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Performance Analysis of Magnetic Refrigeration Systems Using Nanofluids with Propylene Glycol Mixture as Base Fluid

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Abstract. This work presents the performance of a magnetic refrigerator with the use of nanofluids as heat transfer fluids, specifically focusing on a base mixture with a 30% mass concentration of propylene glycol. Five types of nanoparticles were studied: aluminum oxide, copper oxide, zinc oxide, silicon dioxide, and silicon carbide. The nanofluid's thermophysical characteristics like density, specific heat capacity, thermal conductivity, and dynamic viscosity were determined through empirical correlations available in literature. The results sufficed to draw a conclusion that volumetric concentration and particle size are the main parameters that define the performance of the nanofluid in a magnetic refrigeration system. It was observed that increasing volumetric concentration and reducing particle size improves refrigerating power, even though it decreases the Coefficient of Performance, especially for a small temperature span. The type of nanoparticle material seems to play a minor role in the results, which would indicate that, in regard to system efficiency, the size of the particles and their volumetric concentration are more important than the material of the nanoparticles. In addition, the overall performance was not affected by temperature-sensitive thermophysical properties. Thus, improving the performance of the system could be achieved by choosing the appropriate size and volumetric concentration of particles rather than choosing the specific material. In conclusion, the size of the particles and the volumetric concentration are the most important variables that affect the performance of the nanofluid, while the material selection is considered a tertiary factor for the efficiency of the magnetic refrigeration system.

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Nomenclature

Acronyms

AMR	Active Magnetic Regenerator
COP	Coefficient of Performance
GWP	Global Warming Potential
HFC	Hydrocarbon
MCE	Magnetocaloric Effect
MCM	Magnetocaloric Material
NG	Natural Gas
W-PG30%	Water - 30% Propylene Glycol mixture

Symbols

B	Magnetic field induction [T]
c_p	Specific heat capacity [J/kg·K]
d_p	Nanoparticle diameter [nm]
h_{eff}	Effective heat transfer coefficient [W/m^2·K]
H	Magnetic field strength [A/m]
k	Thermal conductivity [W/m·K]
k_b	Boltzmann constant [J/K]
M	Magnetization [A/m]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [Pa]
Pr	Prandtl number
$\dot{Q}_{in}$	Cooling load [W]
$\dot{Q}_{ou}$	Heat rejected [W]
Re	Reynolds number
t, τ	Time, period [s]
T	Temperature [K]
u	Fluid velocity [m/s]

Greek Letters

α	Fluid volume fraction
β_s	Specific surface area of the solid [m^{-1}]
ΔT_{ad}	Adiabatic temperature change [K]
ΔT_{span}	Temperature span $(T_H - T_C)$ [K]
μ	Dynamic viscosity [Pa·s]
ρ	Density [kg/m^3]
Φ	Dimensionless utilization factor
ϕ	Nanoparticle volumetric concentration

Subscripts

ad	Adiabatic
b	Brownian
bf	Base fluid
c	Cold
f	Fluid
fr	Freezing
h	Hot
nf	Nanofluid
p	Nanoparticle
s	Solid (MCM)

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1 Introduction

1.1 Magnetic Refrigeration

Refrigeration is a technological process that consists of removing heat from a room or substance, thus reducing its temperature. Today it has become a technology of vital importance for humans, as demonstrated by its many applications: the preservation of food, pharmaceuticals, environmental comfort in air conditioning, the transport of Natural Gas (NG) and other various technological applications. The refrigeration has seen significant progress in recent years, driven by the growing demand for efficient, sustainable and environmentally friendly cooling solutions. As is well known, conventional refrigeration technology is based on the vapor compression cycle. This technology has direct and indirect effects on global warming in two ways. Loss of refrigerant from system components or its spread to the outside during service can be considered a direct effect, as the refrigerants commonly used are Hydrocarbons (HFCs), i.e. greenhouse gases with Global Warming Potential (GWP). The indirect effect is related to the use of a carbon-emitting engine for the generation of electricity used by the compressor, which is also a disadvantage since it has to compress a large amount of refrigerant vapour, requiring a considerable amount of energy to operate. In addition, environmental factors limit the lower temperature of the refrigeration cycle and therefore result in a lower Coefficient Of Performance (COP) than the Carnot cycle [1].

Among the technologies that represent a promising alternative to the well-known vapor compression cycle, there is magnetic refrigeration, which is based on the Magnetocaloric Effect (MCE), calculable by equation(1). This phenomenon consists of the variation in temperature (ΔT_{ad}) of a magnetic material subjected to an external magnetic field under adiabatic conditions [2].

$$\Delta T_{ad}(T, H_{in}, H_{fin}) = -\int_{H_{in}}^{H_{fin}} \left(\frac{T}{c_p(T,H)}\right)_H \left(\frac{\partial M(T,H)}{\partial T}\right)_h dH \qquad (1)$$

Where ΔT_{ad} is the adiabatic temperature difference, T is the temperature, H is magnetic field applied, c_p is the specific heat of the solid and M is the magnetization of refrigerant.

Magnetocaloric Material (MCM), such as gadolinium, changes its temperature when subjected to an adiabatic variation of the magnetic field (ΔB). The temperature difference ΔT_{ad}, i.e. the temperature variation of a fluid during a thermodynamic process without heat exchange with the surrounding environment, is of a few degrees when using a Magnetic field of the order of a few Teslas. However, using a regenerative cycle, as illustrated in figure 1, it is possible to obtain temperature gradients comparable to those of a vapor compression refrigeration cycle [3]. A comprehensive overview of the state of the art in magnetic refrigeration technology was presented in [4]. Magnetic refrigerators can be classified according to various factors, including the type of movement, which can be linear alternating or rotational [5].

The Active Magnetic Regenerative (AMR) refrigeration cycle consists of four cyclic phases:

I. **Adiabatic Magnetization** (1-2): The Magnetocaloric Material (MCM) is magnetized and increases its adiabatic temperature.

II. **Hot Blow** (2-3): The working fluid absorbs the heat of the material due to the previous adiabatic magnetization, which it then transports to the hot heat exchanger (T_H) and is released into the environment.

III. **Adiabatic Demagnetization** (3-4): The MCM undergoes demagnetization with a consequent decrease in temperature adiabatically.

IV. **Cold Blow** (4-1): The demagnetized material absorbs heat from the heat transfer fluid, which cools, the cold fluid flows to the cold heat exchanger (T_C) where it absorbs the heat from the environment to be cooled.

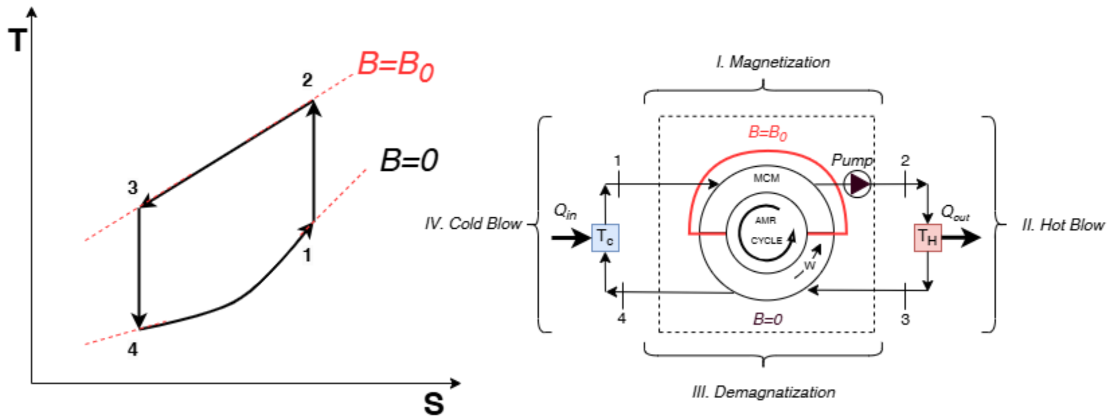

Figure 1: AMR Cycle

1.2 Heat transfer enhancement with nanofluids

Bocanegra et al. [6] presents an experimental investigation on a rotary AMR powered by a mixture of water and glycol. The results of the aforementioned paper showed how the efficiency of the system, expressed by the Coefficient of Performance (COP), the cooling power and the efficiency decreases as the glycol in the mixture increases, especially for small thermal jumps. The cause of this behavior is rightly to be found in the increase in viscosity of the fluid, with the consequent expenditure of energy to make it slide and to operate the pump, which translates into a lower "optimal" rotation frequency. This denotes the great caution that is required to make the choice of the most suitable refrigerant, where the need to extend the operating temperature range of a mixture through the use of glycol must be balanced with the loss of yield and with the increase in energy consumption. This study, which certainly provides rather interesting ideas, is still limited to traditional refrigerants only.

This present paper develops and continues the aforementioned study by focusing on the use of nanofluids based on 30% by mass Propylene Glycol (W-PG30%), a mixture that, as stated by Bocanegra et al. [6], has attracted greater interest for practical application as a working fluid. Aluminum Oxide (Al_2O_3), Copper Oxide (CuO), Zinc Oxide (ZnO), Silicon Dioxide (SiO_2), and Silicon Carbide (SiC) are the five types of nanoparticles chosen, and their effect of volumetric concentration and size on the thermophysical properties of the fluid, and consequently on the system's performance, has been evaluated. The idea behind this study is that the introduction of nanoparticles results in improved thermal conductivity and heat transfer capability, thus allowing to overcome the limits imposed by viscosity encountered.

2 Materials and Methods

This study focuses on the study of the energetic performance of the AMR using nanofluids based on the W-PG30% mixture as the heat transfer fluid. the thermophysical properties of the considered nanoparticles for the present study will be considered constant at the reference temperature of 20°C. The simulations examine the variation of performance by changing two parameters:

- Size of the nanoparticles (d_p): 20nm, 50nm, or 80nm.
- Volumetric concentration (ϕ): 3% or 6%.

2.1 Thermophysical Properties of the Nanofluids
The thermophysical properties of the W-PG30% mixture were considered to be temperature dependent with values derived from ASHRAE [7], by a fitting process in the temperature range from −12°C to 45°C.

Instead, the thermophysical properties of the nanoparticles will be considered constant at the reference temperature of 20°C.

To model the thermophysical properties of nanofludes below are the relationships considered for this study:

- **Thermal conductivity of the nanofluid** (k_{nf}): For the thermal conductivity we refer to Corcione's relation [8], equation(2) takes into account the Reynolds and Prandtl numberd and Brownian motion of the nanoparticles.

$$\frac{k_{nf}}{k_f} = 1 + 4.4Re^{0.4}\mathrm{Pr}^{0.66}\left(\frac{T_{nf}}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\phi^{0.66} \tag{2}$$

Where T_{nf} and T_{fr} are respectively the temperature of the nanofluid and the freezing temperature of the base fluid, both expressed in [K], Pr is the Prandtl number of the base fluid and Re is the Reynold number of the nanoparticle, defined as:

$$Re = \frac{\rho_f u_b d_p}{\mu_f} \tag{3}$$

The Brownian mean velocity (u_b) is calculated in terms of the he Boltzmann constant (k_b):

$$u_b = \frac{2k_b T_{nf}}{\pi \mu_f {d_p}^2} \tag{4}$$

- **Viscosity of the nanofluid** (μ_{nf}): For viscosity, we refer to Corcione's semi-empirical model [9], equation(5),allows to estimate the increase in viscosity caused by the presence of the nanoparticles, a factor as mentioned earlier that is critical and limiting with regard to the performance of the system.

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 0.10255{d_p}^{-0.264}\phi^{1.028}} \tag{5}$$

2.2 Modeling of the AMR System
A One-Dimensional (1D) approach was used to model the AMR system. The regenerator is considered to consist of gadolinium (Gd) plates with fixed dimensions (height 5mm, thickness, 0.5mm, distance between plates 0.25mm arranged in two parallel blocks and weight of 1 kg), gadolinium's thermophysical and magnetocaloric properties are crucial for the model's accuracy and are considered dependent on both temperature and the applied magnetic field. The key properties are detailed in the work by [10] and are not reported here for brevity. The Gd is subjected to an oscillating magnetic field between 0 and 1 Tesla (synchronized with the demagnetization and magnetization phenomena considered immediate), which generates the magnetocaloric effect (MCE) with temperature changes proportional to the magnetic field. Laminar and incompressible heat transfer fluid flow is considered, no heat loss to the outside, negligible radioactive contribution as are the magnetic effects on nanoparticles since there are no specific experimental data on the subject.

In this study, we investigate the behavior of a refrigerator equipped with an Active Magnetic Regenerator (AMR), simulated using a one-dimensional analytical-numerical model, whose validation and application are described in detail in [11]. The model is based on two energy balance equations (6) and (7), the former governing the magnetocaloric material (MCM) and the latter involving the heat transfer fluid.

$$\rho_s c_s(T_s, B)\frac{\partial T_s}{\partial T} = k_s\frac{\partial^2 T_s}{\partial x^2} - h_{eff}\frac{\beta_s}{1-\alpha}(T_s - T_f) + \dot{Q}_{MCE} \tag{6}$$

In this equation, the term $\dot{Q}_{\text{MCE}}$ represents the heat source or sink associated with the magnetocaloric effect that occurs during the previously described cycles. It is calculated using the appropriate equation based on the magnetic entropy change, which depends on the variation of the external magnetic field and the resulting changes in the material's thermophysical properties, as described in [12]. The hot and cold temperatures vary symmetrically while maintaining a constant mean temperature, defined as $T_m = (T_{\text{hot}} + T_{\text{cold}})/2 = 21°\text{C}$.

The other two main terms that influence the operating parameters of the Active Magnetic Regenerator (AMR) are related to heat conduction within the solid and heat exchange with the heat transfer fluid.

$$\rho_f c_f\left(\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial u}\right) = k_f\frac{\partial^2 T_f}{\partial x^2} + h_{eff}\frac{\beta_s}{\alpha}(T_s - T_f) - u\frac{dP}{dx} \tag{7}$$

2.3 Performance and Control Parameters

The performance parameters include the cooling load ($\dot{Q}_{\text{in}}$) and the coefficient of performance (COP). The COP is given by equation (8) and is a measure of the efficiency of the refrigeration cycle. The cooling load is given by equation (9). In these equations, τ_c represents the cycle time, m_f represents the mass flow rate of the fluid, and $\dot{Q}_{\text{out}}$ represents the heat removed.

$$COP = \frac{\dot{Q}_{in}}{\left|\dot{Q}_{out} + \dot{Q}_{in}\right|} \tag{8}$$

$$\frac{\dot{Q}_{in}}{M_s} = \frac{1}{\tau_c M_s}\int_0^{\frac{\tau_c}{2}} \dot{m}_f c_f(T_{c'} - T_c)dt \tag{9}$$

The main control parameter analyzed is the mass flow rate represented by the dimensionless utilization factor (10).

$$\Phi = \frac{\dot{m}_f c_s}{M_s c_s}\tau_c \tag{10}$$

3 Results and Discussion

The simulations conducted were to determine whether the addition of nanoparticles to the base fluid W-PG30% show the result with could compensate and improve its yields in the context of magnetic refrigeration in terms of cooling power ($\dot{Q}_{\text{in}}$) and COP. The evaluations were carried out according to the two most relevant operational parameters namely the fluid flow rate represented by the dimensionless parameter Φ and the rotational frequency of the refrigerating machine. The properties of the nanoparticles were modeled according to relationships for density and specific heat and according to Corcione's relationships (which take into account the physics of thermal transport and the rheology of nanofluids) for thermal conductivity and viscosity.

As it had already been studied the W-PG30% mixture due to its high viscosity and low thermal conductivity had low cooling power values. Simulations, however, showed that the addition of the nanoparticles significantly mitigated this problem by improving heat transfer. All nanoparticles exhibited the same behavior as an example Figure 2 shows the graphical results of SiC, where there is the trend of variation of cooling load ($\Delta\dot{Q}_{in}$), equation (11), as a function of ΔT_{span}.

$$\Delta\dot{Q}_{in}\% = \frac{\dot{Q}_{in,nf} - \dot{Q}_{in,bf}}{\dot{Q}_{in,bf}} \times 100 \qquad (11)$$

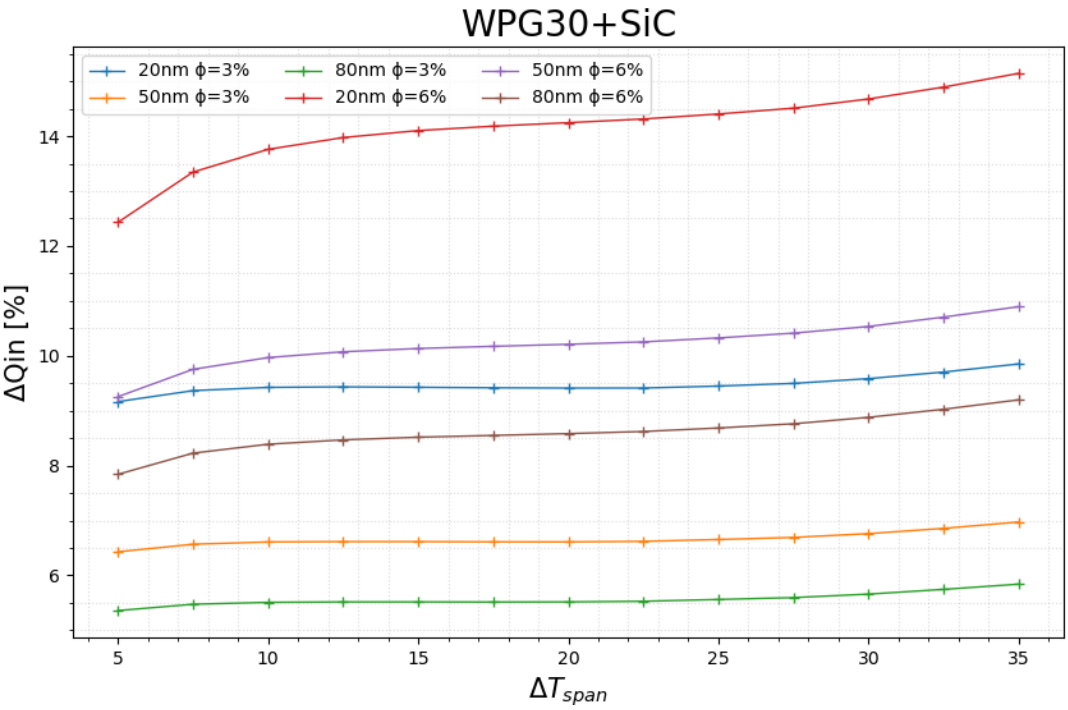

Figure 2: $\Delta\dot{Q}_{in}\ of\ WPG30\% + SiC$

As can be seen at the same material and volumetric concentration (ϕ) of the nanoparticles as the nanoparticle size (d_p) increases, $\Delta\dot{Q}_{in}$ decreases, which is also to be expected from Corcione's relations since the increase in d_p would have worsened the average Brownian velocity thus worsening Reynolds and the thermal conductivity of the nanofluid.

For the same d_p and material, increasing the volumetric concentration, results in higher $\Delta\dot{Q}_{in}$ as there is an increase in thermal conductivity and more convective energy related to the Brownian effect.

These results are obtained in spite of the fact that the addition of nanoparticles increases the viscosity of the heat transfer fluid, so this negative effect is largely offset by the improvement of other thermophysical properties, leading to higher refrigeration powers than with the base fluid, especially at high ΔT_{span} as these are associated with an increase in the driving force for heat transfer, making the positive contribution of the improved thermal properties of the nanofluid more significant.

The best configuration in all cases is the one with the smallest particle size and the highest volumetric concentration, interestingly, a higher volumetric concertation does not always produce a higher cooling power than one with a lower concentration, this is the case for the ϕ=3% and d_p=20nm configuration that produces a higher $\Delta\dot{Q}_{in}$.

Regarding COP, Figure 3 showing $\Delta COP\%$, equation (12), as a function of ΔT_{span}, this shows an inverse behavior with respect to $\Delta\dot{Q}_{in}$, i.e., the introduction of the nanoparticles produced a worsening, especially at low values of ΔT_{span}, worsening that increasing ΔT_{span}

mitigates. Physically what happens is that the increased viscosity generated by the particles, especially at high concentrations and small sizes, leads to increased pumping work, reducing the overall efficiency of the system.

Therefore what in terms of $\Delta\dot{Q}_{in}$ turned out to be the best configuration, in terms of $\Delta COP\%$ is the worst, this implies how in order to get good results in terms of COP and $\dot{Q}_{in}$ one has to find a compromise, which in this study might have been found in the ϕ=3% and d_p=20nm configuration that penalizes the COP but not too much and increases the refrigeration power enough.

It is important to note that these results occur when the simulation is aimed at optimizing maximum cooling power. This means that simulations aimed instead at maximizing COP can lead to better results in terms of higher rotational frequencies and flow rates at which the maximum COP is achieved, thus obtaining higher values overall. An example of the above is the paper [13], in which both $\dot{Q}_{in}$ and COP are optimized. In this paper, reference is made to areas, as a function of frequency and flow rate, where both parameters can be optimized and maximized simultaneously, keeping them within 95% of their maximum value. However, in this particular case, the heat transfer fluid used was water.

$$\Delta COP\% = \frac{COP_{nf} - COP_{bf}}{COP_{bf}} \times 100 \tag{12}$$

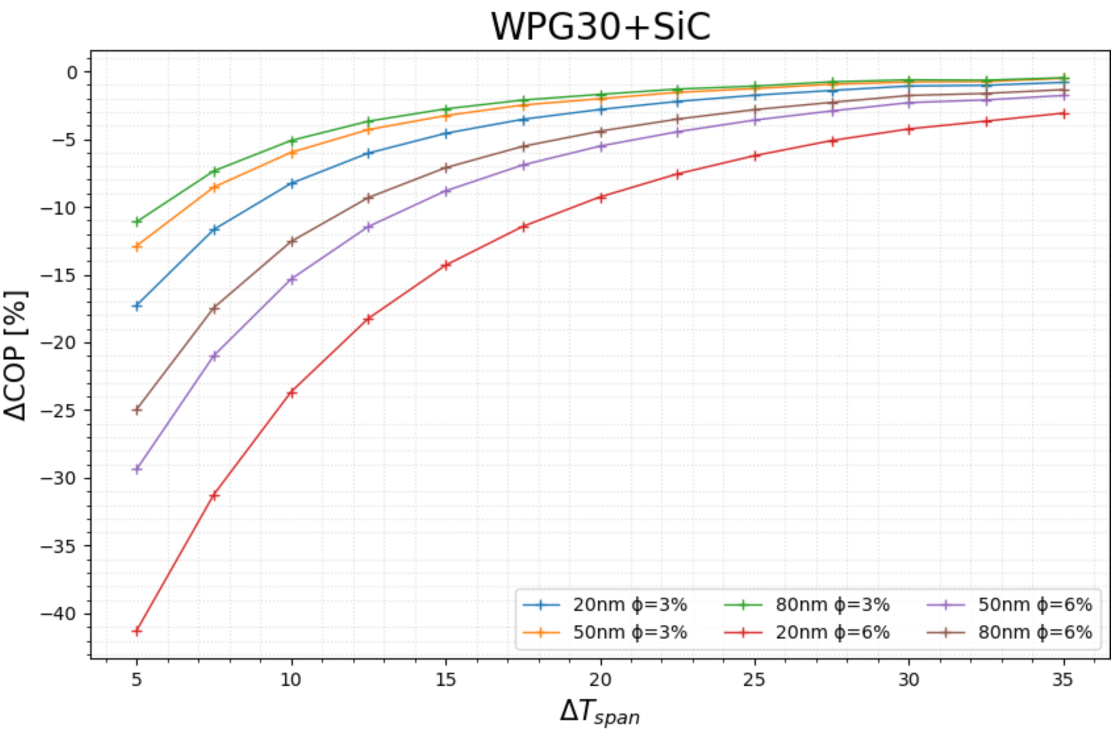

Figure 3: $\Delta COP\%$ of WPG30%+SiC

4 Conclusion

The study showed that the performance of a magnetic refrigeration system is strongly influenced by the volumetric concentration and size of nanoparticles used in a W-PG30%-based nanofluid.

It has been observed:

- Particles with smaller size and higher volumetric concentration are able to improve the cooling performance up to 15% more, this improvement is due to the increase in thermal conductivity and convective coefficient compared to the low fluid.
- However, high dynamic viscosity is associated with this configuration, resulting in high pumping work to maintain fluid flow, thus penalizing system efficiency (COP), especially when the ΔT_{span} is low.
- From this emerges the need to have to find a design compromise that does not penalize COP too excessively and maximizes cooling power.

In summary, the research finds considerable interest regarding the possible uses of nanofluids in magnetic refrigeration, but cautions that the effectiveness of the application depends on precise calibration of frequency, flow, viscosity and thermal conductivity, parameters also related to the sizing and concentration of the nanoparticles.

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