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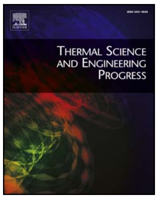

Energy performances and numerical investigation of solid-state magnetocaloric materials used as refrigerant in an active magnetic regenerator

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ABSTRACT

Magnetic is the most diffused, developed and evolved technique among solid-state cooling, a class of ecofriendly refrigeration systems employing solid-state caloric materials. Active Magnetic Regenerative refrigeration cycle (AMR), a Brayton based thermodynamical cycle, is the benchmark cycle for magnetic refrigeration. This paper aims to provide a map of energetic performances of an Active Magnetic Refrigerator by the development of a two-dimensional numerical model, whom replies the behaviour of one of the regenerators mounted in 8Mag, the experimental prototype of the first Italian Rotary Permanent Magnet Magnetic Refrigerator (RPMMR), mounting gadolinium. To this hope, through the model a performance map has been delineated and it has been investigated the behaviour of the AMR regenerator, mounting gadolinium, in order to explore the limit conditions of prototype working, in terms of cold-hot heat exchanger range, fluid flow rate and frequency. In a second step, the performance map has been extended to other MCE materials, possible candidates for magnetic refrigeration at room temperature.

1. Introduction

We live in a world where we recognize the climate changing: global warming increases day after day, earth has been getting warmer and glaciers melts. There is an indisputable evidence that human activities, in particular the burning of fossil fuels and the resulting increment of greenhouse gases in the atmosphere, have accelerated the warming trend [1]. Refrigeration occupies 20% of the overall energy consumption pie and most of the actually operating plants are based on vapor compression refrigeration whom employs refrigerants carrying relevant intrinsic contribution in global warming (high GWP) [2–6]. In the last decades many measures have been adopted, observing the points prescribed by Montreal [7] and Kyoto [8]. Protocols about gas emission but now is time to change: the traditional concepts of refrigeration and air conditioning must give up the step to emerging of ecological technologies [9]. The main hope is that, in a not so far away future, solid-state refrigeration [10,11] could substitute vapor compression. Solid-state refrigeration is based on caloric effect detected in some ferrocaloric solid-state materials that, due to changes in applied driving field, show reversible thermal changes parameterized via adiabatic temperature change and isothermal entropy change. Solid-state cooling is mentioned to indicate a class of refrigeration containing a number of techniques particularized by the nature of the driving field [12–15]. If the driving fields are the electrical or magnetic fields, we are in presence of electrocaloric [16–18] or magnetocaloric [19–21] refrigeration, respectively, two really promising techniques that could constitute a real chance to overcome vapor compression refrigeration. Magnetic refrigeration is based on the Active Magnetic Regenerative refrigeration cycle (AMR) [22], descending from Brayton thermodynamical cycle. It is constituted by four sequential processes: two adiabatic (magnetization-demagnetization) and two isofield, where the heat transfer fluid crosses the regenerator. AMR regenerator is the core of a magnetocaloric cooling device since it works both as refrigerant and regenerator. The physical phenomenon, where magnetic refrigeration is based on, is called MagnetoCaloric Effect (MCE) [23] and it takes place in ferromagnetic materials. MCE couples the magnetic moments of magnetocaloric materials with an external magnetic field: due to an increment of the field under adiabatic condition, one can observe a temperature increment into the magnetocaloric materials, since the moments align themselves. Once the field is removed, magnetic moments disposition become random and a decrement of the material's temperature is registered. The benchmark material for magnetic refrigeration at room

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Nomenclature

B	magnetic induction, T
C	specific heat, J kg^{-1} K^{-1}
COP	Coefficient of Performance
H	magnetic field strength, A/m
k	thermal conductivity, W m^{-1} K^{-1}
m	mass flow rate, kg s^{-1}
M	magnetization, A/m
p	pressure, Pa
Q	thermal energy, J
S	entropy, J K^{-1}
s	specific entropy, J kg^{-1} K^{-1}
T	temperature, K
t	time, s
u	longitudinal fluid velocity, m s^{-1}
v	orthogonal fluid velocity, m s^{-1}
W	work, J
x	longitudinal spatial coordinate, m
y	orthogonal spatial coordinate, m

Greek symbols

Δ	finite difference
η	isoentropic efficiency
θ	period of the whole AMR cycle, s
μ	dynamic viscosity, kg m^{-1} s^{-1}
μ_0	vacuum magn. perm. T m A^{-1}
ν	cinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ	period of each phase of the cycle, s

Subscripts

ad	adiabatic
CF	cold-to-hot flow process
D	demagnetization process
F	fluid
HF	hot-to-cold flow process
M	magnetization process
T	constant temperature

temperature is gadolinium [24–26], belonging to rare-earth group of periodic table, since it exhibits a peak of MCE at 294 K.

This paper aims to provide a map of energetic performances of an AMR refrigerator by the development of a two-dimensional numerical model whom replies the behavior of one of the AMR regenerators mounted in 8Mag, the experimental prototype of the first Italian Rotary Permanent Magnet Magnetic Refrigerator (RPMMR) [27]. In particular, after validating the model at zero-load and iso-load, the model aims to identify the "limit conditions" to which the prototype can operate providing satisfactory results. Moreover, such limit conditions are identified in terms of frequency, range of temperature, temperature of hot heat exchanger and volumetric flow rate. Additionally, the investigation has been extended to other magnetocaloric materials manifesting a relevant MCE at room temperature.

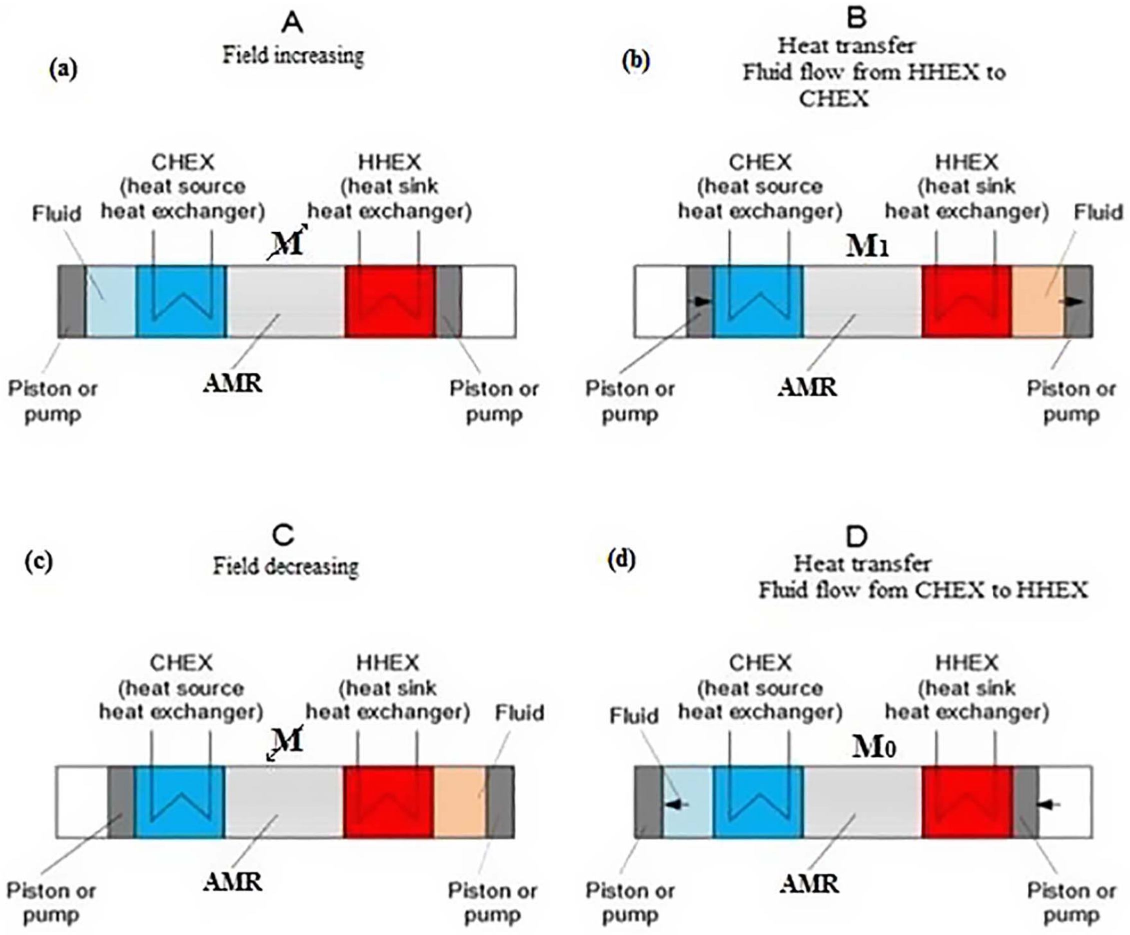

Fig. 1. Processes of AMR cycle: a) magnetization; b) cold-to-hot fluid flow; c) demagnetization; d) hot-to-cold fluid flow.