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Experimental and numerical results of a high frequency rotating active magnetic refrigerator

J.A. Lozano [a,b,*], K. Engelbrecht [a], C.R.H. Bahl [a,**], K.K. Nielsen [a],
J.R. Barbosa Jr. [b], A.T. Prata [b], N. Pryds [a]

[a] *Department of Energy Conversion and Storage, Technical University of Denmark (DTU), Frederiksborgvej 399, DK-4000 Roskilde, Denmark*
[b] *POLO – Research Laboratories for Emerging Technologies in Cooling and Thermophysics, Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Florianopolis, SC 88040-900, Brazil*

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ABSTRACT

Experimental results for a recently developed prototype magnetic refrigeration device at the Technical University of Denmark (DTU) were obtained and compared with numerical simulation results. A continuously rotating active magnetic regenerator (AMR) using 2.8 kg packed sphere regenerators of gadolinium (Gd) was employed. With operating frequencies up to 10 Hz and volumetric flow rates up to 600 L h^{-1}, the prototype has shown high performance and the results are consistent with predictions from numerical modelling. Magnetocaloric properties of the Gd spheres were obtained experimentally and implemented in a one-dimensional numerical AMR model that includes also the parasitic losses from the prototype. The temperature span for a thermal load of 200 W as a function of frequency was measured and modelled. Moreover, the temperature span dependence on the cooling capacity as a function of cycle frequency was determined. A detailed study of these parasitic losses was carried out experimentally and numerically.

Réfrigérateur magnétique actif rotatif à haute fréquence: résultats expérimentaux et numériques

Mots clés : Régénérateur actif magnétique ; Froid magnétique ; Expérience ; Modélisation numérique ; Analyse des pertes parasitiques

1. Introduction

It has been suggested that high frequency AMR devices will allow for higher cooling power per mass of magnetocaloric material and temperature spans (Yu et al., 2010). Most of the developed magnetic refrigerators work with permanent magnets and gadolinium (Gd) as magnetocaloric regenerative bed. Okamura et al. (2007) obtained a maximum cooling

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* *Corresponding author*. Tel.: +55 48 3721 7970; fax: +55 48 3234 5166.
** *Corresponding author*. Tel.: +45 46775491; fax: +45 46775858.
E-mail addresses: jaime@polo.ufsc.br, jaimealozano@gmail.com (J.A. Lozano), chrb@dtu.dk (C.R.H. Bahl).

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Nomenclature

Roman

c	specific heat, J kg^{-1} K^{-1}
H	magnetic field, A m^{-1}
M	magnetization, A m^{-1}
N	demagnetization factor, –
Δs_{mag}	magnetic entropy change, J kg^{-1} K^{-1}
T	temperature, K
ΔT_{ad}	adiabatic temperature change, K
$\dot{W}$	power, W

Greek

ε	porosity, –

Subscripts

0	zero field
appl	applied
free	without the valves
fric	friction loss
H	hot end
int	internal
sys	system with the valves

Abbreviations

AMR	Active magnetic regenerator
DTU	Technical University of Denmark
Gd	Gadolinium
MFT	Mean field theory

capacity of 140 W kg^{-1} at 0.5 Hz and a cooling capacity of 40 W kg^{-1} with a temperature span of 5 K with a magnetic field of 1.1 T. Tura and Rowe (2011) achieved a cooling capacity of 455 W kg^{-1} at 10 K span and no thermal load temperature span of 29 K with a magnetic field of 1.4 T and a maximum operating frequency of 4 Hz. Russek et al. (2010) demonstrated a maximum zero-span cooling capacity of 948 W kg^{-1} and a cooling capacity of 449 W kg^{-1} with a temperature span of 10 K at 4.7 Hz employing a magnetic field of 1.4 T.

Experimental results for the device presented in this work for cycle frequencies up to 10 Hz show that the performance begins to degrade at higher frequencies with the optimum operating frequency near 2 Hz. In order to understand the results, the system is studied using a 1D AMR model developed by Engelbrecht et al. (2007). During the modelling phase of this work, focus was put on using accurate magnetocaloric properties as an input for the model, understanding frequency-dependent parasitic losses and understanding thermal parasitic losses. Magnetocaloric properties were measured on the commercial grade gadolinium taking into account the demagnetizing field in the measured sample. In the current experiments, frequency-dependent losses were studied while keeping all other operating conditions constant and the frequency was varied. The temperature span of the device decreases with increasing cooling power, allowing cooling curve experiments to be used to study thermal losses. The loss analysis is used to suggest design improvements.

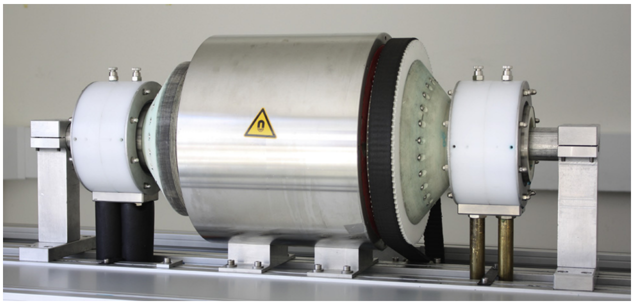

Fig. 1 – Rotating active magnetic refrigerator at DTU.

2. Experimental

Experiments on a rotating active magnetic refrigerator device at DTU (Fig. 1) working with a 4-pole static permanent magnet and 24 rotating regenerator beds were carried out at frequencies up to 10 Hz. The permanent magnet has a peak flux magnetic density of 1.24 T in the high field regions and it is close to 0 T in the low field regions (Bjørk et al., 2010). The regenerator beds consist of 99.99% pure commercial grade Gd spheres sieved to diameters between 0.25 and 0.8 mm and packed with a porosity of 0.36. The dimensions of the beds are 100 mm in the flow direction and a cross section of 12.5 mm width by 18.6 mm height. Each bed is connected to the valve by two separate channels dedicated to flow in and out of the bed, respectively. Thus, oscillating flow in the system is eliminated ensuring that losses due to mixing of fluid at different temperatures are avoided. The beds are rotated inside the magnet by an electrical motor with a variable rotation speed that is controlled by a frequency inverter. The volumetric fluid flow rate is manually controlled by a bypass valve at the outlet of a constant flow rate pump. At the cold end, the thermal load is simulated by an electric resistance heater, and the hot end temperature, T_H, is controlled by a heat exchanger in contact with a water chiller. More details on the design and operation of the device are presented in Bahl et al. (2011, 2014), Engelbrecht et al. (2012) and Lozano et al. (2013).

In this work, two different sets of experiments were carried out. First, the temperature span as a function of the frequency with a constant thermal load of 200 W was investigated. Then, the temperature span as a function of the cooling capacity at different frequencies was examined. The experimental results were compared with numerical results from a one-dimensional numerical model described in Engelbrecht et al. (2007). The model was modified to simulate the conditions of this experimental device. A packed sphere bed correlation (Kaviany, 1995) was employed for heat transfer in the regenerator beds. For modelling purposes, the ambient temperature was assumed constant at 295 K, which is a good approximation of the room temperature during the experiments.

The Gd spheres were characterized by a LakeShore 7407 Vibrating Sample Magnetometer (VSM) and a custom-built Differential Scanning Calorimeter (DSC) described in