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Design and experimental tests of a rotary active magnetic regenerator prototype

*D. Eriksen**, *K. Engelbrecht, C.R.H. Bahl, R. Bjørk, K.K. Nielsen, A.R. Insinga, N. Pryds*

Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark

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ABSTRACT

A rotary active magnetic regenerator (AMR) prototype with efficiency and compact design as focus points has been designed and built. The main objective is to demonstrate improved efficiency for rotary devices by reducing heat leaks from the environment and parasitic mechanical work losses while optimizing the utilization of the magnetized volume. Heat transfer calculations combined with 1D AMR modeling have revealed the necessity for an insulating air gap between magnet and regenerator when designing for high efficiency. 2D finite difference AMR modeling capturing the interplay between heat transfer fluid flow and an inhomogenous time-varying magnetic field in the individual regenerator beds has been used in the design process. For one operating point a COP of 3.1 at a temperature span of 10.2 K and a cooling power of 103 W were measured. Major issues limiting the performance have been identified and improvements are outlined for future work.

Conception et essais expérimentaux d'un prototype de régénérateur rotatif magnétique actif

Mots clés : Froid magnétique ; Conception ; Modèle ; Efficacité ; Expérimentale

1. Introduction

Magnetic refrigeration is a promising alternative to conventional vapor compression technology. It is based on the magnetocaloric effect in ferromagnetic materials, hereafter referred to as magnetocaloric materials (MCM). As a consequence of this effect, the temperature of an MCM will, under adiabatic conditions, change as a response to a change in an applied magnetic field, such that the temperature will increase when the field is increased and vice versa. The effect, which is most pronounced in the vicinity of the Curie temperature of the material, can be utilized in heating or cooling devices; see e.g. Smith et al. (2012). In 1982 Barclay demonstrated a cooling device based on a concept where the MCM itself was used to regenerate heat which was transported between a cold and a hot reservoir via a heat transfer fluid; see Barclay, (1982). Since then this principle, known as the active

* *Corresponding author.*
E-mail address: daer@dtu.dk (D. Eriksen).
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Nomenclature

Acronyms

AMR	active magnetic regenerator
COP	coefficient of performance
GFRE	glass fiber reinforced epoxy
HHEX	hot heat exchanger
MCM	magnetocaloric material

Symbols

B	magnetic flux density (T)
c_f	fluid heat capacity (J kg K^{-1})
c_s	MCM heat capacity (J kg K^{-1})
f	AMR operating frequency (Hz)
m_f	mass of fluid flowing through a bed during one blow period (kg)
m_s	mass of MCM in a bed (kg)
$\dot{Q}$	cooling power (W)
$\dot{Q}_{Loss}$	total heat loss (W)
T	temperature (K)
T_C	cold side temperature (K)
T_H	hot side temperature (K)
T_∞	ambient temperature (K)
ΔT	temperature span (K)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
$\dot{W}$	work input (W)
$\dot{W}_{mag}$	magnetic work (W)
$\dot{W}_{pump}$	pump work (W)
ϕ	utilization factor (–)

magnetic regenerator (AMR) cycle, has been used in an increasing number of devices with the aim of making magnetic refrigeration near room temperature a competitive alternative to conventional vapor compression technology. For a more comprehensive description of the AMR cycle; see Engelbrecht et al. (2012). In general, magnetic refrigeration has the advantage of not using gaseous refrigerants. The absence of a compressor opens the possibility of silent operation. Furthermore, some of the losses associated with vapor compression are avoided, which may lead to a higher efficiency. Already in 1998, COPs above 6 were obtained at cooling powers exceeding 500 W, see Zimm et al. (1998). However, this device used a liquid helium cooled superconducting 5 T magnet and the power used for the magnet itself was not included in the COP calculation. Superconducting magnet AMRs are not economically viable with the present technology. Over the years, permanent magnets have been used in an increasing number of published devices; see e.g. Bjørk et al. (2010a) and it seems that devices based on rotary concepts with permanent magnets have a good potential for high performance; see e.g. Yu et al. (2010).

A design with a rotary magnet structure and regenerator with reciprocating flow provided by a diplacer has produced high temperature spans, e.g. a temperature span of 29 K has been achieved by Tura and Rowe (2011). Recently, a temperature span of 33 K was demonstrated for an improved version of the same device; see Arnold et al. (2014). In other devices, a compartmentalized regenerator and a magnet system are mechanically rotated relative to each other. The flow system in these devices is of major importance. By applying valve systems to control the heat transfer fluid flow, it is possible to achieve a continuous flow circuit driven by a pump to transport heat to and from the regenerator while ensuring a reciprocating flow in the regenerator compartments; see eg. Tusek et al. (2010), Engelbrecht et al. (2012) and Jacobs et al. (2014). By carefully balancing magnetic forces and fluid flow, a smooth and efficient operation may be obtained. However, during each AMR cycle, the work performed on the regenerator is negative during magnetization and positive during demagnetization. In order to obtain efficient operation which is comparable to numerical AMR model predictions, the work performed by the regenerator during magnetization has to be utilized. In a multi bed rotary AMR configuration, such as the one presented in this paper and the earlier device presented by Engelbrecht et al. (2012), this is done by always having beds moving into the magnetic field, thus contributing to the driving torque, while others are moving out. However, a poorly mechanically and magnetically balanced configuration will result in large torque fluctuations and drive train losses. How to achieve an optimum configuration in this regard is not well understood. With the presented device, an improved drivechain is realized by minimizing the thickness of the walls separating the regenerator beds in order to obtain a more even distribution of MCM and hence a more smooth driving torque. Furthermore, an odd number of regenerator beds are combined with a two pole magnet in order to avoid magnetic equilibrium positions during rotation.

Although much work has been conducted over the years to improve the efficiency of the devices, there are still significant technical challenges that need to be overcome. Recently, it was shown that care should be taken to reduce a number of parasitic losses associated with the overall COP of an AMR system; see Lozano et al. (2013). In this paper we report a compact new regenerator design, bringing these losses down. In the process, detailed numerical AMR modeling has been used as a design tool to address heat loss issues and the inhomogeneous magnetic field in regenerator compartments.

2. System design

The AMR device consisting of a regenerator, a magnet and a flow control system is shown in Fig. 1. For the device presented here, the MCM is confined in a cylindrical regenerator which is divided into eleven compartments. The regenerator is fixed on the outside of an iron core that is a part of the magnet system. The core consists of laminated plates of iron and glass fiber reinforced epoxy (GFRE) in order to minimize losses due to eddy currents and thermal conduction in the axial direction. On the upper and lower sides of the regenerator, valve arrangements ensure reciprocating flow of the heat transfer fluid in the regenerator compartments and a continuous, unidirectional flow in the external flow circuit. Special