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Improvements of a room-temperature magnetic refrigerator combined with Stirling cycle refrigeration effect

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ABSTRACT

A high pressure hybrid refrigerator that combines the active magnetic refrigeration effect with the Stirling cycle refrigeration effect at room temperature is studied here. In the apparatus, a helium-gas-filled alfa-type Stirling refrigerator uses Gd sheets as the regenerator and the regenerator is put in a magnetic field varying from 0 to 1.4 T, which is provided by a Halbach-type rotary permanent magnet assembly. With an operating pressure of 5.5 MPa and a frequency of 2.5 Hz, a no-load temperature of 273.8 K was reached in 9 minutes, which is lower than that of 277.6 K for pure Stirling cycle. For the hybrid operation, cooling powers of 40.3 W and 56.4 W were achieved over temperature spans of 15 K and 12 K, respectively. For the latter case, the cooling power improves by 28.5% if compared with that exploiting only the Stirling cycle refrigeration effect.

Conception et améliorations d'un réfrigérateur magnétique à température ambiante combiné avec un effet frigorifique à cycle de Stirling

Mots clés : Réfrigérateur hybride ; Froid magnétique ; Froid à cycle de Stirling ; Performance de refroidissement ; Angle de phase

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Nomenclature

CHEX	cold end heat exchanger
COP	coefficient of performance
F	frequency [Hz]
HHEX	hot heat exchanger
HR I	first hybrid refrigerator
HR II	second hybrid refrigerator
MCE	magnetocaloric effect
PTFE	poly tetra fluoro ethylene
T	temperature [K]
T_H	hot end temperature [K]
T_L	cold end temperature [K]
$T_{H\text{-}N}$	hot end temperature without magnetocaloric effect [K]
$T_{L\text{-}N}$	cold end temperature without magnetocaloric effect [K]
$T_{H\text{-}60}$	hot end temperature at phase angle of 60 [K]
$T_{L\text{-}60}$	cold end temperature at phase angle of 60 [K]
$T_{H\text{-}a}$	hot end temperature at phase angle of a [K]
$T_{L\text{-}a}$	cold end temperature at phase angle of a [K]
a	phase angle [°]

1. Introduction

Magnetic refrigeration based on the active magnetic regenerator (AMR) is an emerging environmentally friendly technology and has the great potential to substitute vapor compression in many typical cooling applications (Gschneidner and Pecharsky, 2008). There are many configurations for an AMR device using different methods of generating the magnetic field and magnetocaloric materials in recent years (Kitanovski et al., 2015; Yu et al., 2010). Zimm et al. (1998) built a reciprocating magnetic refrigerator with superconducting magnets. They obtained a maximum cooling power of 500 W in a 5 T magnetic field using Gd as the working material. The University of Ljubljana presented its study of a reciprocating AMR testing device in the papers (Kitanovski et al., 2014; Tušek et al., 2013, 2014). In their experimental studies, different AMR geometries, consisting of gadolinium or different Curie temperatures $LaFe_{13\text{-}x\text{-}y}Co_xSi_y$ materials, were tested. Zimm et al. (2006) built a rotating-type magnetic refrigerator that used permanent magnets to provide a magnetic field of 1.5 T. Using Gd as the magnetocaloric refrigerant, a maximum temperature span of 25 K and a cooling power of 49 W over a temperature span of 0.3 K were obtained. A large-scale rotary magnetic refrigerator has been fabricated by Jacobs et al. (2014). It has produced 3042 W of cooling power at zero span and 2502 W over a temperature span of 11 K with COP > 2. Their results show quite well application potential. A rotary magnetic refrigerator prototype was built at the University of Salerno (Aprea et al., 2014, 2015, 2016). The device consisted of eight static AMR beds and a rotating magnet assembly, and its best results were a maximum temperature span of 11.9 K at the zero load and a maximum COP of 2.5 with a thermal load of 200 W. Arnold et al. (2014) designed a novel rotary magnetic refrigeration device, and using 650 g Gd spheres, a no-load temperature span of 33 K at 0.8 Hz was reported. Bahl et al. (2014) designed and constructed a magnetic refrigerator using Gd spheres as the working material and attained a maximum no-span cooling power of 1010 W and a maximum no-load temperature span of 25.4 K. Eriksen et al. (2015) designed and built a rotary AMR prototype which obtained a COP 3.1 (11.3% of the Carnot Efficiency) at a temperature span of 10.2 K and a cooling load of 102.8 W.

Meanwhile, some researchers are also investigating combining magnetic refrigeration with other refrigeration technologies to achieve a better cooling performance. A cryogenic refrigerator concept was studied using numerical simulations by Yayama et al. (2000). The concept combined the Gifford McMahon (GM) gas cooling cycle with Brayton magnetic cooling cycle and a remarkably high refrigeration power has been shown. Kim et al. (2013) presented an experimental investigation on a refrigerator hybridizing the GM type pulse tube refrigerator with AMR refrigerator. Their refrigerator reached a temperature span of about 56 K and a lowest no-load temperature of 24 K. He et al. (2013) in the present group built a hybrid refrigerator (formerly called HR I here) that combines the active magnetic refrigeration effect with the Stirling cycle regenerative refrigeration effect. In HR I setup, experiments at a gas pressure of 1 MPa and an operating frequency of 1.5 Hz with various phase angles were conducted. Using 198 g Gd sheets, a no-heat-load temperature of 276.6 K at the cold heat exchanger was achieved and cooling powers of 6 W and 10 W were achieved over temperature spans of 14.9 K and 7.9 K, respectively.

In this paper, a modified high pressure hybrid refrigerator (HR II) that combines the rotary AMR device with the Stirling cycle regenerative refrigerator is presented. The objectives of this work are to investigate different factors that affect the performance of this hybrid system.

2. Experimental setup and instrumentation

2.1. Experimental setup

The Stirling regenerative refrigeration cycle consists of four thermodynamic processes: compression process, hot to cold process, expansion process and cold to hot process. Likewise, the typical magnetic refrigeration cycle has very similar four thermodynamic processes, except that pressure swing is replaced with magnetic field swing. The four processes are: magnetization process, cold to hot flow process, demagnetization process and hot to cold flow process. By carefully coordinating the two refrigeration cycles, it is possible to generate a higher cooling performance.

A schematic diagram and photograph of the experimental setup are shown in Figs. 1 and 2. The main components of the HR II include: a compression piston with cylinder, an expansion piston with cylinder, a hot heat exchanger (HHEX), a regenerator, a cold end heat exchanger (CHEX), a thermal buffer tube and a magnet. Among them, the HHEX, the regenerator and the CHEX are shared by both the high pressure Stirling cycle refrigerator and the magnetic refrigerator. The HHEX is of rectangular fin configuration made through electrical discharge machining and uses water as the coolant. In the experimental