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To cite this article: J A Bocanegra *et al* 2025 *J. Phys.: Conf. Ser.* **2940** 012018

Journal of Physics: Conference Series **2940** (2025) 012018 doi:10.1088/1742-6596/2940/1/012018

Investigating the Impact of Water-Glycol Mixture Ratios as Heat Transfer Fluid on the Performance of a Rotary Magnetic Refrigerator

J A Bocanegra*, F Scarpa and L Tagliafico

[1] Department of Mechanical, Energy, Management and Transportation Engineering, University of Genoa, Genoa, GE 16145, Italy

* Corresponding author: augusto.bocanegra@unige.it

Abstract. Magnetic refrigeration offers an eco-friendly and sustainable alternative for cooling applications. The selection of an appropriate working fluid is critical for heat removal and regeneration efficiency in Active Magnetic Regenerators (AMRs). This study evaluates various working fluids, focusing on water mixed with an antifreeze agent, glycol, to extend the temperature range and prevent corrosion. The thermophysical properties of such mixtures differ from pure water, influencing the refrigerator's performance. A parametric investigation using a numerical model of a rotative magnetic refrigerator was conducted to analyze the effects of varying the water-glycol mixture ratios. The study systematically varied operational parameters, such as rotation frequency and mass flowrate, to determine optimal performance conditions. Results indicate that the performance, measured by the Coefficient of Performance (COP), cooling load, and efficiency, declines with increasing glycol content, particularly at lower temperature spans. Increased viscosity in the mixture necessitates higher pumping power and torque for optimal operation, affecting the optimal rotational frequency. This study underscores the importance of balancing the mixture composition to enhance temperature range while minimizing negative impacts on performance, advocating for mixtures with lower glycol content.

1. Introduction

Common vapor-compression refrigerators rely on gas refrigerants with high Global Warming Potential (GWP). In contrast, magnetic refrigeration represents a viable alternative, utilizing solid-state materials instead of these environmentally detrimental gases. An early comprehensive overview of magnetic refrigeration technology was presented in 2007 [1], followed by a review of various prototypes developed before 2010 [2] and a subsequent state-of-the-art report in 2021 [3]. Magnetic refrigerators can be classified based on various factors, including the type of motion, which can be either linear reciprocating or rotary [4]. Magnetic refrigeration operates based on the Active Magnetic Regenerative (AMR) cycle, which employs magnetocaloric materials (MCMs) that exhibit the magnetocaloric effect (MCE). This effect involves a temperature increase when the MCM is subjected to a magnetic field and a corresponding temperature decrease when it exits the field. The magnitude of the MCM's temperature change depends on the magnetic field strength; commonly used materials exhibit a temperature change of a few degrees Celsius with a field strength of 1 Tesla. The regenerative cycle enhances the achievable temperature span by continuously moving the MCM in and out of the magnetic field. The AMR cycle employs a working fluid to transport heat throughout the cycle. The fluid must be precisely synchronized to transport heat in the correct direction, achieving the desired cooling load and facilitating heat rejection.

The AMR cycle consists of four cyclical steps:

i. **Adiabatic Magnetization:** During this step, the magnetocaloric material (MCM) is exposed to a magnetic field. As a result, the MCM undergoes adiabatic magnetization, leading to an increase in its temperature without exchanging heat with its surroundings.
ii. **Hot Blow:** In this phase, the heated working fluid flows from the MCM to the hot heat exchanger. The heat absorbed during magnetization is transferred to the fluid. The fluid then carries this heat to the hot heat exchanger, where it is expelled into the environment.
iii. **Adiabatic Demagnetization:** After the hot blow, the magnetic field is removed. The MCM undergoes adiabatic demagnetization, during which its temperature decreases. This step cools the MCM without any heat exchange with the surroundings.
iv. **Cold Blow:** In the final step, the working fluid flows back to the MCM. The cold fluid absorbs heat from the MCM. This cooled fluid then flows to the cold heat exchanger, where it absorbs heat from the space or substance being cooled.

In this way, the working fluid exchanges heat with the MCM matrix, and the energy is transported from the cold side heat exchanger (performing the cooling load) to the hot heat exchanger (performing the heat rejection).

Choosing a suitable working fluid for efficient heat removal and regeneration in AMRs is crucial for optimizing the performance of magnetic refrigerators. The working fluid must alternately and synchronously transport heat in coordination with the changes in the magnetic field. Various fluids have been studied, including common heat transfer fluids such as alcohol and water and advanced options like nanofluids [5] and liquid metals [6]. When selecting water as the working fluid, it is essential to consider mixing it with antifreeze agents, such as glycol, to create a water-glycol blend. This blend extends the operational temperature range by lowering the freezing point and mitigates corrosion effects. However, the thermophysical properties of the water-glycol mixture differ significantly from those of pure water, which impacts the overall performance of the magnetic refrigerator.

Numerical methods have been widely used to study AMR systems [7], typically employing one-dimensional (1D) or two-dimensional (2D) spatial representations of the regenerator. An example of a 1D model applied to near-room temperature refrigeration was presented by [8]. The present study conducts a parametric investigation into the performance of a rotary magnetic refrigerator by varying the ratio of the water-glycol mixture used as the working fluid. A well-established numerical model is utilized to simulate the performance of a rotary AMR with different working fluids. Systematic variations in operational parameters, such as rotation frequency and mass flowrate, are considered to ensure optimal refrigerator performance.

2. Methods

2.1. Numerical model

The numerical model employed in this research is a one-dimensional model that discretizes the solid and fluid regions. The energy balance is calculated for each interacting solid and fluid element. For the solid elements, the energy balance is represented by equation (1), and for the liquid domain, by equation (2). Quantities related to the solid and fluid domains are denoted by the subscripts s and f, respectively, with the fluid velocity denoted by u. Two geometrical ratios characterize the regenerator: the ratio of the heat transfer surface area to the total volume inside the regenerator ($\beta = A/V$) and the ratio of the fluid volume to the total volume of the channel ($\alpha = V_f/V$), where $V = V_f + V_s$. The solid and fluid thermophysical properties include density (ρ_s, ρ_f), specific heat (c_s, c_f), and thermal conductivity (k_s, k_f).

$$\rho_s c_s(T_s, B)\frac{\partial T_s}{\partial t} = k_s \frac{\partial^2 T_s}{\partial x^2} - h_{eff}\ \frac{\beta}{1-\alpha}\ (T_s - T_f) + \dot{Q}_{MCE} \tag{1}$$

$$\rho_f c_f\left(\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x}\right) = k_f \frac{\partial^2 T_f}{\partial x^2} + h_{eff}\ \frac{\beta}{\alpha}\ (T_s - T_f) - u\frac{dP}{dx} \tag{2}$$

The first equation includes the MCE experienced during the magnetization and demagnetization steps, denoted as $\dot{Q}_{MCE}$. The MCE term $\dot{Q}_{MCE}$ is calculated directly using the adiabatic temperature change ΔT_{span}, obtained from the change in the thermophysical properties by the action of the applied magnetic field, as described in detail in our previous publications [9]. The other two terms correspond to thermal conduction and the heat exchanged with the fluid domain. The second equation encompasses fluid conduction, heat exchange with the solid domain, and pressure losses due to friction. While this term has limited relevance when using water as the working fluid, it was included because its importance increases under certain conditions, such as when the fluid properties or operating conditions change, inducing an increased required pumping power, as shown in the results section. It was assumed that the regenerator is isolated from the environment and only connected to the thermal reservoirs. The boundary conditions for this study include imposed mass flow rate and fluid inlet temperatures, as illustrated in Fig. 1. Regarding the numerical modeling, an explicit finite difference scheme was applied to solve the discretized equations. Thermophysical properties are calculated at each solid and fluid node during each timestep. The thermophysical properties of the fluids used in this study have been evaluated using the SecCool software (www.ipu.dk/products/seccool/), which calculates properties based on data in Melinder's book [10].

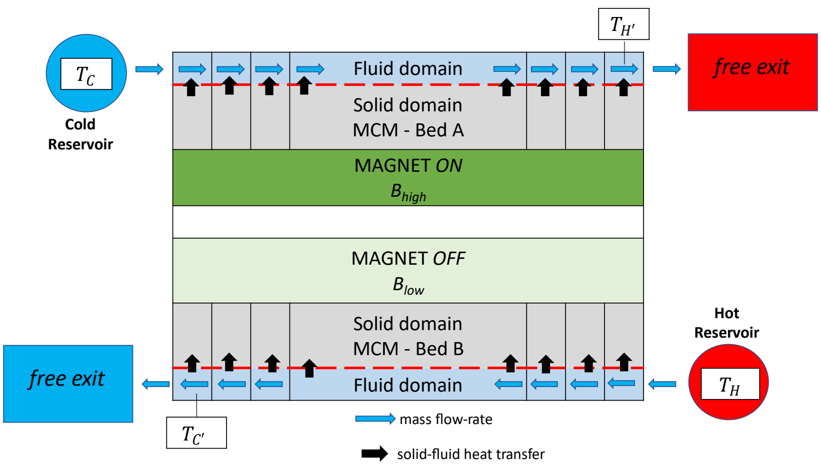

Figure 1. Sketch of the numerical model

Figure 1 presents a sketch of the numerical model, illustrating the solid and fluid domains. The two beds are exchanged in each half-cycle to complete the AMR cycle. It is important to note that an ideal thermal reservoir imposes the inlet temperature of the fluid for each bed. Table 1 lists the main parameters that were fixed during this study.

Table 1. Main geometrical parameters of the considered case study

Parameter	
α	1/3
β	2660 m^{-1}

Lx	0.17 m
Ly	0.08 m
B_H	0.945 T
B_L	0.056 T

2.2. Performance indicators
The performance of the device is measured by two key indicators: the coefficient of performance (COP) and the weighted cooling load (Q_{in}/M_s). The COP, given by equation (3), measures the efficiency of the refrigeration cycle. The weighted cooling load, given by equation (4), is the cooling load's ratio to the solid material's mass. In these equations, τ_c represents the cycle time, $\dot{m}_f$ denotes the fluid mass flowrate and $\dot{Q}_{out}$ represents the heat rejection.

$$COP = \frac{\dot{Q}_{in}}{|\dot{Q}_{out} + \dot{Q}_{in}|} \tag{3}$$

$$\dot{Q}_{in}/M_s = \frac{1}{M_s \tau_c} \int_0^{\tau_c/2} \dot{m}_f c_f \,(T_{C'} - T_C) dt \tag{4}$$

Additionally, equation (5) presents the exergetic efficiency (η_{II}), defined as the ratio of the COP to the coefficient of performance of a Carnot cycle (COP_{carnot}) operating between the same temperatures.

$$\eta_{II} = \frac{COP}{COP_{carnot}} = COP \frac{T_H - T_C}{T_C} \tag{5}$$

2.3. Operative parameters
The primary operative parameters include the rotation frequency f and the fluid mass flowrate of the working fluid, $\dot{m}_f$. In some studies, the utilization factor (Φ), a dimensionless parameter, is used instead of the fluid mass flowrate, as shown in equation (6):

$$\Phi = \frac{\dot{m}_f c_f}{M_s c_s} \tau_c \tag{6}$$

Operational optimization typically involves maximizing performance indicators, such as the cooling load. While machine learning techniques have been applied to optimize the performance of such devices [11], this study employs a different approach. Here, a parametric sweep is conducted, systematically varying the frequency and utilization factor to obtain optimal parameters that ensure the maximum cooling load for each temperature span.

3. Results
Simulations demonstrate a significant performance dependence on the mix ratio, as measured by the Coefficient of Performance (COP), cooling load, and efficiency. Particularly noteworthy is the inverse relationship observed, whereby performance deteriorates with increasing glycol content in the mixture. This effect is especially pronounced at low-temperature spans, as illustrated in Figure 2. At low ΔT_{span}, the observed increase in COP aligns with the theoretical trend of the Carnot COP; however, it is important to note that this study considers only the internal losses of the regenerator, while a complete system would also include additional losses across the entire circuit.

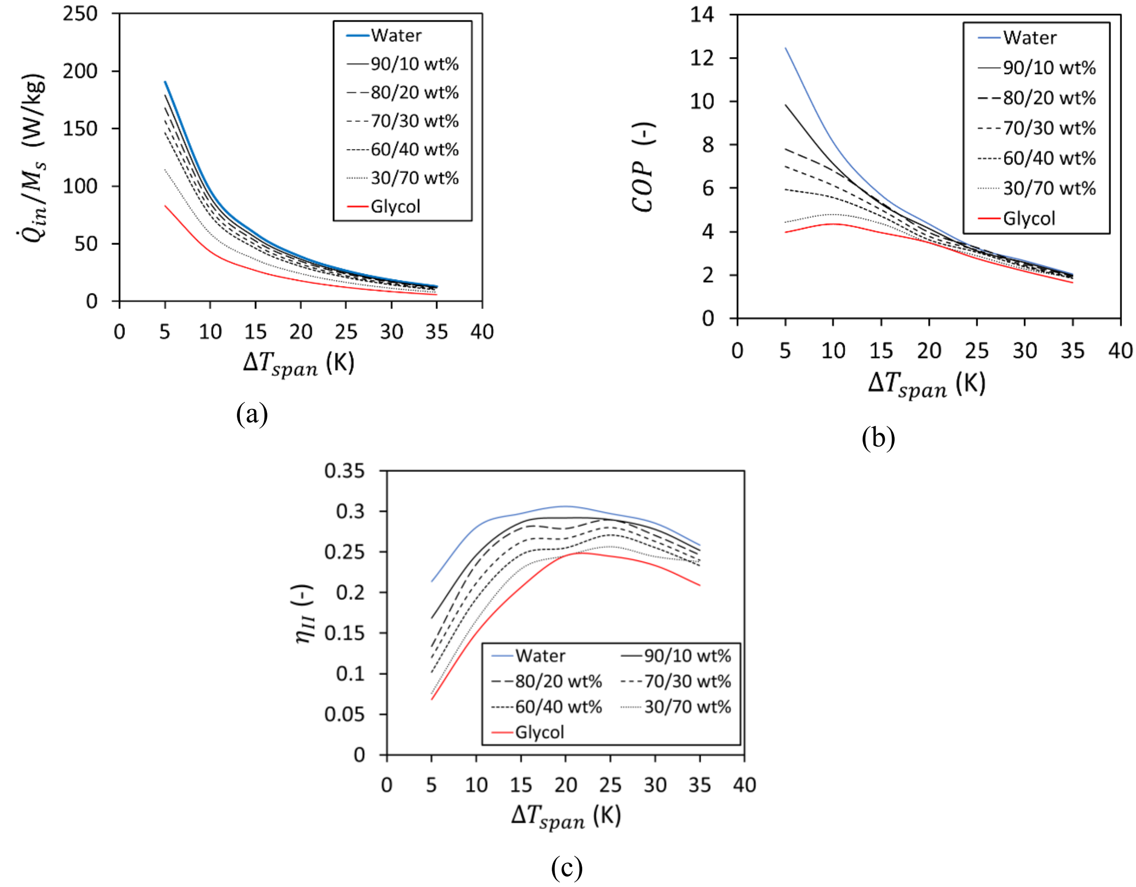

Figure 2. Effects of the mix ratio on the performance of the rotary AMR.

Due to changes in thermophysical properties, such as increased viscosity, optimal operation requires higher pumping power and torque (refer to Figure 3). The oscillations observed in the torque figure may correspond to numerical artifacts.

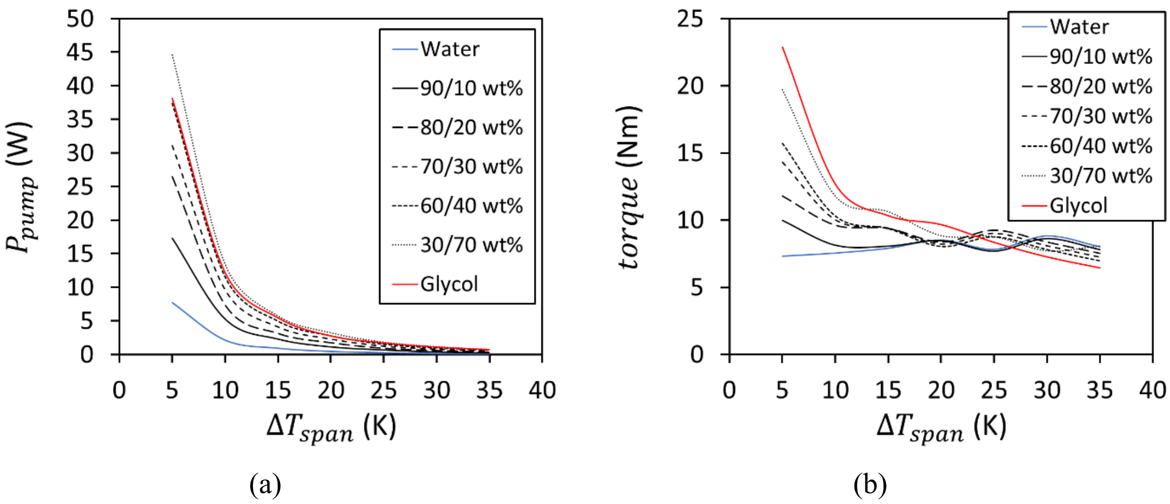

Figure 3. Effects of the mix ratio (wt%) on the pump power (a) and torque (b)

Each mixing ratio modifies the optimal operational parameters, primarily decreasing the optimal rotational frequency (see Figure 4). Optimal control curves are presented only for pure water and a 70/30 wt% mixture to enhance clarity. Notably, the 70/30 wt% mixture is of practical interest, while ratios with higher glycol concentrations are included in the paper to illustrate their effects. The curves represent optimal values for different temperature spans; it is evident that to operate at a higher temperature span, both the frequency and mass flowrate must be decreased. Furthermore, although the required utilization factor remains practically unaltered when comparing the mixture with pure water, representing the mass flowrate instead of the utilization factor reveals a reduction in the optimal value.

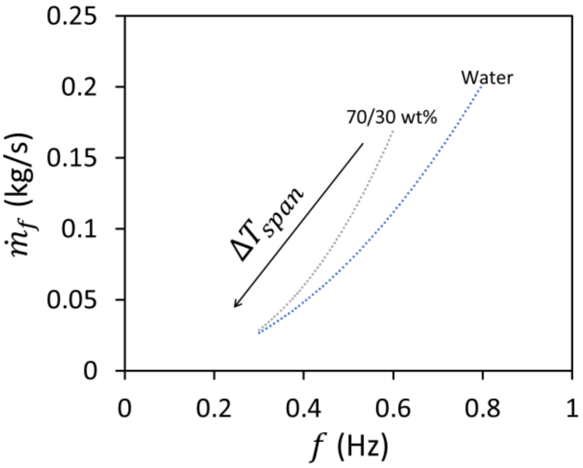

Figure 4. Optimal operative parameters (fluid mass flowrate and frequency) for different temperature spans. Comparison of water and 70/30 wt% water/glycol mixture.

4. Conclusions

This paper presents a numerical investigation of a rotary magnetic refrigerator, exploring the effects of varying the water-glycol mixture ratio as the working fluid. Performance evaluation was based on cooling power, coefficient of performance, and exergetic efficiency, while optimal control parameters, torque, and pumping power were also studied across different temperature spans.

Insights into the impact of working fluid composition on the regenerative thermodynamic cycle of rotary magnetic refrigeration were provided. A delicate balance is necessary when selecting a mixture, weighing the benefits of widening the operative temperature range (anti-freezing effect) against potential negative impacts on performance. Emphasis is placed on mixtures with low wt%.

While numerical results offer valuable insights, experimental validation is essential. Future studies will focus on refining the numerical method, including enhanced fluid properties modeling and considering alternative fluids.

While this technology shows promising potential, its current limitations must be acknowledged. One significant challenge is the high cost of both the magnetic materials and, in particular, the magnetocaloric materials (MCM), which represent a key barrier to widespread adoption. Additionally, the system's scalability remains an area of focus, as transitioning from small-scale prototypes to industrial applications requires addressing technical complexities and economic feasibility. However, with increasing interest in cleaner and more sustainable energy solutions, this technology holds great promise for integration into larger energy systems. Future advancements in material science and system design are expected to reduce costs and improve efficiency, further enhancing the appeal of this innovative approach.

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Acknowledgments

The present work was supported by MUR (Italian Ministry of University and Research). Project FISR2019_04798 SUSSTAINEBLE A Solution Using Solid-STate-cooling: An INvestment Eco-compatiBLE).