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Design improvements of a permanent magnet active magnetic refrigerator

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ABSTRACT

A second-generation room-temperature permanent magnet active magnetic regenerator test apparatus using Halbach arrays is described. The magnet arrays consist of three concentric cylinders. Each cylinder is constructed using 12 permanent magnet segments. The inner magnet array is stationary while the intermediate and outer arrays are designed to rotate in opposite directions so as to create a sinusoidal magnetic field waveform with a stationary field direction. The fluid flow system utilizes a novel check valve configuration so that fluid dead volumes are minimized. The system construction is modular to allow for quick replacement of material or system components. Fringing fields near the outer and inner diameters of the arrays are found to create large forces between arrays leading to large torques. Test results using 650 g of gadolinium spheres produce a no-load temperature span of 33 K at 0.8 Hz.

Amélioration de la conception d'un réfrigérateur magnétique actif permanent

Mots clés : Réfrigérateur magnétique actif permanent ; AMR cycle de froid magnétique actif

1. Introduction

The magnetocaloric effect has been extensively studied in recent years as a potential alternative to conventional cycles for refrigeration, heat pumping, and liquefaction. In theory, the active magnetic regenerator (AMR) cycle has an efficiency limit equivalent to a Carnot cycle; however, implementing the AMR cycle in a working machine is challenging due to numerous loss mechanisms and imperfect material properties. Research efforts toward better magnetocaloric refrigerant materials are important for the development of this technology. The development and characterization of prototype machine designs are also essential for improving the performance of AMR technologies.

There are many possible configurations for an AMR device using different methods of generating the magnetic field and flow waveforms (Yu et al., 2010, Roudaut et. al. 2010, Rowe, 2011). The only one way designs can be differentiated is by the amount of working material relative to the volume of permanent magnet material. Tura et al. describe a particular

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Nomenclature

B	magnetic field, T
c	specific heat, $J\,kg^{-1}\,K^{-1}$
Ex	exergy rate, W
f	frequency, Hz, s^{-1}
L	regenerator length, m
m	mass, kg
Q	heat transfer rate, W
t	time, s
T	temperature, K
V	volume, cm^3
Greek	
Λ	magnetic utility metric, mT
ε	porosity, –
τ	period, s
ϕ	utilization, –
θ	angle of rotation, degree
μ	normalized exergy metric, $W\,T^{-1}\,cm^{-3}$
Subscripts	
B	magnetic field region
b	blow
C	cold or cooling capacity
c	cycle
d	displaced
H	hot or high field
L	low field
net	net
p	constant pressure
PM	permanent magnetic material
R	regenerator
S	solid
Q	cooling power

permanent magnet device (PM I) using dual Halbach cylindrical magnets (Tura and Rowe, 2007) and have since reported on other experimental, theoretical and numerical information regarding this machine (Tura et al., 2012). Other research groups have built working room-temperature PM-AMRs with a wide range of operating parameters and performance results (Yu et al., 2010). The PM I device is an effective test apparatus which uses small amounts of material, operates at high frequency, and is easy to work with. However, performance is limited by the small volume available for refrigerant and the magnetic field waveform. To improve on some of these deficiencies, a second-generation dual Halbach test apparatus has been developed.

This paper describes the main design features of a dual Halbach-type AMR test apparatus (PM II). Design changes with respect to the PM I device are discussed as problems with the new magnet system. Design changes to increase flexibility and to improve performance are described. Experimental data using the magnets in a co-rotating mode are presented for gadolinium spheres.

2. Device design

The second-generation (PM II) design is based on the original PM I device in that the basic configuration has remained the same. Both are rotary systems that employ concentric nested Halbach arrays to generate a variable magnetic field. The regenerators are cylindrical and held stationary within the field region. Liquid heat transfer fluid oscillates through the regenerator by a piston-cylinder displacer in fixed phase with the magnetic cycle. A cut-away rendering and photograph of the new machine are shown in Fig. 1.

The most significant changes made with respect to the PM I device include the design of the magnetic field generators, the regenerator aspect ratio and the hydraulic system. Other features include a modular sub-system assembly and easily accessible regenerator core for fast material exchange. Machine sizing and operating parameters for both PM I and PM II are listed for comparison in Table 1.

2.1. *Field generator and regenerator*

The field generators of PM I consist of two assemblies of dual nested Halbach arrays where each array is composed of eight segments. The inner array rotates with respect to the stationary outer array. When the field vector within the bores of the two arrays are aligned the individual intensities of each array sum to the maximum high-field state. When the inner array is rotated by 180° the fields cancel resulting in the minimum low-field state. This is explained graphically in Fig. 2(a). With this configuration, and due to differences between the inner and outer arrays, the actual field strength at low-field is non-zero and the average strength of the low field over the half cycle is much higher than the minimum field. Also, the total field vector orientation inside the regenerator volume rotates which can induce rotational forces and eddy currents in the regenerator. These factors combine to reduce net cooling potential and efficiency.

The PM II magnetic field generator is designed to address some of these problems. The new magnet design uses three nested Halbach cylinders, each comprised of 12 segments. Increasing the number of magnet segments improves the homogeneity and strength of the magnetic field. The purpose of having three Halbachs rather than two is the ability to rotate the intermediate and outer arrays in opposing directions as shown in Fig. 2(b). This counter-rotating feature is the method for producing a sinusoidal field waveform and a stationary field vector. The inner array is stationary and produces approximately one half of the total high-field intensity. The intermediate and outer arrays each produce approximately one-quarter of the high-field intensity. Analogous to the dual array design, the three field vectors sum to full strength when their bore vectors are aligned and cancel when the intermediate and outer arrays are rotated 180° with respect to the inner array. The intermediate and outer arrays can also be co-rotated in the same direction which produces essentially the same waveform as the magnet design in PM I. This allows for experimental comparisons between field waveforms.

The magnetic interactions of the three arrays were modeled using *COMSOL Multiphysics*. The simulated magnetic