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Modeling of in-vehicle magnetic refrigeration

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ABSTRACT

A high-performance magnetic refrigeration device is considered as a potential technology for in-vehicle air conditioners in electric vehicles. The high power consumption of a conventional air conditioner in an electric vehicle has considerable impacts on cruising distance. For this purpose the demands on cooling power density, temperature difference between hot and cold side, transient properties and COP, will be high. In this paper the potential to reach these demands are explored for two technologies, firstly a conventional AMR device and secondly a novel magnetocaloric device based on control of the axial thermal conductivity.

Modèlisation du froid magnétique pour véhicules

Mots clés : Régénérateur magnétique actif ; Modèle numérique ; Froid magnétique ; Interrupteur thermique

1. Introduction

Numerical simulations have been performed to explore the feasibility of in-vehicle magnetic refrigeration. An ambitious goal of comparatively high cooling power density and large temperature difference between the hot and cold sides has been set. The goal has been deemed necessary to place magnetic refrigeration as a viable option for electrical vehicles. In order to reach the goal an open-minded parameter search has explored the limitations of multiple systems, both conceptual and well-established. One set of simulations has been made stretching the parameter space of a conventional AMR device (Bahl et al., 2008) and another has been made considering a novel solid-state approach (Tasaki et al., 2012). Extreme material properties have been invoked to fix performance boundaries and aid to find the most promising development paths. Both sets of simulations uses algorithms based on a 1D approach (Engelbrecht et al., 2005) employ the use of Curie

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Nomenclature

Roman

ΔT_{ad}	Adiabatic temperature change K
Q_C	Heat removed from reservoir on cold side J
Q_H	Heat transferred to reservoir on hot side J
W	Work done by cooling device J
T	Temperature K
S	Entropy J (kg K)$^{-1}$

Greek

τ	Duration of operation cycle s
τ_1	Duration with no fluid flow s
τ_2	Duration with fluid flow s

Abbreviations

AMR	Active Magnetic Regenerator
COP	Coefficient of performance
MFT	Mean Field Theory
TS	Thermal Switch
MCM	Magnetocaloric material
Gd	Gadolinium

temperature graded magnetocaloric materials stressing the importance of accurate control of the Curie temperature in order to employ multiple materials in reaching the goal. The main factors influencing the performance in both approaches have been studied and compared. The focus has been on variations of thermal conduction and thermal convection as it is recognized in the field to represent an important bottleneck (Kitanovski and Egolf, 2010). Kitanovski and Egolf (2010) suggest the use of thermal switches (TS) for thermal control. In this paper the concept of a material with a thermal conductivity switchable between 0 and 400 W/K/m is used. Examples of thermal switches between two surfaces can be the breaking and making of a physical contact between the surfaces or moving a conducting fluid in and out of a thin crevasse between the surfaces. A third example is Peltier elements (Tomc et al., 2013).

The ambitious goal has been set to obtain significant cooling power at a temperature span of 60 °C. The high temperature span will ensure sufficient temperature difference between ambient temperature and heat exchangers to give cooling in extremely hot environments and still run the heat exchangers efficiently. Experimental results with conventional compression cooling will typically give ~1–2 kW cooling in this condition with a COP of ~1–2 depending on operation conditions (Joudi et al., 2003) the figures demonstrate the need for more efficient units to be used in electrical vehicles.

1.1. Model

The work presented in this paper models two different designs for a magnetic cooling device. Firstly model V, a conventional AMR design using parallel plate regenerators and an aqueous solution as heat transfer fluid. Secondly model D, a novel design proposed by Kitanovski and Egolf (2010) and further developed by Nissan (Tasaki et al., 2012) utilizing the conceptual properties of thermal switches to avoid the use of a heat transfer fluid.

For both models a graded magnetocaloric material (MCM) has been used. Since the study intends to explore and compare the nature of the two regenerator configurations the material properties have been taken from the MFT model (Morrish, 1965; Petersen et al., 2008). The high temperature difference makes a single material regenerator unfeasible (Nielsen et al., 2010). Instead of just using an arbitrary higher number of materials a perfectly graded MCM has been implemented. A similar approach was used by Bjørk et al. (2011) although with a ΔT_{ad} constant in temperature. In this study each numerical node in the material was assigned a Curie temperature corresponding to its temperature. The temperature of a node was found from its position and a linear thermal profile between the heat exchangers. The temperatures of the hot and the cold heat exchangers are 308 K and 248 K respectively.

The 1D algorithm used in this study has repeatedly been validated in literature for this type of AMR cycle (Engelbrecht, 2008; Engelbrecht and Bahl, 2010; Lozano et al., 2013). It represents the regenerator by nodes consisting of either fluid or MCM. The nodes correspond to the center of regularly spaced divisions of the regenerator. MCM nodes are thermally coupled with neighbor MCM nodes and a single corresponding fluid node. The fluid nodes are thermally coupled to a single MCM node and the neighbor fluid nodes. The heat is exchanged by conduction between MCM nodes and by conduction from dispersion in the fluid. At the heat exchangers the MCM interact by conduction and the fluid entering the heat exchanger is assumed to obtain perfect thermal equilibrium with the temperature of the heat bath before the fluid reenters the regenerator. The algorithm uses implicit calculations of temperature for all nodes. This makes it an efficient method for the parameters used in this study which results in fast and large temperature fluctuations. Pressure drop is included in the model based on the hydraulic diameter of the flow channels and the transient velocity of fluid flow. From the fluid flow the pump work during the cycle is calculated.

1.2. Model V

This model has the MCM in the form of parallel plates and water is used as the heat transfer fluid. The operation of the AMR cycle consists of 4 parts lasting a total time, τ: 1. The MCM is magnetized, 2. Hot blow, the fluid is pushed from the cold to the hot reservoir, 3. The MCM is demagnetized, 4. Cold blow, the fluid is pushed from the hot to the cold reservoir. Magnetization and Demagnetization occur linearly and lasts an equal time τ_1. The two blows also last an equal time τ_2. The length the fluid is pushed is characterized by its ratio to the length of the MCM.

The study has the aim of exploring the boundaries of performance. It is recognized that thermal contact to the heat transfer fluid plays an important role in the performance of an AMR device (Dragutinovic and Baclic, 1998). In the pursuit of increasing the thermal contact the influence of the plate surface has attracted the attention of research (Ciofalo et al.,