Applied Energy 111 (2013) 669–680

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance analysis of a rotary active magnetic refrigerator

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HIGHLIGHTS

- Experimental results of a novel rotary active magnetic refrigerator are obtained.
- Experiments are compared to predictions from a 1D numerical AMR model.
- Performance is evaluated considering parasitic losses for a range of conditions.
- A cooling power of 200 W is produced at a span of 16.8 K with a COP of 0.69.
- The attained overall second-law efficiency is around 5%.

ARTICLE INFO

Article history:
Received 6 February 2013
Received in revised form 29 April 2013
Accepted 14 May 2013
Available online 12 June 2013

Keywords:
Magnetic refrigeration
Regenerator
Coefficient of performance
Performance analysis
Efficiency

ABSTRACT

Performance results for a novel rotary active magnetic regenerator (AMR) and detailed numerical model of it are presented. The experimental device consists of 24 regenerators packed with gadolinium (Gd) spheres rotating inside a four-pole permanent magnet with magnetic field of 1.24 T. A parametric study of the temperature span, cooling power, coefficient of performance (COP) and efficiency of the system was carried out over a range of different hot reservoir temperatures, volumetric flow rates and cooling powers. Detailed modeling of the AMR using a 1D model was performed and compared with the experimental results. An overall mapping of the thermal losses of the system was performed, and good agreement between the experimental and numerical results was found when parasitic heat losses were subtracted from the modeling results. The performance of the system was evaluated via the COP, the exergetic-equivalent cooling power (Ex_Q), and the overall second law efficiency, η_{2nd}. Losses mapping indicated that friction and thermal leakage to the ambient are the most important contributors to the reduction of the system performance. Based on modeling results, improvements on the flow distributor design and reduction of the cold end thermal parasitic losses are expected to enhance the efficiency of the system. For an operating frequency of 1.5 Hz, a volumetric flow rate of 400 L/h, a hot reservoir temperature of 297.7 K, and thermal loads of 200 and 400 W, the obtained temperature spans, ΔT_S, were 16.8 K and 7.1 K, which correspond to COPs of 0.69 and 1.51, respectively. The maximum overall second-law efficiency was 5.6% for a ΔT_S of 12.9 K at 500 L/h and 400 W.

1. Introduction

An active magnetic regenerator (AMR) refrigerator is an alternative cooling technology that uses a solid refrigerant that has no ozone depleting potential and no direct global warming potential. Instead the technology relies on the magnetocaloric effect, a coupling between the temperature and magnetic field of magnetic materials. Since the magnetization/demagnetization of a magnetocaloric material (MCM) can be reversible, it may be possible to build highly efficient cooling devices around the effect for a diverse number of applications including chip and sensor cooling [1] and low-cost magnetic energy conversion devices [2].

A room temperature regenerative magnetic refrigerator was first demonstrated by Brown [3]. In 1982 the active magnetic regenerator (AMR) concept was introduced, in which the regeneration was achieved by the active material itself [4]. Since then, many new devices have been reported [5], with modern AMRs generally using permanent magnets and regenerators made of packed spheres [6,7], packed particles [8] or parallel plates [9,10] of MCM. A comprehensive overview of the material and the regenerator technology was recently given in Ref. [11]. The AMR cycle uses a heat transfer fluid to transport the heat generated from magnetizing and demagnetizing the MCM to the hot and cold reservoirs. The

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http://dx.doi.org/10.1016/j.apenergy.2013.05.039

Nomenclature

Roman

A_c	cross-sectional area of regenerator, m^2
A_{HT}	total surface area for heat transfer, m^2
B	internal magnetic field, T
c	specific heat capacity, J/(kg K)
d_h	hydraulic diameter, m
Ex_Q	exergetic-equivalent cooling power, W
f_f	friction factor, –
f	frequency of operation, Hz
h	convection coefficient, W/(m^2 K)
k_{disp}	thermal conductivity of the fluid due to axial dispersion, W/(m K)
k_{eff}	effective conductivity, W/(m K)
m	mass, kg
$\dot{m}_f$	mass flow rate of fluid, kg/s
p	pressure, bar
$\dot{Q}$	parasitic loss, W
$\dot{Q}_C$	cooling capacity, W
$\mathcal{R}$	thermal resistance, K/W
Δs_{mag}	magnetic entropy change, J/kg K
T	temperature, K
t	time, s
ΔT_{ad}	adiabatic temperature change, K
ΔT_C	temperature difference at the cold heat exchanger, K
ΔT_H	temperature difference at the hot heat exchanger, K
ΔT_S	temperature span, K
T_C	cold reservoir temperature, K
T_H	hot reservoir temperature, K
T_R	room temperature, K
$\dot{V}$	volumetric flow rate, L/h

Greek symbols

ϵ	porosity, –
η	efficiency, –
ϕ	utilization factor, –
ρ	density, kg/m^3

Subscripts

2nd	second-law
AMR	AMR cycle
comp	component
cond	conduction
conv	convection
cy	cycle
e	external
f	fluid
fl	flow distributors
i	internal
id	ideal cycle
in	inlet of the pump
mag	magnetic
M	electric motor
max	maximum
ME	mechanical and electrical
nl	no load
no-fl	without flow distributors
out	outlet of the pump
OP	overall pumping
P	pumping
rad	radiation
s	solid regenerator material
visc	viscous

Abbreviations

AMR	active magnetic regenerator
CFD	computational fluid dynamics
COP	coefficient of performance
DTU	Technical University of Denmark
Gd	gadolinium
MCM	magnetocaloric material

AMR cycle has four basic processes: magnetization, the cold-to-hot blow, demagnetization, and the hot-to-cold blow. During magnetization, the temperature of the MCM increases, then fluid is pumped from the cold reservoir to the hot reservoir in order to reject the magnetic work to ambient. The regenerator is then demagnetized, causing a decrease in temperature and a cooling load is accepted from the cooled space by pumping fluid from the hot reservoir across the regenerator and into the cold reservoir. The system performance is mostly a function of the MCM, heat transfer characteristics in the regenerator, and cycle parameters such as frequency and fluid flow rate.

Rotary AMRs, where the magnetic field in the regenerators is varied by rotating the regenerator relative to the magnet, have been shown to operate effectively at higher cycle frequencies. Devices with stationary magnets and rotating regenerators have been demonstrated by Ref. [6,12], while systems with stationary regenerators and rotating magnets have been demonstrated by Ref. [7,13–15]. Several AMR devices have been reported recently using Gd regenerators, which is the benchmark MCM for use in AMR devices. A magnetic refrigerator using stationary regenerator beds and a rotating permanent magnet was shown to produce a maximum cooling power of 844 W at zero temperature span and 400 W at a temperature span, ΔT_S, of 8.1 K using a 0.89-kg Gd regenerator [15]. This device operated continuously with a maximum reported operating frequency of 4.7 Hz, and an exergetic equivalent cooling power of 14 W was obtained. Efficiency was not reported. A rotary magnet device using a fluid displacer to distribute the fluid flow was reported to operate at a no-load temperature span of 29 K. This device produced a cooling power of 50 W at a ΔT_S of 10 K, using a 0.11-kg Gd regenerator at a maximum operating frequency of 4 Hz [16]. A maximum COP of 1.6, which included all motor inefficiencies and drive loss, was calculated for a cooling capacity of 50 W at a ΔT_S of 2.5 K and a frequency of 1.4 Hz. The COP could be increased to 2.2 if the motor inefficiency were removed [16].

The machine evaluated in this paper was described in detail in Refs. [17–20] together with some experimental results. It consists of a novel concentric magnet assembly design [21] with a 24-bed regenerator rotating continuously in the magnet gap. Fluid flow is provided by a continuously operating gear pump and flow distributor system. The flow distributors are designed such that a minimum of eight regenerator beds are open to flow at any given time to minimize fluctuations in flow to the regenerator. This device demonstrated a maximum cooling power of 1010 W at a ΔT_S of 0.3 K and a maximum no-load ΔT_S of 25.4 K and that it absorbs a cooling power, $\dot{Q}_C$, of 100 W at a ΔT_S of 21 K [18]. A maximum operating frequency of 10 Hz was experimentally proved at a ΔT_S of 12.1 K and 200 W [20].

This paper presents experimental data, numerical results obtained using a 1D model of the AMR [22] and, for the first time, a detailed assessment of the system efficiency over a range of operating conditions. The power consumption associated with several components have been measured, and methods for improving the system performance and increasing its efficiency are suggested.