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Thermal investigations of an experimental active magnetic regenerative refrigerator operating near room temperature

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ABSTRACT

In this paper, numerical and experimental investigations on a magnetic refrigeration device based upon the active magnetic regeneration (AMR) cycle operating near room temperature are presented. A numerical 1D model based on the transient energy equations is proposed for modelling the heat exchange between the magnetocaloric material and the carrier fluid in the regenerator bed. The validity of 1D AMR-numerical model is investigated through the recently developed magnetic cooling demonstrator by Clean Cooling Systems SA (CCS) at the University of Applied Sciences of western Switzerland (HES–SO). The obtained results including the temperature span, the coefficient of performance and the cooling power are presented and discussed. In general, good agreements have been noted between the experimental and numerical results.

Etudes thermiques d'un réfrigérateur magnétique actif expérimental fonctionnant à température ambiante

Mots clés : Réfrigérateur magnétique actif ; Simulation numérique ; Effet magnétocalorique ; Analyse thermique

1. Introduction

The concept of magnetic refrigeration is based on the magnetocaloric effect (MCE), which consists in the entropy change of a magnetic material when adiabatically magnetized or demagnetized, resulting respectively in heat rejection or absorption of magnetic material. The phenomenon was discovered by Warburg in 1881 on iron. Later, in 1976, Brown

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Nomenclature

Standard

A	Heat transfer area, m^2
B	Magnetic field, T
C	Specific heat, J (kg K)$^{-1}$
COP	Coefficient of performance, –
D_h	Hydraulic diameter, m
F	Force, N
h	Coefficient of convection heat transfer, W K^{-1} m^{-2}
K	Thermal conductivity, W (K m)$^{-1}$
L	Length, m
MCE	Magnetocaloric effect, K
$\dot{m}_f$	Mass-flow rate, kg s^{-1}
Nu	Nusselt number, –
P	Pressure, Pa
$\dot{Q}$	Power, W
T	Fluid temperature, °C
t	Time, s
V	Volume, m^3
W	Work, J
x	Spatial coordinate, m

Greek

α	Porosity, –
λ	Friction coefficient, –
ρ	Density, kg m^{-3}
η	Pump efficiency, –
θ	Solid temperature, °C
τ	Time period, s

subscripts

C	Cold
e	Thickness
f	Fluid
H	Hot
M	Magnetic
mcm	Magnetocaloric material
P	Pump
r	Regenerator
TDMA	The tridiagonal matrix *algorithm*

successfully demonstrated the feasibility of a magnetic refrigerator operating near room temperature. His demonstrator was indeed able to decrease the temperature from 310 K to 240 K using a 7 T superconducting magnet and Gadolinium as a refrigerant. The magnitude values of MCE are about 1–8 K per 1–2 T of magnetic field change for typical ferromagnets near their Curie temperature (Gschneidner et al., 2005). Hence practical magnetic devices are based on regenerative thermodynamic cycles. Among the cycles that have been extensively studied and built in experimental magnetic refrigerators, is the active magnetic regeneration (AMR) cycle (Barclay, 1982). Several numerical methods to predict the performance of the AMR has been investigated previously (Smaïli and Chahine, 1998; Allab et al., 2005; Smaïli et al., 2011; Nielsen et al., 2011; Aprea et al., 2011; Kawanami et al., 2011; Roudaut et al., 2011). These researches, however, were performed with different conditions and assumptions. For more applications of the magnetic refrigeration near room temperature Yu et al., 2010 and Romero Gómez et al., 2013 explain in detail recent developments on prototypes. In this paper, the validity of 1D AMR-numerical model is investigated through the recently developed magnetic cooling demonstrator by Clean Cooling Systems SA (CCS) at the University of Applied Sciences of western Switzerland (HES–SO). The obtained results including the temperature span, the coefficient of performance and the cooling power are presented and discussed. The capability of the numerical model of predicting consistent results has been shown.

2. Description of AMR device

Fig. 1 shows a schematic of an AMR device, which is constituted of (i) a two block AMR bed (i.e. solid magnetic material which can act as refrigerant and regenerator media), (ii) a blower to force the flow throughout the regenerator at convenient velocity, (iii) a circulating heat transfer fluid (i.e. in this study water). The AMR cycle consists of four processes, namely, magnetization/demagnetization steps, by application and removal of a magnetic field (through adiabatic or isothermal steps; in this study, only adiabatic steps, are considered), as well as cold and hot blows (i.e. cooling and heating the circulating fluid).

The AMR thermodynamic cycle can be described as follows:

- *Adiabatic magnetization process*: The bed is magnetized adiabatically when the magnetic field increases from zero to B, without flow.
- *Hot blow at applied field*: The fluid is then forced by the pump to move from the cold to the hot ends, entering the bed, the fluid temperature rises along the flow direction, and it leaves the bed at the average hot outlet temperature, $T_{av,H}$, higher than the hot reservoir temperature, T_H. Passing through the hot heat exchanger, the fluid temperature drops to T_H by rejecting an amount of heat rate $\dot{Q}_H$
- *Adiabatic demagnetization process*: By reducing magnetic field from given strength B to zero with no flow.

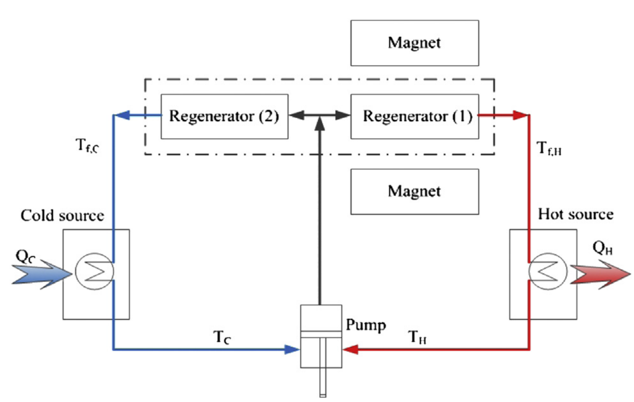

Fig. 1 – Schematic diagram of the active magnetic regeneration refrigerator setup built at HES-SO.