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Active magnetic regenerators implemented as a magnetocaloric heat pump for residential buildings

Hicham JOHRA[(a)], Konstantin FILONENKO[(b)], Per HEISELBERG[(a)], Christian T. VEJE[(b)], Stefano DALL'OLIO[(c)], Kurt ENGELBRECHT[(c)], Christian R. H. BAHL[(c)]

[(a)]Aalborg University, Division of Architectural Engineering, Department of Civil Engineering Thomas Manns Vej 23, DK-9220 Aalborg ¯st, Denmark, hj@civil.aau.dk

[(b)]University of Southern Denmark, Center for Energy Informatics Campusvej 55, DK-5230 Odense M, Denmark

[(c)]Technical University of Denmark, Department of Energy Conversion and Storage Frederiksborgvej 399, DK-4000 Roskilde, Denmark

ABSTRACT

The main objective of the ENOVHEAT project is to develop, build and test the prototype of an innovative and efficient heat pump system based on the active magnetic regenerator technology and to demonstrate that it can be used for building space heating applications. With a maximum COP of 3.93 and a nominal useful heating power output of 2600 W, the ENOVHEAT Gadolinium magnetocaloric heat pump can be integrated into a low-energy house with a vertical borehole ground source heat exchanger and a radiant under-floor heating system within a single hydronic loop. It is able to provide for the dwelling's space heating needs under Danish winter conditions. Moreover, a control strategy for heat energy storage in the indoor environment can be employed to optimize the MCHP operation and reach seasonal COPs of up to 3.51. However, the layered $La(Fe,Mn,Si)_{13}H_y$ prototype is currently not suitable for such application.

Keywords: Magnetocaloric heat pump, magnetic heating, active magnetic regenerator, innovative heating system, building heating energy flexibility controller.

1. INTRODUCTION

100 years ago, the magnetocaloric effect (MCE) was discovered by Weiss and Piccard (1918). A couple of decades later, the MCE was commonly used as a standard cooling method to achieve absolute temperatures below 1 K (Giauque and MacDougall, 1935). The magnetic cooling technology for near room-temperature applications gained popularity after Barclay and Steyert (1985) developed the active magnetic regenerator (AMR) cycle. The cooling/heating thermodynamic cycle for heat transfer is thus generated from the reversible MCE of the materials used as solid refrigerant and regenerator which is alternately magnetized and demagnetized (Smith et al., 2012).

In recent years, several research teams have built and tested different AMR prototypes. Engelbrecht et al. (2012) reported a maximum cooling capacity of 1010 W and a 25.4 K no-load temperature span for a rotary AMR device. The magnetic cooling device of Okamura and Hirano (2013) was operating at a COP of 2.5 with a 5 K temperature span. The prototype of Jacobs et al. (2014) performed 2502 W of cooling power with a COP above 2 and a temperature span of 12 K. Eriksen et al. (2016) presented a cooling device reaching 81.5 W of cooling capacity with a COP of 3.6 and a temperature span of 15.5 K.

AMR-based systems have a great potential for high COP because of the reversible nature of the MCE. In addition, this technology has the advantage of not employing toxic or greenhouse gases, can operate with low level of vibration and noise, and presents the possibility for recycling its components (Smith et al., 2012). However, magnetic heating/cooling has yet to prove its competitiveness against conventional vapour-compression heat pump technologies. To that matter, the ENOVHEAT project (Bahl, 2015) aims at demonstrating that a magnetocaloric heat pump (MCHP) can be integrated in a building and provide for its indoor space heating needs. This article presents a numerical investigation carried out for the ENOVHEAT project. Firstly, the magnetic heating system and its integration in a residential building are described. The performances of two types of magnetocaloric material (MCM) and two different control strategies for the MCHP are then compared. Finally, a conclusion and suggestions for further research close the article.

2. MAGNETOCALORIC HEAT PUMP SYSTEM

2.1. Characteristics of the magnetocaloric heat pump

The magnetocaloric heat pump prototype developed by the ENOVHEAT project is a rotary active magnetic regenerator system (see Figure 1). The vertical stator comprises 13 active magnetic regenerators mounted on an iron ring. The vertical rotor is composed of a two-pole magnet assembly attached to a shaft which is connected to an electrical motor. The MCM is placed as packed bed spheres inside the trapezoidal shaped–cassette regenerators. The rotation of the magnets (rotation frequency ranging from 0.5 Hz to 4 Hz) creates a varying magnetic field (maximum value of 1.46 Tesla) in the regenerators which alternately magnetizes and demagnetizes the MCM (Johra et al., 2018).

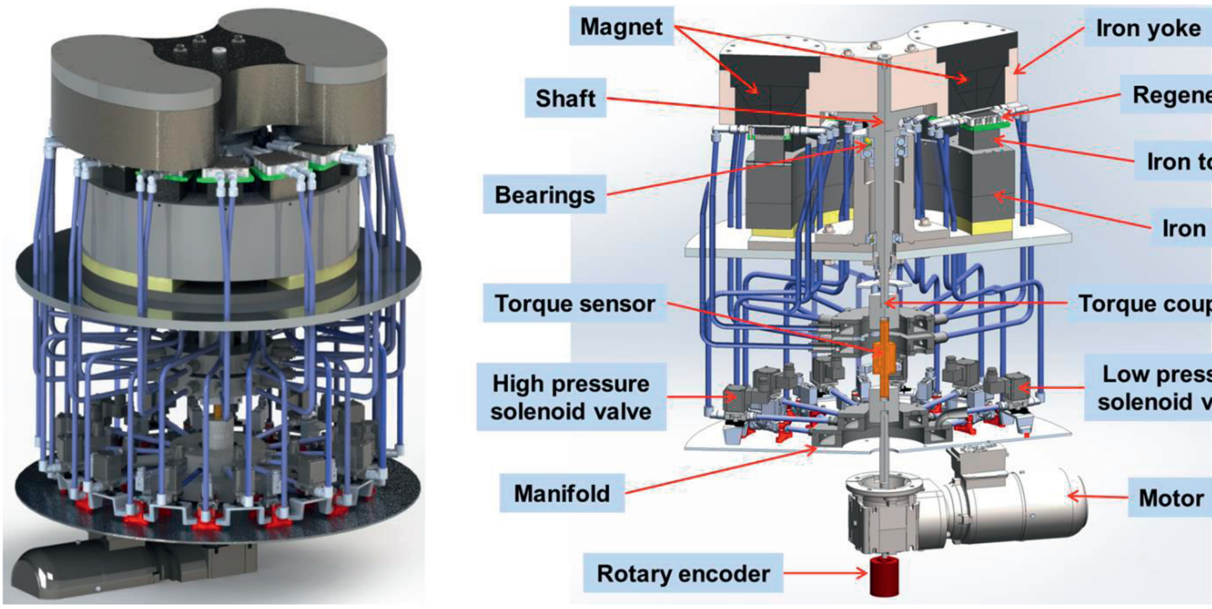

Figure 1: Full view CAD model (left) and detailed description (right) of the magnetocaloric heat pump prototype of the ENOVHEAT project: "MagQueen"

The 13 regenerators are connected to 2 manifold collectors and 2 manifold distributors, one of each for the cold side (heat source) and similarly for the hot side (heat sink). A set of 26 synchronized valves allows bi-directional flow of the heat transfer fluid (20%vol ethylene glycol; 80%vol water) through the individual MCM packed bed spheres regenerators (Johra et al., 2018).

2.2. The magnetocaloric materials

Two types of MCMs are modelled in this numerical study. The first one is Gadolinium (Gd), which is considered as the reference for the MCE at room-temperature (Smith et al., 2012). The Gadolinium MCHP contains 2.8 kg of MCM. However, the abundance of Gadolinium in the Earth's crust is limited (Taylor, 1964). As an alternative to Gadolinium, intermetallic compounds such as $La(Fe,Mn,Si)_{13}H_y$ have attracted significant attention. These compounds can exhibit an appreciable MCE at near-room-temperature and are composed of chemical elements which are more abundant and low-cost (Smith et al., 2012). Moreover, the Curie temperature of these MCMs can be finely tuned to optimize the MCE inside the regenerators according to the inherent temperature gradient inside the latter (graded or multi-layered regenerator) (Navickaitė et al., 2018). The second MCM of this study is $La(Fe,Mn,Si)_{13}H_y$. The layered $La(Fe,Mn,Si)_{13}H_y$ MCHP contains 2.9 kg of MCM arranged in 10 layers.

2.3. Numerical modelling of the magnetocaloric heat pump

The original detailed numerical model of the AMR prototype was created by Engelbrecht (2008) and validated with experimental data. Because this detailed model is too computationally demanding for a direct use in a building simulation tool, it is approximated by 5-dimentional lookup tables. The latter contain around 1600 output points generated by the detailed model with the parameters of the ENOVHEAT prototype. The other components of the MCHP (valves, motor, circulation pump) are modelled with simple functions fitting data from measurements on the prototype and from manufacturers (Johra et al., 2018).

3. INTEGRATION OF THE MAGNETOCALORIC HEAT PUMP IN A BUILDING

The building study case for this numerical investigation is a low-energy (yearly heating need of 16 kWh/m²) single-story house located in Denmark with 126 m² of heated floor. The outdoor conditions are extracted from the national Danish weather file 2013. The testing heating period is from 1st of January to 30th of April. The dwelling is equipped with a low-temperature hydronic radiant under-floor heating (UFH) system (heat sink). The heat source of the heating system is a single collector vertical borehole ground source heat exchanger (GSHE) with a depth of 100 m (average temperature fluid outlet of 8.17 °C). The MCHP is integrated in the building within a single hydronic loop connecting the GSHE and the UFH system. There is no intermediate heat exchanger or water storage tank in the circuit. The same heat transfer fluid is circulated through the GSHE, the UFH and the MCHP by a single circulation pump (Johra et al., 2018).

The numerical model of the building study case has been created with the MATLAB-Simulink software. The heat transfer in each construction elements of the multi-zone building model is calculated with a one-dimensional finite volume method formulation comprising a limited number of control volumes (also known as Resistance-Capacitance network model). The UFH system and the GSHE are modelled by coupling a "plug flow" model with the ε-NTU method. The thermal interactions between the different legs of the hydronic circuits are taken into account. The entire building model and its sub-components have been validated against well-known commercial software and experimental data (Johra, 2018).

Two MCHP control strategies are tested in this study. The first one is an ON/OFF controller on each of the 9 UFH sub-loops of the building. If the temperature in a thermal zone is below/above the set point of 22 °C, the valve of the corresponding sub-loop is fully open/closed. The speed of the circulation pump is adjusted accordingly to keep nominal volumetric flow rate in each UFH sub-loops constant. The second control strategy is a temperature set point modulation scheme which takes advantage of the heating energy flexibility of the building to store thermal energy in the indoor space and optimize the MCHP operation. During the storage period, the set point is raised up (between 22 °C and 24 °C) and the MCHP runs continuously at optimum flow rate with highest coefficient of performance (COP). Once the maximum limit temperature is reached, the magnetic heating system is turned off. The MCHP is reactivated when the temperature of coldest room reaches the minimum limit temperature (between 22 °C and 20 °C) (Johra, 2018).

4. RESULTS

4.1. Nominal performance of the magnetocaloric heat pump

The first tests are performed with the MCHPs running at constant fluid flow rate and heating up only one thermal zone of the house (living room) during the four-month heating test period. The Figure 2 presents the average useful heating power output of the MCHPs for different constant fluid flow rates. The Figure 3 presents the COPs of the MCHPs. COP_{AMR} only considers work inside the AMR due to pressure losses and magnetic work. COP_{system} considers all work from the heating system including valves, pump and motor's work (Johra et al., 2018). One can see that the Gadolinium device can generate up to 2600 W of heating power with a COP_{system} up to 3.93 and temperature span of 19.9 K when operating at rotation frequency of 1 Hz or 2 Hz and with maximum fluid flow rate of 2100 L/h. The layered $La(Fe,Mn,Si)_{13}H_y$ device has more modest performance with a maximum heating power output of 160 W, a maximum COP_{system} of 0.83 and maximum temperature span of 11.9 K. The Curie temperatures of the layered $La(Fe,Mn,Si)_{13}H_y$ regenerator prototype have not been optimized for the current operation conditions, which can explain the limited heating capacity of the latter compared to the Gadolinium MCHP which has a large MCE across a wider temperature range.

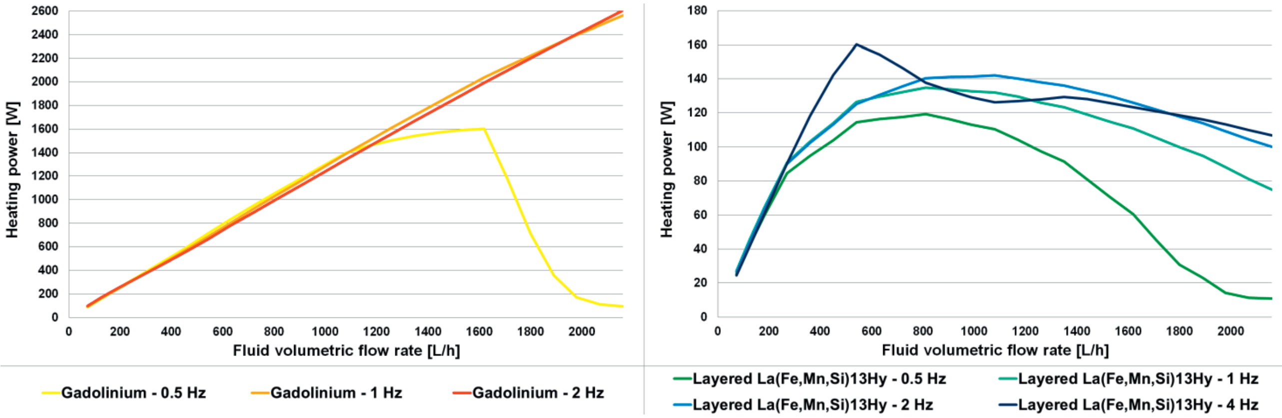

Figure 2: Average heating power output of the MCHP systems (Gadolinium on the left, layered $La(Fe,Mn,Si)_{13}H_y$ on the right) as function of the fluid volumetric flow rate

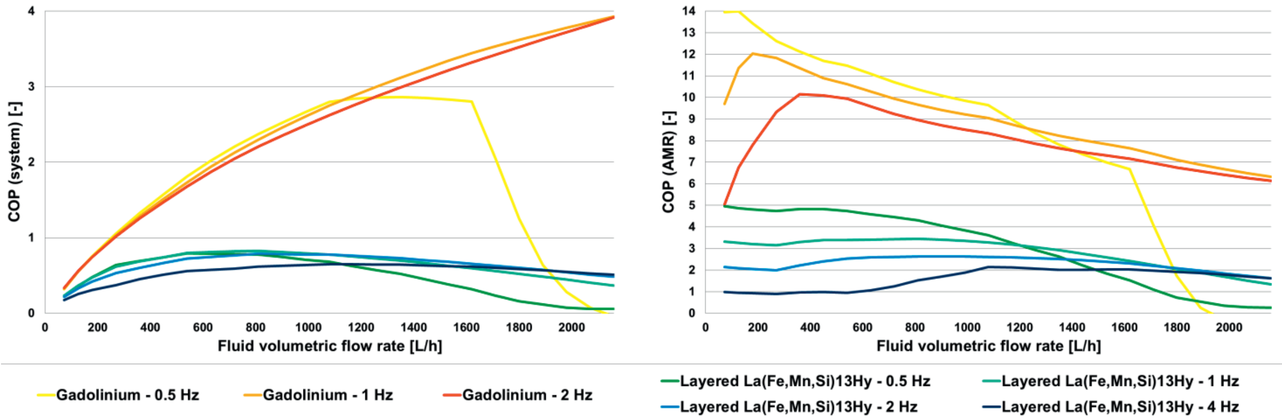

Figure 3: Average COPs of the MCHP systems as function of the fluid volumetric flow rate

4.2. Operation performance of the magnetocaloric heat pump with simple controller

The second test consists in using the MCHPs to provide for the indoor space heating needs of the entire house study case during the four-month heating test period with a basic ON/OFF control strategy.

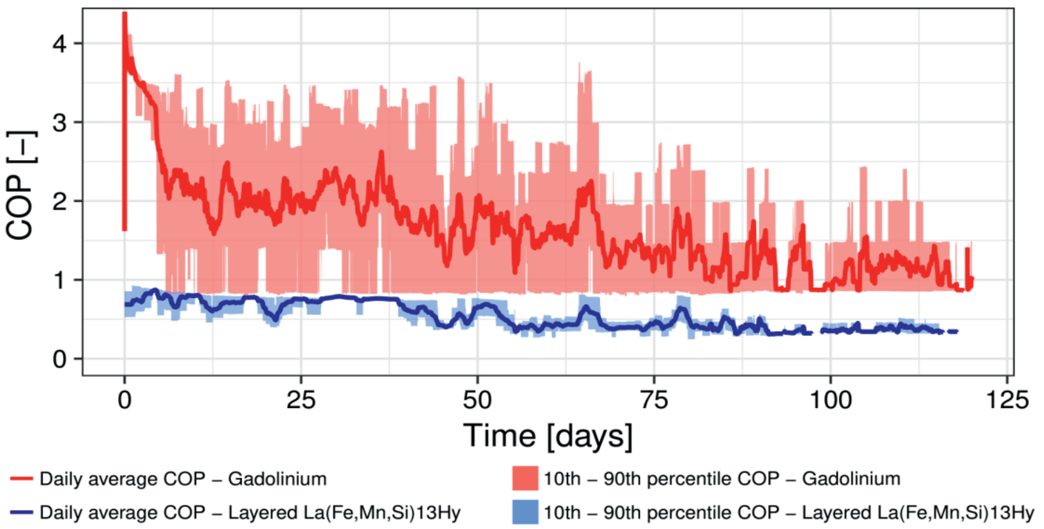

Figure 4: COP_{system} of the MCHPs during the four-month heating test period

Because the Gadolinium prototype can provide enough heating power for the low-energy house, the latter is integrated as such in the single hydronic loop of the heating system. The rotation frequency of this MCHP is kept constant at 1 Hz and the nominal fluid flow rate in each UFH sub-loops is kept at 240 L/h. On the other hand, the layered $La(Fe,Mn,Si)_{13}H_y$ prototype cannot provide enough heating power for the entire house. Therefore, each thermal zone in the dwelling is equipped with a dedicated layered $La(Fe,Mn,Si)_{13}H_y$ device operating at rotation frequency of 4 Hz and nominal fluid flow rate of 540 L/h. One can see on Figure 4 the COP_{system} of the two MCHP prototypes during the four-month heating test period. The layered $La(Fe,Mn,Si)_{13}H_y$ prototype does not perform very well with an average COP_{system} of 0.58. Moreover, it does not manage to generate enough heating output to keep the indoor temperature at 22 °C in every room of the building all the time. On the other hand, the Gadolinium prototype can keep the dwelling at 22 °C with an appreciable COP_{system} of 1.84. However, the MCHP with a simple controller operates on partial-load most of the time, which leads to performances which are much lower than the aforementioned ones.

4.3. Operation performance of the magnetocaloric heat pump with energy flexibility control strategy

The last test of this study consists in assessing the performance of the Gadolinium MCHP when controlled with a heat storage strategy. The goal of this controller is to maximize the operation time of the magnetic heating system at maximum fluid flow rate. The temperature span between the maximum and minimum indoor temperature limits is varied between 0 K (no heat storage in the built environment) and 4 K (maximum range of temperature variation for acceptable indoor thermal comfort). Three variations of the house study case with different structural thermal inertia (and thus different thermal storage capacity) are considered. One can see on Figure 5 that the MCHP operation can be substantially optimized by employing a heat storage control strategy. Increasing heat storage temperature span and building thermal inertia positively impacts the MCHP performance. The seasonal COP_{system} can thus be raised up to 2.90, 3.48 and 3.51 for light, medium and heavy structural thermal inertia houses respectively. With a heat storage temperature span of 2 K or higher, the MCHP reaches COPs which are comparable to the ones of conventional vapour compression heat pump systems

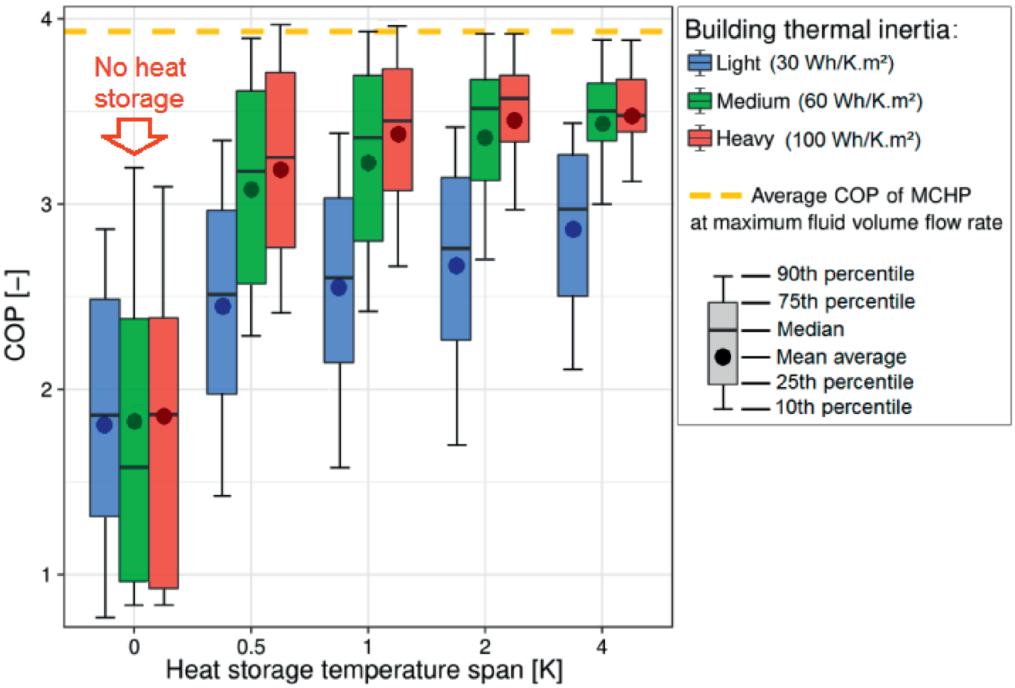

Figure 5: Box plot diagram of the Gadolinium MCHP COP_{system} as function of heat storage temperature span for different classes of building thermal inertia

5. CONCLUSIONS

With a maximum COP_{system} of 3.93 and a nominal heating power of 2600 W, the ENOVHEAT Gadolinium magnetocaloric heat pump can be integrated into a low-energy house with a vertical borehole ground source and an under-floor heating system and provide for building's space heating needs under Danish winter conditions. Moreover, a control strategy for heat energy storage in the indoor space can be employed to optimize the MCHP operation and reach seasonal COPs of up to 3.51. However, the layered $La(Fe,Mn,Si)_{13}H_y$ prototype is currently not suitable for such application. Further research should be carried out to improve MCM compounds and layered active regenerators. Finally, AMR cascading configurations could extend the MCHP temperature span for higher temperature applications such as radiator heat emitters, space heating in buildings with poor envelope performance, or domestic hot water production.

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