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Enhancing the Frequency of Magnetic Refrigerators Using Dummy Regenerators

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Abstract. *Magnetic Refrigeration (MR) has emerged as one of the most viable alternatives to vapor compression refrigeration, attracting interest from both industry and academia. Yet, even after decades of research and development, the technology is not commercially available and the prototypes did not achieve the expected thermodynamic performance. Among several factors, one can highlight the fact that in rotary Magnetic Circuit (MC) devices the magnetic interaction between the Active Magnetic Regenerators (AMR) and MC is responsible for generating high torques to rotate the MC. Such high torque requirements prevent the operation of the MR systems at high frequencies, limiting it to a few Hertz. With that in mind, the present work proposes the application of the so-called dummy regenerators (DRs), which are composed by particles of non-magnetocaloric soft ferromagnetic materials, positioned between an array of eight non-contiguous AMRs. The objective of the DRs is to reduce the maximum torque associated with the rotation of the MC and enhance the operating frequency of magnetic refrigeration systems. Among several results, the application of the DRs reduced the peak values of the torque associated with the rotation of the MC by 75% and enabled the maximum system frequency to be increased from 0.75 Hz up to 1.64 Hz.*

Keywords: *magnetic refrigerator, active magnetic regenerator, magnetic circuit, performance enhancement*

1. INTRODUCTION

Refrigeration systems are vital technologies in contemporary societies. Nowadays, the refrigeration sector accounts about 20% of the global electricity consumption and employs over 15 million people worldwide (Dupont *et al.*, 2019). Furthermore, Dupont *et al.* (2019) estimate that the global electricity consumption demanded by refrigeration systems could more than double by 2050. In terms of the technologies applied in such systems, vapor compression refrigerators dominates both household and commercial applications, being a well established technology with more than a century of development (Bansal, 2016). However, mechanical compression refrigeration systems exhibit inherent inefficiencies (Monfared, 2018) and operate with flammable, toxic and environmentally harmful refrigerant fluids.

In the pursuit for higher system efficiencies and environmentally friendly refrigerants, Magnetic Refrigeration (MR) presents itself as one of the most promising alternative technologies to mechanical vapor compression refrigeration (Kitanovski *et al.*, 2015). The principle that governs the operation of a MR system is the magnetocaloric effect (MCE), defined as the thermal response of a magnetocaloric material (MCM) to a varying magnetic field. Due to the reversible nature of the MCE in many materials, MR has the potential to achieve higher efficiencies when compared with vapor compression systems. Furthermore, a MR system operates with a solid refrigerant, preventing the leakage for the atmosphere, and the permanent magnets (PM) in the Magnetic Circuit (MC) can be recycled or reused (Trevizoli and Barbosa Jr, 2020).

A MR system can operate in accordance with different thermodynamic cycles, however, the easiest to implement in order to achieve high temperature spans and cooling capacities is the thermo-magnetic Brayton cycle, which is composed of two isofield and two isentropic processes (Kitanovski *et al.*, 2015). The cycle is presented in Fig. 1 and its four steps are described below:

1. **Adiabatic magnetization:** the magnitude of the applied magnetic field is increased over the Active Magnetic Regenerator (AMR) adiabatically. Due to the MCE, the MCM temperature increases.

2. **Constant magnetic field cold blow:** the applied magnetic field is kept constant and fluid from the cold reservoir flows through the magnetized porous MCM matrix, absorbing heat from the porous medium. As a consequence, the fluid temperature increases above the hot reservoir temperature and rejects heat to the latter.

3. **Adiabatic demagnetization:** the magnitude of the applied magnetic field is reduced to zero over the AMR adiabatically. Due to the MCE, the MCM temperature decreases.

4. **Constant magnetic field hot blow:** the applied magnetic field is kept constant and fluid from the hot reservoir flows through the demagnetized porous MCM matrix, rejecting heat to the porous medium. As a consequence, the fluid temperature decreases below the cold reservoir temperature and absorbs heat from it.

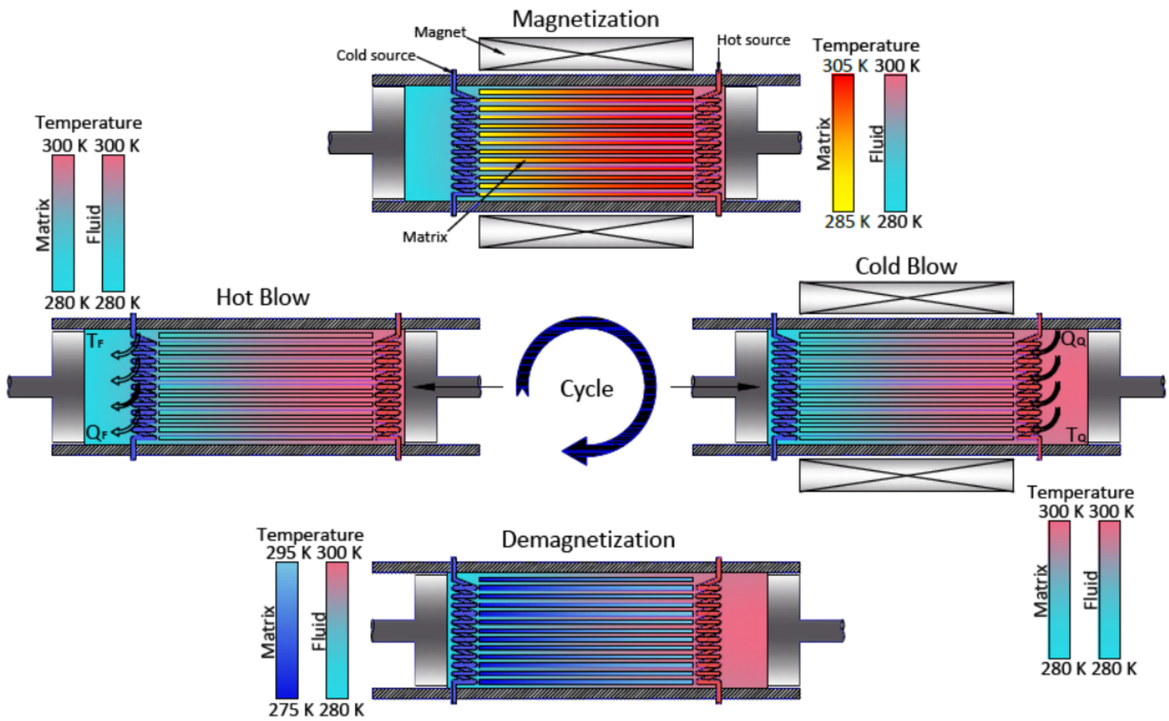


Figure 1: Schematic diagram of a magnetic refrigerator cycle based on the ideal thermo-magnetic Brayton cycle (Barbosa Jr *et al.*, 2014).

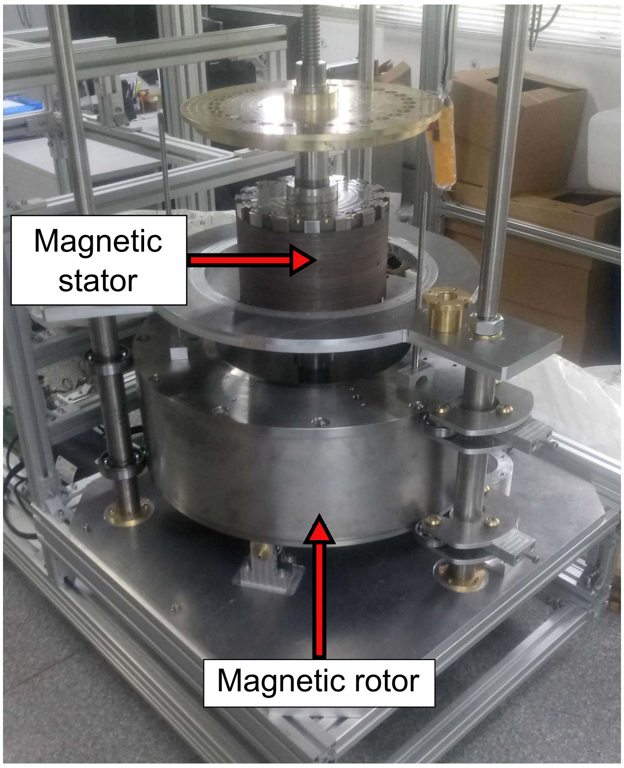
Even tough decades of research and development have been dedicated to MR, the technology is not commercially available since the prototypes developed so far have not achieved the expected thermodynamic performance yet. Among several factors, one can highlight the low magnitude of both the MCE provided by the available materials and the magnetic field intensity reached by the PM MCs employed in such devices. Furthermore, in rotary magnetic circuit devices (the configuration known to reach the highest cooling capacities) the magnetic interaction between the AMR and MC is responsible for generating high torques to rotate the MC. Such high torque requirements prevent the operation of the MR systems at high frequencies, causing major performance limitations.

To reduce the magnetic interaction between the AMRs and MC, strategies such as employing an odd number of AMR beds or an array of even-number contiguous AMRs have been proposed (Dall'Olio *et al.*, 2021). However, for many times such approaches were not effective and, to compensate for the low operating frequencies, MR systems must employ strategies that are highly detrimental to the thermodynamic performance and cost of the system, such as large refrigerant masses, high magnetic fields, and high liquid mass flow rates to achieve practicable cooling capacities.

With that in mind, the present work seeks to propose the application of the so-called dummy regenerators (DRs), which are composed of particles of non-magnetocaloric soft ferromagnetic materials, positioned between an array of eight non-contiguous AMRs. The objective of the DRs is to reduce the torque associated with the rotation of the MC and enhance the operating frequency of magnetic refrigeration systems. The DRs are composed of stainless-steel spheres allocated in a 3D printed housing, which were designed by numerical simulations performed in the software COMSOL Multiphysics®.

2. PROBLEM DESCRIPTION

The first step of the project was to evaluate what caused the high torques required to rotate the MC in rotary Magnets MR. Fig. 2a shows the MC configuration developed for a magnetic air conditioner at Polo - Research Laboratories for Emerging Technologies in Cooling and Thermophysics (Peixer *et al.*, 2022). The system operates with a rotary MC in which the outer cylinder, known as the magnetic rotor, is where the PM are located. Additionally, the inner cylinder, known as the magnetic stator, is composed of thin layers of electrical steel E145 to prevent eddy currents. Furthermore, as can be seen in Fig. 2b, the AMRs are positioned in the magnetic stator. An explanatory video presenting the operation of the MR can be found in the following link: https://bit.ly/2ZmbKFI.



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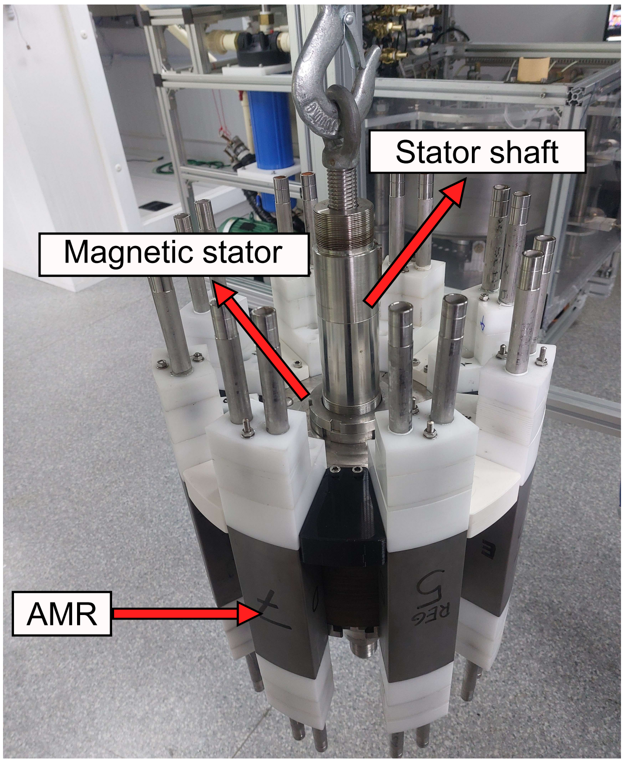


(b)

Figure 2: The magnetic air conditioner prototype developed at the Polo Laboratories (a) magnetic circuit and (b) magnetic stator with the AMRs in place.

With the MC configuration in mind and knowing that the MCM is ferromagnetic during certain steps of the MR cycle, one can understand that the magnetic interaction between the PM and the MCM inside the AMR will generate high torques to rotate the magnetic rotor. For instance, when operating with 8 non-contiguous AMRs and considering that the experimental apparatus is limited to a rotating torque of 40 Nm, the magnetic air conditioner achieved a maximum operating frequency of 0.75 Hz.

Thus, it becomes clear that the high torques generated by the magnetic interaction between the PM and MCM are highly detrimental to the performance of the system, since they reduce its maximum frequency. As a consequence, performance parameters such as the cooling capacity are also affected, which demands an increase of the mass flow rate, magnetic field or MCM mass to compensate such loss. With the motivation of solving the torque problem and, as a consequence, increase the MR system maximum frequency, the idea of the DRs arise. The goal is to fill in the spaces between the 8 non-contiguous AMRs (see Fig. 2b) with casings which will not be submitted to fluid flow and will be filled with soft ferromagnetic material, to refer to these casings the name "Dummy Regenerators" was chosen. The objective of the design is to achieve a frequency of at least 1.5 Hz, deemed adequate for the operation of the system (Peixer, 2020), without modifying the mechanical transmission system and the MC.

The purpose of the DRs is to magnetically interact with the magnetic rotor PM in such a way that the maximum rotation torque of the MC is reduced and the magnetic field profile in the air gap is not greatly affected, thus allowing the MR system to achieve higher frequencies and having little influence on the magnetic field profile that acts on the AMRs. In addition, the DRs casing must be able to resist the mechanical stresses caused by the soft ferromagnetic material when attracted by the magnetic rotor PMs. The design requirements for the DRs are summarized below:

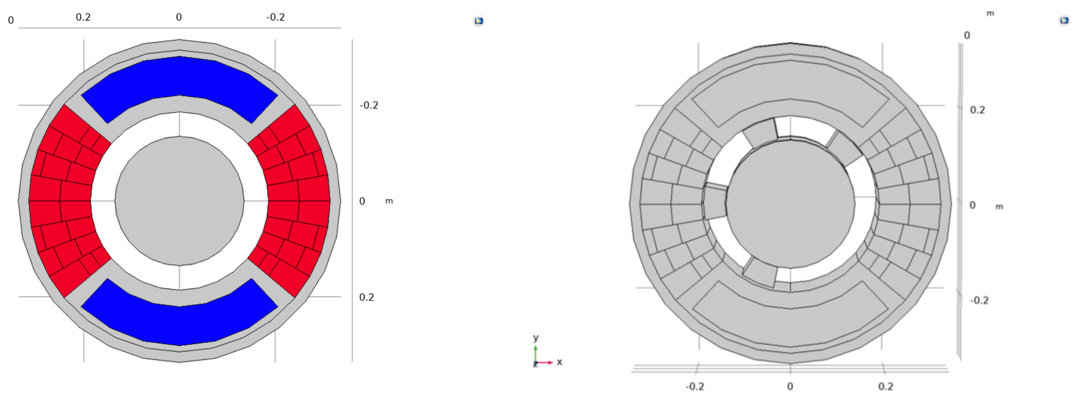
- Reduce the peak torque value associated with the rotation of the MC;
- Have as little impact as possible in air gap magnetic field profile;
- Resist the mechanical stresses caused by the soft ferromagnetic material.

3. MAGNETIC DESIGN OF THE DUMMY REGENERATORS

In this section, the magnetic design of the DRs is presented. The first step of the magnetic design consists of the development of a numerical model capable of predicting with reasonable accuracy the maximum torque to rotate the MC. For that purpose, the software COMSOL Multiphysics® was employed. In possession of a validated model, the second step consists in using this tool to find the best geometry for the DRs.

3.1 Magnetic model

The magnetic model was developed in the Magnetic Field No Currents (MFNC) module of the software COMSOL Multiphysics®. The first step in the development of the model consisted of the implementation of the MC geometry displayed in Fig. 2a, that is schematically presented in Fig. 3a. After that, the AMR geometry was implemented and inserted in the air gap, as shown in Fig. 3b for an array of 4 AMRs asymmetrically positioned in the air gap. One should highlight that the initial goal is to develop the magnetic model and validate it with the use of experimental torque data generated experimentally in the Polo Magnetic Air Conditioner (PMAC) prototype. Although the main objective of the present work is to apply the DRs to a MR system with 8 AMRs, due to simplicity and convenience the experimental torque data used for the magnetic model validation was obtained with the PMAC operating with 4 assymetric AMRs (as illustrated in Fig. 3b).



(a) (b)

Figure 3: Magnetic model: (a) MC geometry implemented in the MFNC module. The red color indicates the permanent magnets, the blue color represents the air inside the magnetic rotor and the grey color the eletrical steel. (b) Geometry used to validate the magnetic model with experimental data.

With the geometry of the MC and AMRs inserted in the software, the magnetic properties of the materials were defined and the problem parameters were implemented (remanence direction of the PMs, magnetic flux conservation, infinite domain and magnetic insulation). A point worth mentioning is relative to the MCM magnetic properties, which were implemented into the software based on the data provided by the manufacturer Vacuumschmelze GmbH & Co. KG. The MCM material used in the PMAC consists of a packed-sphere bed composed of $La(FeMnSi)_{13}H_y$ alloys, referred to as CVHS2, with a relative magnetic permeability of approximately 360 in the linear region of the BH curve. With the magnetic model concluded, the simulations were performed and the simulated torque values were obtained for different angular positions of the magnetic rotor. Finally, Fig. 4 compares the experimental and simulated torque values.

The torque results for experimental (CVHS2 in Fig. 4, orange curve) and simulated (COMSOL in Fig. 4, blue curve) have a considerable deviation in their shape, which is attributed to the modeling of the porous structure of the AMR and

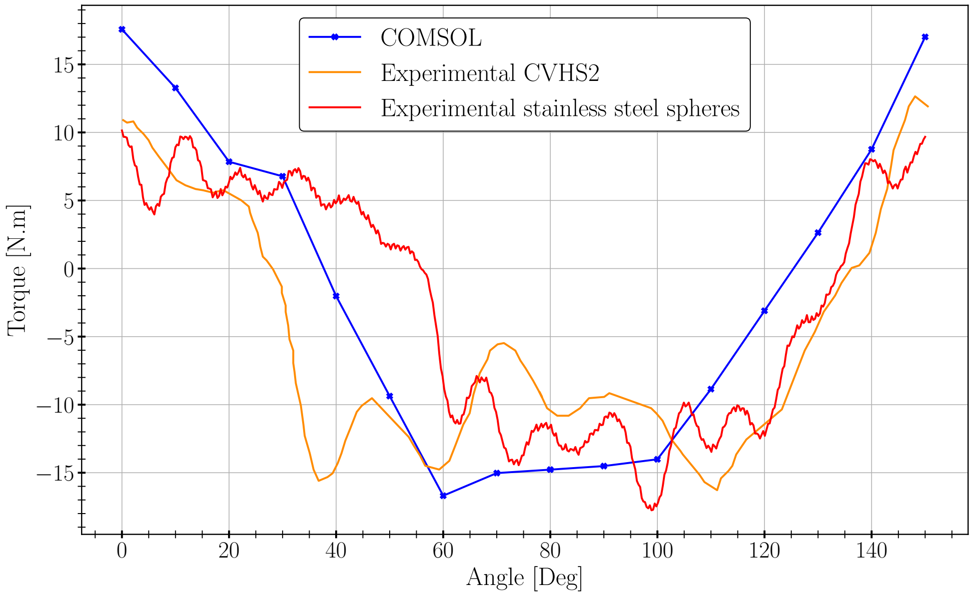


Figure 4: Rotation torque for the MC as a function of the angular position of the magnetic rotor.

the magnetic transtion of the MCM. However, in practical terms, what limits the frequency of the PMAC is the peak value of torque and, as shown in Table 1, the magnetic model has managed to predict with a very good accuracy the peak torque value of the experimental results. Hence, the magnetic model was considered validated for the purpose of the predicting the maximum torque value.

Table 1: Peak torque values for each case of the Fig. 4.

Case	**Peak torque [N.m]**
COMSOL	-17.10153846
Experimental stainless steel spheres	-17.76009
Experimental CVHS2	-16.28271

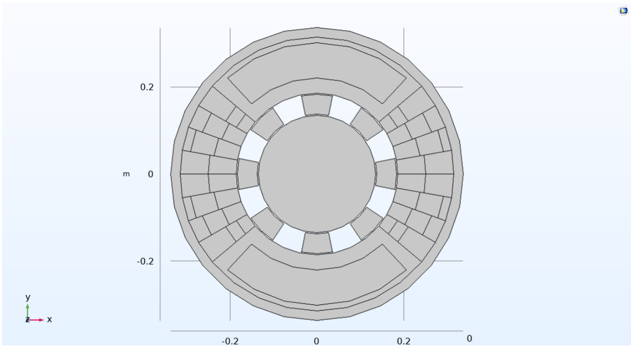
In addition to the experimental and simulated curves for CVHS2 shown in Fig. 4, one extra experimental curve is also shown. It consists of experimental results for the PMAC operating with regenerators filled with stainless steel spheres. Although the spheres are composed of stainless steel and are not supposed to be ferromagnetic, they become soft ferromagnetic due to the manufacturing process. With that information in mind and aiming at selecting a material for the DRs, it was decided to test the PMAC operating with stainless steel spheres and evaluate the torque behavior. As can be seen in Fig. 4, although once again the torque results have a considerable difference in shape, the peak torque value for the regenerators operating with stainless steel spheres showed very good agreement with the regenerators operating with CVHS2 (both experimental and simulated). With such results, the stainless steel spheres were selected for the DRs.

3.2 Design of the dummy regenerators geometry

Having validated the magnetic model and selected the material for the DRs, the second step of the design consists of determining the geometry for the DRs, i.e., finding the geometry that presents the best compromise between reducing the rotation torque of the MC and having as little impact as possible in the air gap magnetic field profile.

To avoid problems during the positioning of the DRs inside the air gap (the space between the magnetic rotor and stator), and also leaving a margin to increase the wall thickness in the final geometry (the DRs casing must resist the mechanical stresses caused by the stainless steel spheres inside them), for all the performed simulations the internal region of the DRs was positioned 10 mm from the magnetic rotor and 5 mm from the magnetic stator. Taking that into consideration, the parameter to be defined through the simulations with the magnetic model is the DRs sector angle. In total, four cases were simulated and Fig.5 provides a description of each case. For each case, the results for rotation torque and air gap magnetic field profile are presented in Fig. 6.

As expected, the results in Fig. 6a show that as the DRs sector angle increases the peak torque decreases. However, as one can also see in Fig. 6b, as the DRs sector angle increases the air gap magnetic field profile is also affected. A point worth mentioning is that in order to maximize the performance of a MR system the MC must provide the highest magnetic field possible in the high field region (between 0° to 12.5° in Fig. 6a) and the lowest magnetic field possible in



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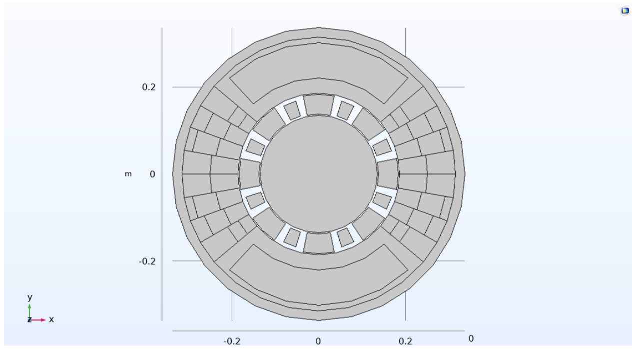

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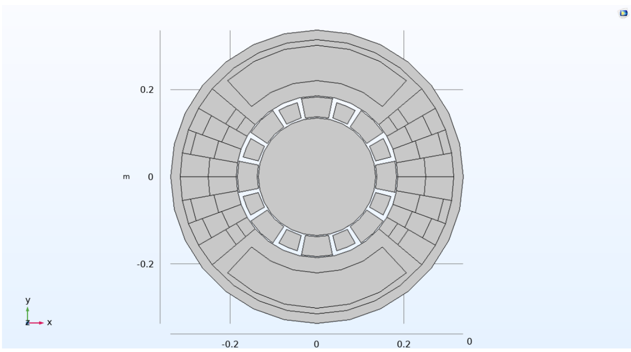

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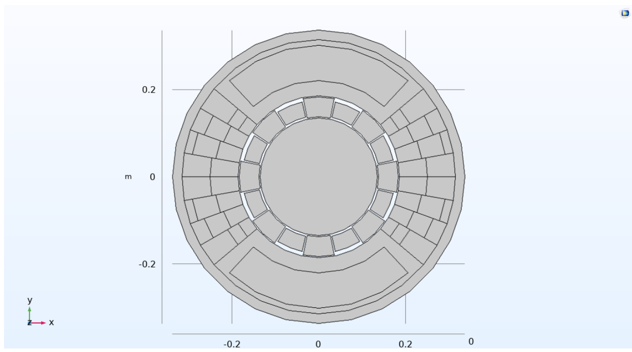
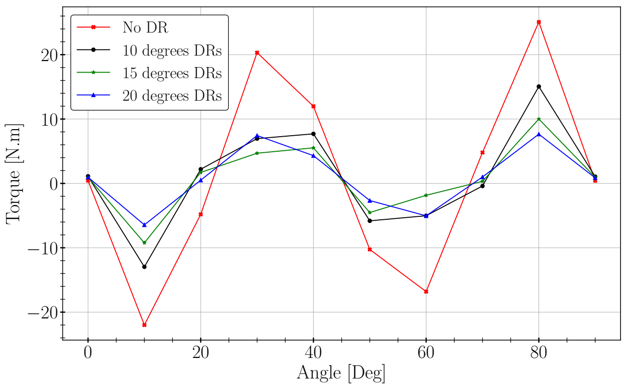


(d)

Figure 5: Cases simulated with the magnetic model for the selection of the DRs geometry. (a) 8 AMRs without DRs. (b) DRs with 10° sector angle, (c) DRs with 15° sector angle. (d) DRs with 20° sector angle.



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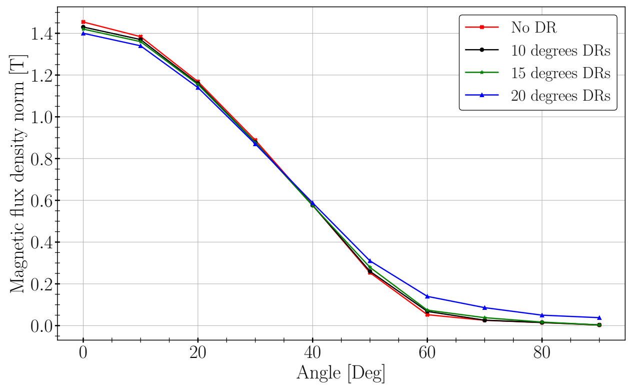


(b)

Figure 6: Simulated results for the selection of the DRs geometry. (a) Torque as a function of the rotation angle. (b) Magnetic flux density norm in the air gap as a function of the rotation angle.

the low field region (between 78.75° to 90° in Fig. 6a).

With that in mind, even though the DRs with 20° sector angle provide the maximum reduction in the peak torque value, they have a considerable impact in the air gap magnetic field profile given the decrease of the magnetic field in the high field region and the increase in the low field region. Taking all that into consideration, the DRs with 15° sector angle were chosen as the final geometry of the magnetic design since they provide the best compromise between peak torque value reduction and low impact in the air gap magnetic field profile.

4. MECHANICAL DESIGN OF THE DUMMY REGENERATORS

The next step in the process is to design the casing for the DRs based on the geometry defined in the magnetic sizing. With that in mind, the mechanical design aims to determine the wall thicknesses of the DRs housing based on the geometry in the magnetic design. Since the DRs will not be subjected to fluid flow, all stresses will be caused by magnetic forces between the magnetic rotor and DRs soft ferromagnetic material. These magnetic forces will press the soft ferromagnetic material against the inner walls of the DRs housing, causing the previously mentioned stresses.

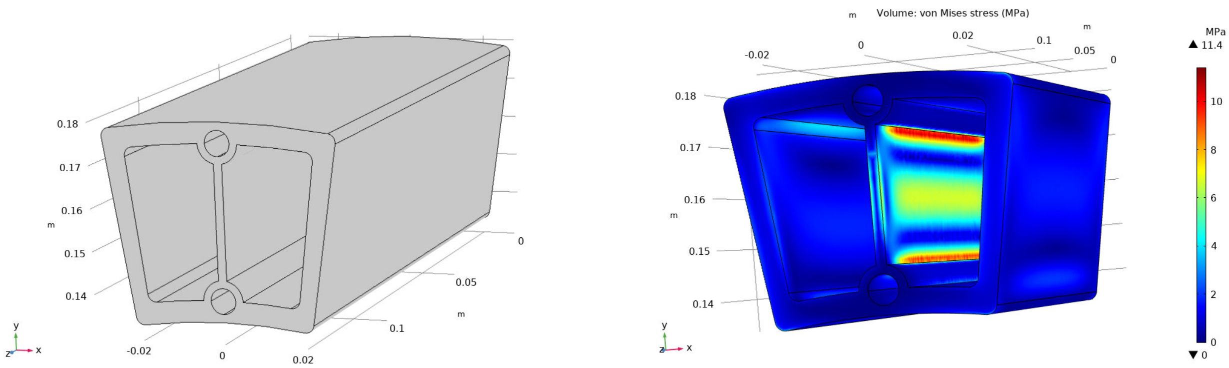
The components of magnetic force (x, y and z) acting in the DRs soft ferromagnetic material were numerically calculated for each angle using the "Force Calculation" tool of the software COMSOL Multiphysics®; the results are shown in Tab. 2. As one can see, the peak value of magnetic force acting in the DRs soft ferromagnetic material occurs for an 80° angle, this peak value was used as an input for the stress analysis simulation.

Table 2: Magnetic force for each angle acting in the DRs soft ferromagnetic material.

theta (deg)	Magnetic force, x [N]	Magnetic force, y [N]	Magnetic force, z [N]
0	2.7145	-0.98127	0.0028836
10	0.32393	-0.016173	-0.0043692
20	0.021457	-0.0064846	-0.00030798
30	-0.084732	0.0029418	0.00036601
40	-1.3113	-0.32483	-0.0021367
50	-5.5535	-2.8293	0.038638
60	-62.391	-65.691	0.076404
70	-427.08	-319.06	-0.58795
80	-572.17	-397.25	-0.32593
90	-448.18	-418.09	0.20521

An internal rib was inserted to increase the mechanical resistance of the geometry. In addition, two holes for threaded bars were inserted to allow for DR alignment in the magnetic stator. Figure. 7a shows the DRs geometry after such changes. One shall highlight that with the exception of the inner rib, the DRs housing hole (where the soft ferromagnetic material will be placed) has the dimensions defined in the magnetic design. In terms of boundary conditions, a fixed constraint was applied to the ends faces of the DR and the inner faces of the holes. Also, a boundary load with the magnitude defined by the peak value of magnetic force in Tab. 2 was applied to all internal faces.

In terms of material, Tritan was chosen for the DRs housing due to the fact that it has the highest mechanical resistance among the filaments available for 3D printing. According to the manufacturer specifications, the former has a tensile yield strength of 45 MPa. The stress analysis through finite element method was performed in the Solid Mechanics module of the software COMSOL Multiphysics® , the results of von Mises equivalent stress are shown in Fig. 7b



(a) (b)

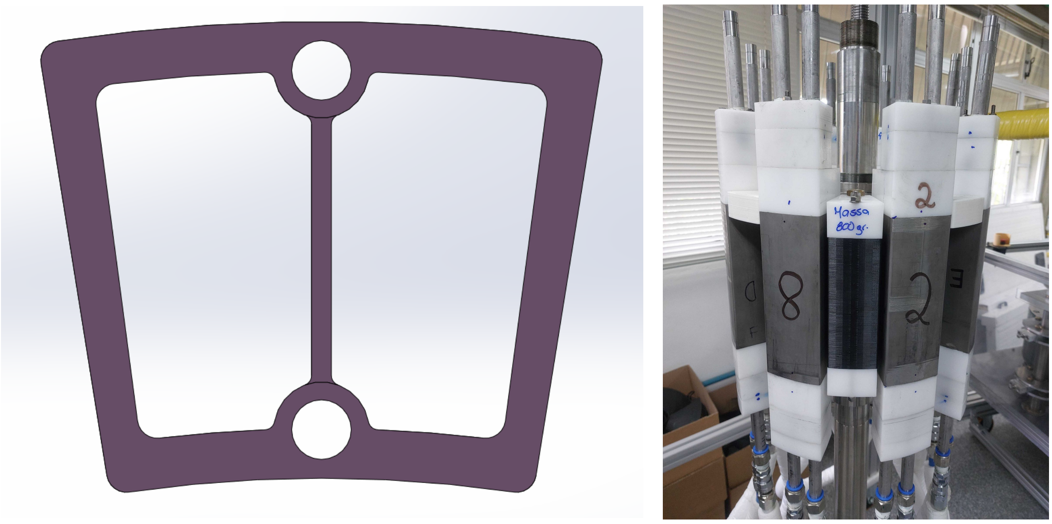
Figure 7: DRs mechanical design (a) geometry used in the stress analysis and (b) results of von Mises equivalent stress.

The final geometry has a housing thickness of 5 mm, rib thickness of 2 mm and a 2 mm rounding in all corners. As one can see, the highest equivalent von Mises stress value obtained was 11.4 MPa, resulting in a safety factor of 3.95.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, the experimental results for PMAC operating with the DRs final geometry is exhibited. The casing geometry shown in Fig. 8a was 3D printed and filled with the stainless steel spheres, in next, the DRs were positioned between the AMRs in the magnetic stator of the PMAC, Fig. 8b shows the positioning process. Finally, Fig. 9 shows the experimental results of torque as a function of the angular position.

It becomes clear by evaluating the experimental curves that the DRs have a tremendous impact in reducing the peak torque value and, as a consequence, increasing the PMAC maximum operating frequency. The DRs reduced the peak torque associated with the rotation of the MC from approximately 40 Nm to 10 Nm, a reduction of around 75%. In terms of frequency, the DRs increased the maximum operating frequency of the PMAC from 0.75 Hz to 1.64 Hz. Therefore, the



(a) (b)

Figure 8: Final geometry of the DRs (a) cross-section and (b) positioning of the DRs (black casing) between the AMRs of the PMAC.

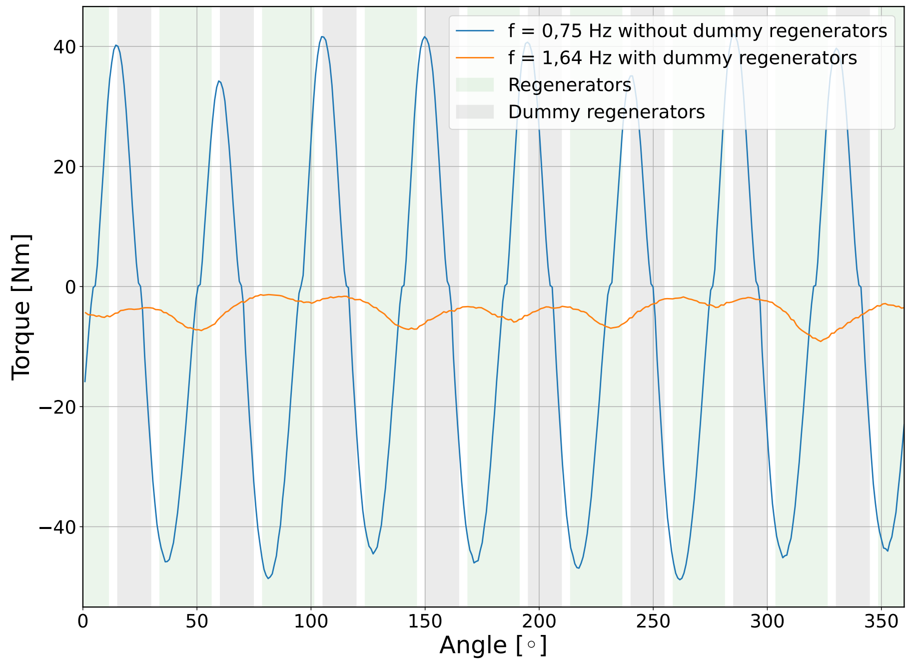


Figure 9: Experimental results of torque as a function of the angular position for the PMAC operating without and with the DRs.

DRs achieved the design requirements and its installation allowed the PMAC to operate at higher frequencies.

6. CONCLUSIONS

In terms of performance improvements of a MR systems, to compensate for the low operating frequencies studies usually employ strategies that are highly costly and detrimental to the thermodynamic performance. In other words, alternatives to increase the system frequency are usually not explored or superficially analyzed. With that in mind, the present work proposes a different approach to the frequency problem with the utilization of the so-called DRs.

In the first part of the study, a magnetic model was developed in the software COMSOL Multiphysics®, the model was able to predict with very good accuracy the maximum torque value of the experimental torque data generated in the PMAC. Furthermore, the experimental data showed a very good agreement between the regenerators operating with stainless steel spheres and the regenerators operating with CVHS2, with such results the stainless steel spheres were selected to be the material inside the DRs.

In next, in possession of a validated magnetic model, the DRs geometry selection is carried out. The DRs with 15°

sector angle were chosen as the final geometry due to the best compromise between peak torque value reduction and low impact in the air gap magnetic field profile. The DRs final geometry was 3D printed, filled with the stainless steel spheres and experimentally tested in the PMAC. As final results, the DRs were successful and reduced the peak torque associated with the rotation of the MC from approximately 40 Nm to 10 Nm, a reduction of around 75%. Beyond that, the DRs increased the maximum operating frequency of the PMAC from 0.75 Hz to 1.64 Hz.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Bansal, P., 2016. “Latest developments in not-in-kind refrigeration technologies”. *Science and Technology for the Built Environment*, Vol. 22:5, pp. 473–474.

Barbosa Jr, J.R., Lozano, J.A. and Trevizoli, P.V., 2014. “Magnetocaloric refrigeration research at the inct in cooling and thermophysics”. In *Proceedings of the ENCIT 2014*.

Dall’Olio, S., Masche, M., Liang, J., Insinga, A.R., Eriksen, D., Bjørk, R., Nielsen, K.K., Barcza, A., Vieyra, H.A., Beek, N.V., Nevez Bez, H., Engelbrecht, K. and Bahl, C.R.H., 2021. “Novel design of a high efficiency multi-bed active magnetic regenerator heat pump”. *International Journal of Refrigeration*, Vol. 132, pp. 243–254.

Dupont, J.L., Domanski, P., Lebrun, P. and Ziegler, F., 2019. “The role of refrigeration in the global economy”. *38th Informatory Note on Refrigeration Technologies, Technical Report*.

Kitanovski, A., Tušek, J., Tomc, U., Plaznik, U., Ožbolt, M. and Poredoš, A., 2015. *Magnetocaloric Energy Conversion: From Theory to Applications*. Springer.

Monfared, B., 2018. “Design and optimization of regenerators of a rotary magnetic refrigeration device using a detailed simulation model”. *International Journal of Refrigeration*, Vol. 88, pp. 260–274.

Peixer, G.F., Silva, M.C.R., Lorenzoni, A., Hoffmann, G., dos Santos, D., Dutra, S.L., Teza, H., Pagnan, E., Vieira, B.P., Nakashima, A.T.D., Lozano, J.A. and Barbosa, Jr., J.R., 2022. “Evaluating the performance of a trl-6 magnetic air conditioner prototype”. In *19th International Refrigeration and Air Conditioning Conference at Purdue*. Purdue, United States.

Peixer, G.F., 2020. “Thermodynamic design of a magnetic cooling system for air-conditioning applications”. Master’s thesis, Universidade Federal de Santa Catarina, Florianópolis, Brazil.

Trevizoli, P.V. and Barbosa Jr, J.R., 2020. “Overview on magnetic refrigeration”. *Encyclopedia of Smart Materials - Reference Module in Materials Science and Materials Engineering*.

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