}})^{2/3}$ which tends to infinity with increasing r_{in} and decreasing cylinder thickness. This does not yield low cost refrigeration, as will be shown.

Bjørk et al. (2010) [30] addresses this shortcoming by defining the air gap size *a priori*, and designs a state of the art magnetic field generator by maximizing Λ_{cool} in a segmented adaptation of the nested quadrupolar Halbach array. The theoretical remanence is defined as

$$\langle B_{rem,r}, B_{rem,\theta} >= ||B_{rem}|| < cos(p\theta), sin(p\theta) \rangle \tag{3}$$

where $2p$ is the number of poles, r and θ are the polar coordinate axis. The optimized field generator is effective and efficient, however the optimized design uses sophisticated magnet shapes with custom remanence directions that cost several times more than their rectangular counterpart [31]. Bjørk re-investigates the nested Halbach design [32] using a topology optimization to replace continuously oriented permanent magnet material (as in Eq. (3)) with soft magnetic material (SMM) over a continuous domain to maximize Λ_{cool}. A high figure of merit is presented, however AMR operation, magnet manufacturability and finite coercive strength are not considered.

Monfared et al. (2014) [33] reported that magnetic refrigeration can only reduce environmental impacts if permanent magnet material is re-used, demonstrating how manufacturability and the end-of-life recyclability must be considered with the capital and operating costs. An appealing solution is to use rectangular magnet segments, as the production costs are significantly lower than magnets with custom shapes or remanence orientations. Rectangular magnets are easily re-purposed, through material recycling [34–36] or a consumer buy-back program where reclaimed magnets directly supply production inventory.

In this paper, we propose a permanent magnet design methodology to minimize the total cost of cooling for a magnetic refrigerator. A commercially oriented magnetic circuit is created by decomposing a sophisticated magnet design into a collection of small, rectangular elements. Each element is assigned the properties of air, soft magnetic material or permanent magnet material with discretized remanence orientations (north, east, south, west). A magnet topology is used to simulate the magnetic field waveform for an AMR model. The performance and topology are used to evaluate the capital and operating costs based on a thermoeconomic cost-rate balance, which serves as the optimization objec-