Room temperature Magneto-Caloric Refrigerator: system level analysis

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Abstract. A system consisting of magneto-caloric fluid, which releases (absorbs) heat in the presence (absence) of a magnetic field, is used to achieve refrigeration. Gadolinium is used as a magneto-caloric material. The influence of using water and galinstan as heat transfer liquid, on the refrigerator performance is numerically analysed by varying the mass flow rate of the magneto-caloric fluid, and MCM volume fraction (0.4 to 0.6). A cooling load up to 20 W at room temperature is obtained over a temperature difference of 0.5 K.

1. Introduction

A Magneto-Caloric Material (MCM) when exposed to a magnetic field in an adiabatic condition, experiences a temperature rise. This is due to the reduction in the magnetic entropy of the material, which leads to increase in lattice entropy, as the overall entropy of the system is constant [1]. When the excess heat is transferred to the ambient, followed by adiabatic demagnetization, MCM experiences a reduction in the temperature. This reduction happens due to the increase in the magnetic entropy at the expense of reduction in lattice entropy. This change in temperature is used to obtain refrigeration in a Magneto-Caloric Refrigerator (MCR). A MCR when compared with a vapour compression refrigeration system, offers an improved energy efficiency. Furthermore, this technology is environmentally friendly due to absence of global warming and ozone depleting working substances [2].

The first prototype of room temperature MCR was built by Brown in 1976 [3], in which gadolinium plates were used as MCM. The subsequent prototypes from the research community explored further designs, for example, different material compositions of MCM, rotary and linear movement between the MCM and the magnetic field, and magnetic field sources [4]. In all the experimentally built MCR so far, a porous/plate form of MCM is used through which a Heat Transfer Liquid (HTL) passes [5].

In order to increase the time of contact between the MCM and HTL, a system based on Magneto-Caloric Fluid (MCF) is proposed (fig. 1), in which a MCM is suspended in a HTL. As the MCF enters the region of magnetic field, it undergoes increase in temperature which is released to the ambient through the Hot Heat Exchanger (HHEX) (A-B-C in fig. 2). The MCF then enters the demagnetized region, where it experiences a temperature reduction (C-D in fig. 2) which then absorbs heat from Cold Heat Exchanger (CHEX). On exit, the MCF undergoes heat transfer with ambient so that it enters HHEX at ambient temperature, thus completing a magnetic Brayton refrigeration cycle (fig. 2). In the present work, a system level analysis of the proposed MCR is performed. The MCM considered is gadolinium (Gd), which is typically chosen as a reference material in the research community [4], although any MCM can be included in the developed model. The HTL considered are water, and galinstan (a liquid metal at room temperature, which is a non-toxic, eutectic mixture of gallium (68wt%), indium (22 wt%),
and tin (10 wt%). The performance of the system is quantified in terms of cooling power, and (thermodynamic) second-law efficiency. Its dependence on mass flow rate of MCF, and volume fraction of MCM in HTL is studied to identify the optimal parameters.

2. Methodology

The following simplifications are made to focus on the parameters mentioned in the introduction: The spherical MCM particles in the suspension have the same velocity as the liquid, i.e. they are stationary relative to each other. The analysis is limited to laminar cases (Re<2000). The MCF is considered to be Newtonian fluid. The magneto-caloric effect, i.e. the temperature rise (reduction) during magnetization (demagnetization) is instantaneous, and it is in thermal equilibrium with the HTL. Steady state, one dimensional (radial) conduction analysis of heat transfer at HEX is performed. Mechanical pump with efficiency of 90% is considered. The length (0.5 m) to diameter ratio of 5 is maintained for CHEX and HHEX, in line with future experimental plan.

2.1. Thermodynamic work

The refrigeration cycle is shown in the T-S diagram in fig. 2. The area enclosed is the work input ($W_{magnetic}$) for refrigeration. In a vapour compression system, the work is required to pump the refrigerant from lower to higher pressure. However, in a magneto-caloric refrigerator shown in fig. 1, the entire system is at a single pressure due to absence of valves. So the work in a MR is needed to move the magneto-caloric fluid across the magnetic field at the HHEX. Near the entry and at the exit of HHEX, there is a gradient in the magnetic field. A magnetic particle when exposed to a gradient magnetic field, experiences a body force given by Eq. 1, where $\mu_0$ is magnetic permeability of vacuum (N/A²), $M$ is the magnetization (A/m), and $H$ is the applied magnetic field (A/m). The magnitude of magnetic field gradient is the same at the entry and at the exit of HHEX. So the force on the MCF is proportional to the magnetization of the MCF. The average magnetization at exit of HHEX (C-D in fig. 2) is higher than at the inlet (A-B in fig. 2). So the magnetic work is required to overcome this additional attractive force at the exit. The friction between the MCF and the pipe represents additional work (calculated using Poiseuille’s relation), and the total work is given by Eq. 2.

$$F = \mu_0 (M \cdot \nabla)H$$

$$W = W_{magnetic} + W_{friction}$$

2.2. Boundary conditions and fluid properties

The walls of the HHEX and the CHEX are considered to be sufficiently thin to impose constant temperature boundary condition. The adiabatic temperature rise of the MCM in a given magnetic field is highest near its Curie temperature (due to a magnetic phase transition), which is 293 K for gadolinium [3]. So the wall of HHEX is maintained at this temperature, while the CHEX is at 292.5 K. An uniform magnetic field of 1 tesla is applied at HHEX which is obtainable using permanent magnet assembly. The effectiveness-NTU method is used for heat exchanger analysis [6]. As the MCF consists of
suspensions of solid MCM in a liquid, the effective viscosity and thermal conductivity are given by Eq. 3 [7] and 4 [5] respectively.

\[ \eta_{MCF} = \eta_{HTL} \left[ \frac{\phi_v}{(1-\Phi_v/\Phi_{v\text{max}})^{1/3}} \right] \]  

\[ k_{MCF} = k_{HTL} \left[ \frac{2+\Phi_v-\Phi_{v\text{max}}^{10/3}}{2+\Phi_v-\Phi_{v\text{max}}^{10/3} - (1-\Phi_v/\Phi_{v\text{max}})^{1/3}} \right] A = \frac{k_{MCM}}{k_{HTL}} \]  

where \( \eta \) is the dynamic viscosity [kg/(m s)], and \( k \) is the thermal conductivity [W/(m K)]. \( \Phi_v \) and \( \Phi_{v\text{max}} \) is the actual and maximum volume fraction. Though for spherical suspensions, \( \Phi_{v\text{max}} \) is 0.74, the validity of Eq. 3 is verified with experiments only till \( \Phi_{v\text{max}} = 0.625 \) [7], which is adapted in the present analysis. The mass flow rate of MCF is restricted to 0.3 kg/s to remain in the laminar region.

3. Results and Discussion

For the same amount of heat released (or absorbed) by the MCM during magnetization (or demagnetization), the temperature rise (or decrease) is higher for galinstan based MCF relative to water based. This is due to specific heat of galinstan (296 J/(kg K) [8]) being similar to gadolinium (~ 263 J/(kg K) [9], however highly temperature dependent near Curie temperature), as opposed to water (4180 J/(kg K)). This combined with its high thermal conductivity (16.5 W/(m K) for galinstan (as compared to 0.61 W/(m K) for water), results in higher heat transfer at HHEX and CHEX, as can be seen from the corresponding inlet and outlet temperatures in fig. 3 – fig. 5. For all volume fractions, the galinstan based MCF has a lower HHEX outlet temperature for the same MCF mass flow rate (fig. 3). Note that at lower flow rates (less than 0.04 kg/s in fig. 3), the water based MCF has a lower HHEX exit temperature for a higher \( \Phi_v \), and this trend reverses at higher flow rates. This is because, for a water based MCF, as \( \Phi_v \) increases, the effective thermal conductivity increases (Eq. 3) since MCM (8 W/(m K) [9]) has higher thermal conductivity than water. However, a higher \( \Phi_v \) also stipulates a higher heat load to transfer. At flow rates lower than 0.04 kg/s (fig. 3), the increase in thermal conductivity can transfer this additional heat, whereas at higher flow rates, the increase is not sufficient enough to perform this transfer adequately. For galinstan, its effective thermal conductivity decreases with increasing \( \Phi_v \), and hence a higher volume fraction has higher HHEX exit temperature (fig. 3).

The influence of HHEX exit temperature can be seen on the CHEX inlet and outlet temperature in fig. 4 and fig. 5 for galinstan and water based MCF respectively. Note that for water based MCF, the maximum flow rate is only 0.05 kg/s (\( \Phi_v = 0.6 \)) for the geometry considered, as at higher flow rates the CHEX inlet temperature is higher than the cold environment (292.5 K) and thus no refrigeration can be achieved. In general, as the MCF flow rate increases, due to reduced residence time, the difference in CHEX inlet and outlet decreases. However, there is an optimal mass flow rate for which the highest cooling rate is achieved as indicated in fig. 6a. Owing to desirable properties of galinstan, nearly tenfold increase (up to 20 W \( \Phi_v = 0.6 \)) in cooling power relative to water based MCF (fig. 6a) is obtained for all volume fractions considered. It also results in a higher second law efficiency, with a maximum of 17 % for \( \Phi_v = 0.6 \) (fig. 6b). However, there is an offset between the MCF mass flow rate for the highest cooling power and the highest second law efficiency for all volume fractions. Fig. 6a and 6b indicates the mass flow rate ranges for operating the MCR in performance or efficiency mode.

4. Conclusion

The utilization of a HTL with specific heat close to that of the suspended MCM, and a higher thermal conductivity results better second law efficiency of a MCR. A cooling load of 20 W in obtained over a temperature difference of 0.5 K at room temperature. The determined optimal parameters enables the operation of the MCR in higher cooling capacity or higher efficiency mode.
5. Future work
An experimental investigation of the MCR (fig. 1) is planned to be performed based on the range of optimal process parameters identified from the presented model. The MCM to be tested include gadolinium, Gd(Si₂Ge₂), LaFe(Mn,Si)H, and MnFe(P,Si).

Figure 3. HHEX outlet temperature.

Figure 4. CHEX inlet and outlet temperature of MCF – gadolinium (Gd) in galinstan.

Figure 5. CHEX inlet and outlet temperature of MCF – gadolinium (Gd) in water.

Figure 6. (a) Cooling power and (b) second law efficiency dependence on mass flow rate of MCF.

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