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Performance Analysis of Amicrochannel Amr Magnetic Refrigerator Using Different Heat Transfer Fluids

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Abstract: A numerical investigation has been carried out to determine the performance of a magnetic refrigerator having microchannel AMRs for glycols and their aqueous solutions as heat transfer fluids. The effects of thermophysical properties of heat transfer fluids on cooling characteristics and overall performance of magnetic refrigerator have been determined.A microchannel regenerator made of gadolinium has been numerically simulated using FLUENT. Temperature span, cooling capacity, pumping power and cooling capacity per unit pumping power of room temperature AMRmagnetic refrigerator have been compared and presented.The no-load temperature spans and cooling capacities for pure glycols and their aqueous solutions are found to be lower than that of water.The pumping power required for glycols is higher than that of water. This is majorly due to the lower heat capacities of ethylene glycol, propylene glycol and their aqueous solutionswhich correspondingly require higher mass flow rates.

Key words: Magnetic refrigeration · Numerical investigation · Microchannel regenerator · Magnetocaloric material · Aqueous solutions of glycols

Highlights:

- Performance comparisonsof microchannel AMR refrigerator were made for pure glycols and their aqueous solutions.
- No-load temperature spans and cooling capacities of pure glycols and their aqueous solutions are lower than that of water.
- Cooling capacitiesper unit pumping power of glycols are lower than that of water.

INTRODUCTION

Magnetic refrigeration is an emerging cooling technique which is based on magnetocaloric effect (MCE) of magnetic materials [1-5]. The materials having MCE are known as magnetocaloric materials (MCMs). Magnetic refrigeration does not involve any ozone depleting gases, greenhouse gases and hazardous chemicals which makes it an environmentally friendly cooling technology with potential to replace conventional vapor compression systems [6-8]. Magnetocaloric effect is an adiabatic temperature change or an isothermal entropy change of a magnetocaloric material when it is exposed to a varying external magnetic field [9-12]. Magnetic refrigeration has been employed to achieve very low temperatures which are even hard to attain using conventional gas compression systems [13].

History of magnetic refrigeration starts with the discovery of magnetocaloric effect by Warburg in 1881. He noticed an increase in the temperature of an iron piece when brought into the magnetic field and reduction in the temperature when the iron piece was taken away [14]. In 1918, Weiss and Piccard [15] explained the physics of magnetocaloric effect. In 1933, Giauque and MacDougall

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[16] verified the method by conducting the experiment on demagnetization of $Gd_2(SO_4)_3.8H_2O$ at liquid helium temperature. The fact that the magnetocaloric effect produced by the permanent magnets was not enough to produce the required cooling in Ericson cycle lead to the discovery of active magnetic regenerative (AMR) refrigeration systems [17]. An AMR is usually a porous bed of magnetic material which plays the role of refrigerant as well as the regenerator for heat transfer fluid [7]. There are four stages of regenerative magnetic cycle [18], namely (a) magnetisation: increase in the magnetic field intensity which causes the temperature of MCM to rise; (b) cold blow: working fluid flows from cold to hot side of the regenerator; (c) demagnetisation: reduction in magnetic field intensity which causes the temperature of MCM to drop; (d) hot blow: working fluid flows in from hot to cold side. Since the discovery of AMR, some significant refrigeration systems employing regenerative magnetic cycles have been developed. In 1976,Brown [19] developed the very first rotating magnetic refrigerator prototype employingregenerative stirling thermodynamic cycle, gadolinium parallel plates as the magnetic refrigerant and achieved a temperature span of 47°C. In 1978, Steyert [20] developed a system involving an AMR with a rotating disk of magnetocaloric material exposed to varying magnetic field. Later on, a team of "Polytechnic University of Catalonia in Barcelona" developed a refrigeration mechanism involving a magnetic disk having ribbons of gadolinium as the magnetocaloric material. It was the first ever device which produced magnetic field using permanent magnet assemblies. They achieved a temperature span of 5K at a magnetic field of 0.95T [21]. Another significant advancement is the development of an AMR refrigeration system by "The Astronautics Corporation in Madison". The system consisted of a wheel having 6 beds of gadolinium which produced a temperature span of 20°C and a cooling capacity of 100W with an operating frequency of 2Hz [22]. Similarly, Tura and Rowe [23] built a magnetic refrigeration system which employed a Halbach array of permanent magnets with regenerators having length and diameter of 110mm and 16mm respectively and produced a temperature span of 13.2°C.

Along with the development of experimental prototypes of AMR magnetic refrigerators, numerical and mathematical modelling has also been carried out by various researchers. For instanceTušek *et al*. [24], Li *et al*. [18], Lei *et al*. [25], Nikkola *et al*. [26], Vuarnoz and Kawanami [27], Nielsen *et al*. [28] and Lionte *et al*. [29] have performed numerical analysis to investigate, improve and optimize the performance of AMR magnetic refrigerators.

A magnetic refrigerator usually consists of the following major components: (a) AMR: a magnetic material which acts both as a refrigerant as well as regenerator e.g. Gd; (2) Heat transfer fluid: channelize the heat energy to/from regenerator and external heat exchangers e.g. water; (3) Magnetic field source: produces the desired magnetic field strength; (4) Hot end heat exchanger: gives up the heat energy of fluid to ambient; (5) Cold end heat exchanger: provides cooling power to the space; (6) Hydraulic system: reciprocates the heat transfer fluid throughout the system.Further details of these components can be found in Kamran [30].

From the extensive literature review, it can easily be deduced that major focus of researchers has been inclined towards experimental or numerical optimization of the performance of magnetic refrigerators considering different MCMs with various shapes, sizes and structures. Very limited research has been carried out to investigate the performance of AMR refrigerators using different heat transfer fluids, which can significantly affect the overall performance of a magnetic refrigerator.

Properties of a heat transfer fluid are strongly related to the heat transfer taking place in the regenerator and external heat exchangers. The heat transfer fluid should be having high thermal conductivity, low viscosity and high heat capacity to improve the cooling characteristics of AMR refrigerator [31].

Although water has most commonly been used as the heat transfer fluid in room temperature magnetic refrigeration, some of the researchers have investigated the performance of magnetic refrigerators using gaseous fluids or other water based solutions.Tura and Rowe [32] reported experimental studies using AMR test apparatus employing helium gas as the heat transfer fluid. The apparatus produced no-load temperature spans more than 50K with a magnetic field of 2T. Zhang *et al*. [13]described an experimental prototype of a reciprocating AMR with two permanent magnets and compared the performance using helium and nitrogen as the heat transfer fluids. They concluded that helium produces better cooling performance with a no-load temperature span of 24.6K and a maximum cooling capacity of 20.5W at a helium pressure of 1.2MPa. Bahl *et al*. [33] built and tested an experimental magnetic refrigeration device employing four different heat transfer fluids namely; water-ethanol, propylene glycol, ethylene glycol and olive oil. It was found that water-ethanol gives maximum temperature span due its thermal conductivity which is more than twice than any of the other fluids compared. Silva *et al*. [34] numerically simulated the heat transfer processes taking place in a magnetic micro-refrigerator with embedded microchannels employing various heat transfer fluids; water, ethanol, tetrafluorethane, propylene glycol, gallium and mercury. It was found that Gallium gives the maximum cooling power of 11.2W mm^{-3}at an operating frequency of nearly 5 kHz. However, the usage of gallium and mercury as heat transfer fluids is not encouraged due to their toxic nature and reactivity with metals.Silva *et al*. [34] also concluded water to be the most efficient heat transfer fluid which gives a maximum cooling power of 0.137 W mm^{-3} around operating frequencies of 50 Hz. Kitanovski *et al*. [35] conducted studies on different regenerator geometries and operating parameters for rotary magnetic chillers using water-ethanol and galinstan (liquid metal) as the heat transfer fluids. They observed that application of galinstan significantly increases the cooling power of magnetic chillers due to very high thermal conductivity (as compared to water) and much higher heat transfer coefficient.

In the present work, the cooling characteristics and overall performance of a microchannel (circular cross-section) AMR magnetic refrigerator is numerically determined and compared for pure glycols and their aqueous solutions as heat transfer fluids. Ethylene Glycol (EG), Propylene Glycol (PG) and their aqueous solutions have been employed as heat transfer fluids.

Table 1 shows the thermophysical properties ofglycols and their aqueous solutions. The thermophysical properties of aqueous solutions of glycols at 20°C with a freezing temperature of -15°C have been taken from Melinder [36]. Thermal conductivities of glycols and their aqueous solutions are lower when compared with that of water. Densities of glycols and their aqueous solutions are higher than that of water while the specific heat capacities are lower than that of water.

Table 1: Thermophysical properties of heat transfer fluids

Fluid	k W/m K	c_P J/kg K	μ Pa.s	ρ kg/m^3
Water	0.59	4180	0.001003	1000
EG Pure	0.25	2415	0.0157	1111.4
PG Pure	0.34	2260	0.0420	1036
EG Aqueous Sol.	0.46	3750	0.00233	1038.4
PG Aqueous Sol.	0.43	3775	0.00348	1025.5

Physical and Mathematical Models: The physical model of the microchannel AMR magnetic refrigerator adopted in this research work has already been explained with details in our previous work [10]. The mathematical models are adopted for conductive heat transfer taking place in solid magnetocaloric material, convective heat transfer along the wall of channels, magnetocaloric effect, heat transfer in CHEX and HHEX and pumping capacity of displacer. Equations of conservation of mass, momentum and energy along with the appropriate boundary conditions have been solved using Fluent. Two-way transient flow of the heat transfer fluid through one circular microchannel is simulated using SIMPLE algorithm. User defined functions (UDFs) have been formulated to simulate the regenerator, heat exchangers, displacer and magnetic step motor. Further details of all the mathematical models along with the conservation equations and appropriate boundary conditions can be found in our previous work [10].

RESULTS AND DISCUSSION

The mathematical models have already been validated and reported in Kamran *et al*. [37] by comparing thesimulation results with experimental data of Dupuis *et al*. [38]. The results have been found to be in good agreement with the experimental data. The influence of various parameters on cooling and overall performance of microchannel AMR magnetic refrigerator has been numerically determined and presented in the coming sections.

Mass Flow Rate: The mass flow rate required for glycols and their aqueous solutions has been determined at the utilization φ = 0.2 and is presented in this section. The mass and porosity of regenerative material are considered to be 225g and 0.50 respectively. It can be observed from Fig. 1 below that the mass flow rate required for EG pure and its aqueous solution is nearly 1.75 and 1.15 times larger than that of water, respectively. Similarly, the mass flow rate required for PGpure and its aqueous solution is nearly 1.85 and 1.10 times larger than that of water, respectively. Relatively higher densities and lower heat capacities of glycols and their aqueous solutions are the reasons behind larger mass flow rates required to maintain the same utilization.

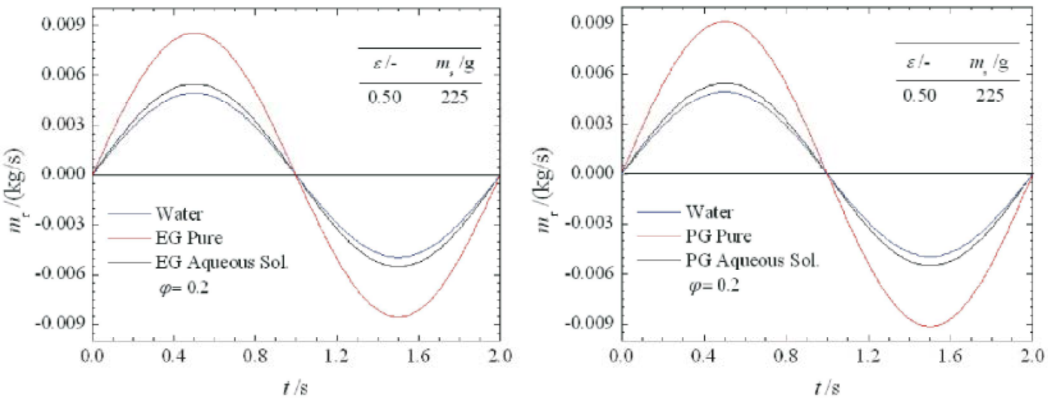

Fig. 1: Mass flow rate profiles for water, pure glycols and their aqueous solutions

No Load Temperature Span: The temperature difference between the cold and hot ends of regenerator has been numerically calculated at $\Delta B = 0.8$ T, $f = 0.5$ Hz for glycols and their aqueous solutions for different utilizations. Fig. 2 and Fig. 3 show the steady state no-load temperature spans for glycols along with theiraqueous solutions.

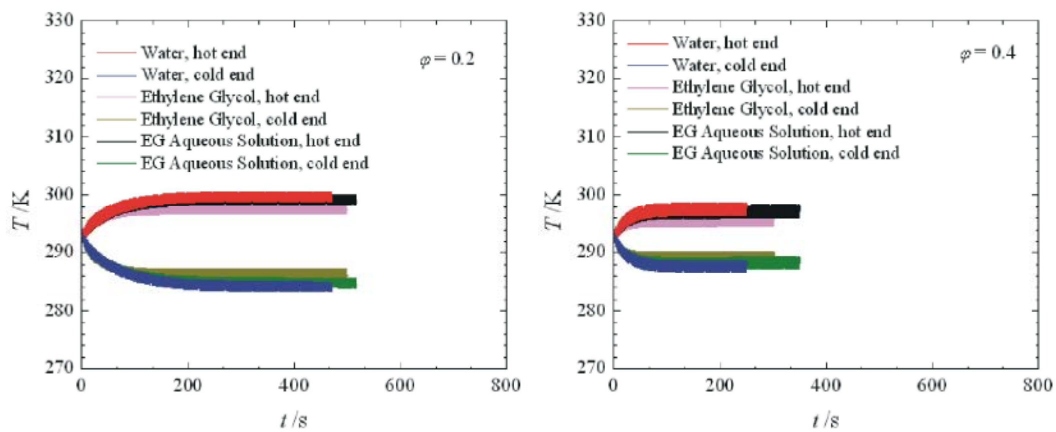

Fig. 2: No-load temperature spans for water, EG pure and EG aqueous solution at different utilizations

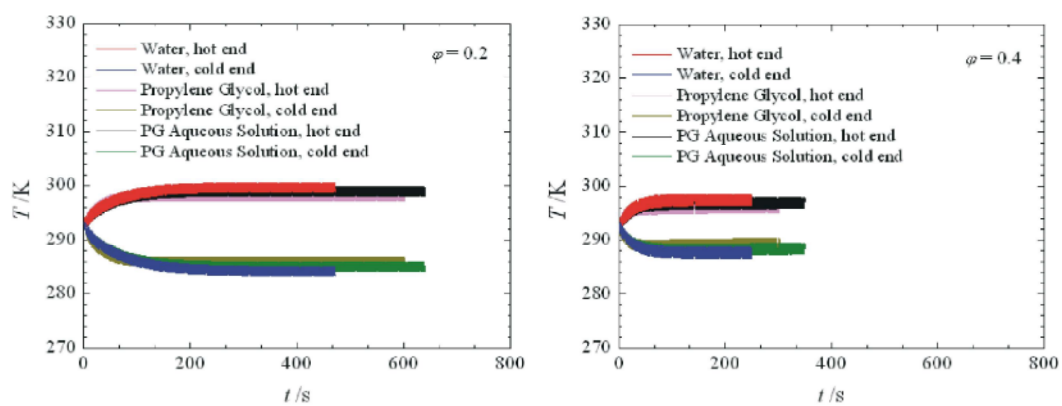

Fig. 3: No-load temperature spans for water, PG pure and PG aqueous solution at different utilizations

The variation of temperature span with utilization for glycols along with their aqueous solutionsis presented below. It can be noticed from Fig. 4that the temperature span for water is higher than that of pure glycols as well as their aqueous solutions. However, aqueous solutions of glycols give better temperature spans when compared with those of pure glycols.

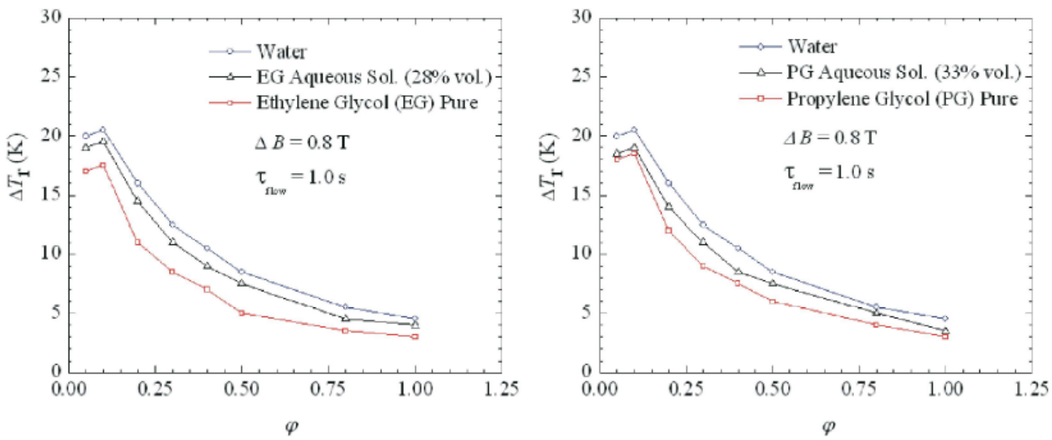

Fig. 4: Temperature span vs Utilization for water, pure glycols and their aqueous solution

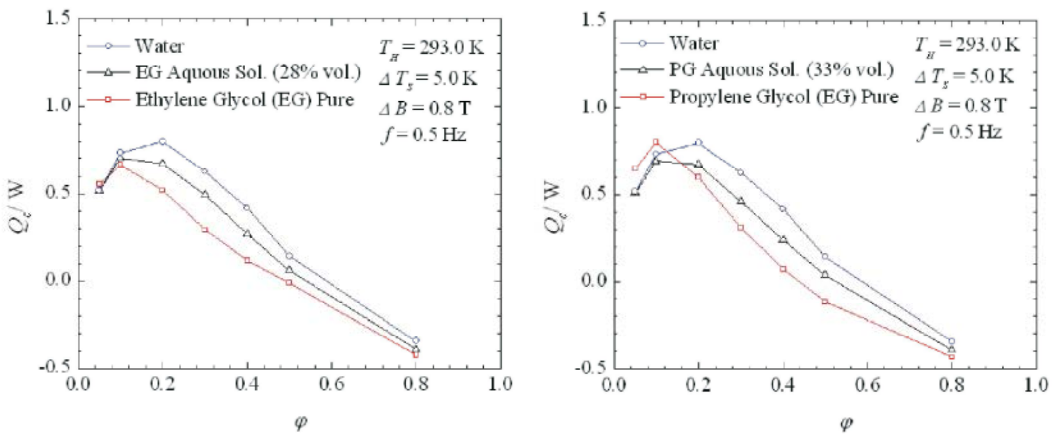

Fig. 5: Cooling power vs Utilization for water, pure glycols and their aqueous solutions

Cooling Power: Cooling power of an AMR magnetic refrigerator is strongly related to the mass flow rate of the heat transfer fluid. The mass flow rate of heat transfer fluid is usually quantified by a dimensionless parameter known as 'utilizationφ'. The utilization further depends upon the mass and heat capacity of the MCM. The cooling power of microchannel AMR is determined and presented for a range of utilization using glycols and their aqueous solutions as heat transfer fluids. The imposed temperature span is kept to be 5°C for glycols as well as their aqueous solution.

Figure 5 shows the variation of cooling power with utilization for glycols along with their aqueous solutions. It can be observed that the maximum cooling powers of glycols and their aqueous solutions occur at the utilization of 0.1. The average cooling power of EG pure and its aqueous solution is found to be approximately 1.5 and 1.1 times lower than that of water, respectively. Similarly, the average cooling power of PG pure and its aqueous solution is approximately 2 and 1.3 times lower than that of water respectively.

Pumping Power: The power required to pump the working fluid throughout the system plays a key role while selecting a suitable working fluid for AMR magnetic refrigerator. The pumping power required for glycols and their aqueous solutions have been calculated and presented in this section. Fig. 6shows the exponentially increasing trend of pumping power with utilization for glycols and their aqueous solutions. It can be noted that the maximum pumping power for EG pure and its aqueous solution at $\varphi = 1.0$ is approximately 7 and 1.5 times higher than that of water, respectively. Likewise, the maximum pumping power for PG pure and its aqueous solution is approximately 17 and 1.6 times higher than that of water, respectively.

The major factors responsible for larger pumping powers required are higher densities and lower heat capacities corresponding to larger mass flow rates required.

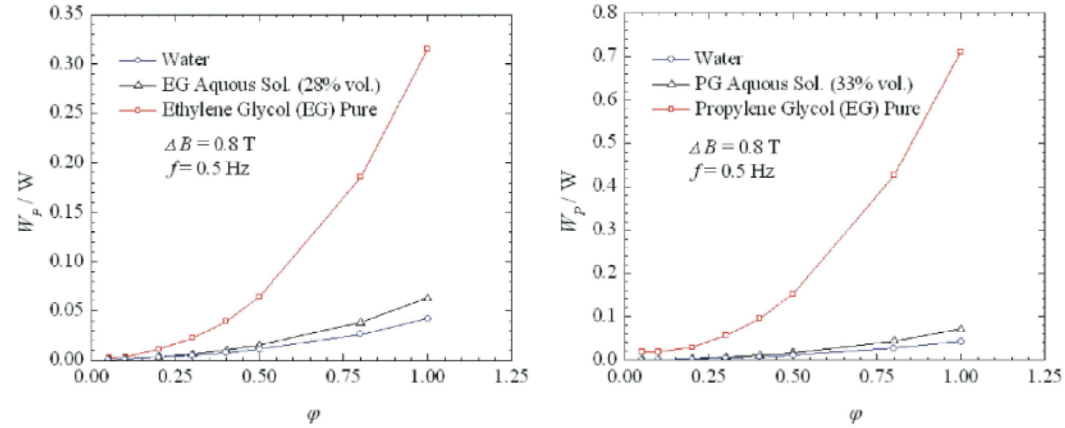

Fig. 6: Pumping power vs Utilization for water, pure glycols and their aqueous solutions

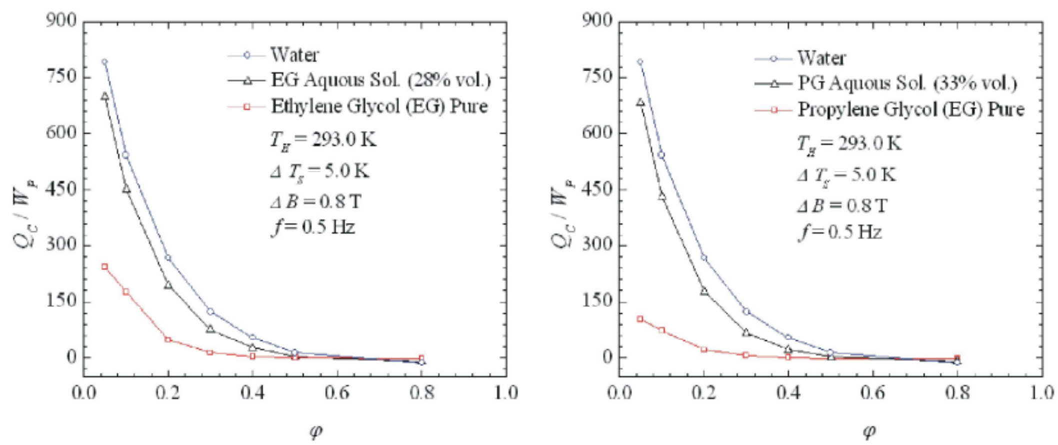

Fig. 7: Cooling capacity per unit pumping power for water, pure glycols and their aqueous solutions

Cooling Capacity per Unit Pumping Power: The overall performance of a magnetic refrigerator is usually quantified by the cooling capacity per unit of pumping power. The cooling capacity per unit pumping power for glycols and their aqueous solutions has been determined for a certain range of utilization and presented below inFig. 7. It has been found that the maximum cooling capacity per unit pumping power of water at $\varphi = 0.05$ is approximately 3.2 and 1.1 times higher than that of EG pure and its aqueous solution, respectively. Likewise, it is approximately 7.7 and 1.1 times higher than that of PG pure and its aqueous solution, respectively.

CONCLUSION

The performance of a microchannel (circular cross-section) regenerator based magnetic refrigerator was numerically assessed using different heat transfer fluids: water, glycols and their aqueous solutions. The no-load temperature spans and cooling capacities produced by glycols and their aqueous solutions are lower than those of water.

The lower thermal conductivities and heat capacities of glycols and their aqueous solutions, which correspond to larger mass flow rates required, are majorly responsibly for the lower overall performance of glycols and their aqueous solutions. Future works in this field may further improve the performance of magnetic refrigeration systems by employing different classes of heat transfer fluids.

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