Simulator development of a rotary magnetocaloric refrigerator by stepwise regenerator modelling approach

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Abstract. Magnetic refrigeration has been seeing as a promising technology based on the magnetocaloric effect. One of its great advantages is it offers smaller global environmental impact relating to conventional refrigeration. Modeling and simulation of such processes can provide important data in the development and optimization of the experimental devices. Among existing designs, the rotary refrigerators presents several challenges in terms of complexity when comparing to reciprocating ones, which is compensated by several properties. A novel full process simulator of a magnetocaloric refrigerator processes was implemented to study the processes performance over different conditions. A stepwise modeling approach was applied, simplifying the phenomena of heat transfer. Gd was chosen as refrigerant material because of its magnetic transition temperature. The routine considered a rotating clockwise Gd wheel with an anticlockwise closed flow loop of water, which percolates the six Gd porous beds, hot and cold heat exchanger. The simulator was able to represent the transient aspects as well as the steady state conditions of the processes, considering both time performance and numerical stability. The inversion in heat transfer profiles along the process was used as a limit in the calculation of the maximum heat transfer absorption in the cold exchanger.

1. Introduction
The magnetocaloric effect (MCE) has been known since the 19th century [1], but devices using this technology only started to be developed in the early 20th century [2]. The MCE makes it possible to develop a green technology that offers an opportunity to use environmentally friendly solid refrigerants, and the potentially high energy efficiency follows the trends of future energy conversion devices [3]. Initially the MCE was used only to reach extremely low temperatures using paramagnetic salts, being a breakthrough in cryorefrigeration [4], because magnetic refrigeration was not feasible for devices operating at room temperature. Despite being more efficient than conventional refrigeration, there were no cost-effective materials that presented the MCE of significant amplitude. Furthermore, creating the magnetic field necessary to observe this effect is another challenge [5]. However, in 1997 that MCE gained great attention from the scientific community [6]. Pecharsky and Gschneidner published a work on the Gd2Ge2Si2 alloy, which presents the giant magnetocaloric effect (GMCE) [7]. From that work, a search was initiated for materials and systems that could manifest GMCE both at room temperature and at lower temperatures [8].
Several materials have been studied in recent years and a large number of possibilities have been discovered [9]. However, one of the main candidates for use as a regenerator in magnetic refrigeration at near-room-temperature remains the rare earth metal gadolinium (Gd) [10]. The Gd metal is a ferromagnetic material at right below room temperature, $T_{300}$, and it is a paramagnet just higher than $T_{300}$. In fact, Gd presents the magnetic transition temperature around $T_C = 20^0C$ [11]. It presents good magnetocaloric properties that makes Gd the benchmark magnetic regenerator material [2]. Actually, it is not easy to find a material with better properties for this application. Several early demonstrations of cooling by MCE were already done using this metal [12–14]. Besides, the first successful proof-of-principle refrigerator device operating at room temperature used Gd as the refrigerant [12]. It is no wonder that many near-room-temperature magnetic cooling machines were built powered by metallic gadolinium up to date [10,15,16].

Modeling and simulation of thermodynamic processes of these refrigerators can provide important data in the development and optimization of the experimental devices. There are some possible designs but among the existing, the rotary refrigerators presents several challenges in terms of complexity when comparing to reciprocating ones, which is compensated by several properties [16–20]. This work is inspired by a project being developed at IPRJ / UERJ and its a novel full process simulator of a magnetocaloric refrigerator processes and it was implemented to study the processes performance over different conditions. A stepwise modeling approach was applied in the script, simplifying the phenomena of heat transfers. For being a standard magnetocaloric material and by focusing in room temperatures applications, Gd was chosen as refrigerant material because of its magnetic transition temperature. The written routine considered a rotating clockwise Gd sectioned wheel with an anticlockwise closed flow loop of water, which percolates the six Gd porous beds, hot and cold heat exchanger. The transient aspects and the steady state conditions of the processes were taken into account in the simulator, which was able to consider both time performance and numerical stability. It was deliberated a limit in the calculation of the maximum heat transfer absorption based in the inversion in heat transfer profiles along the process in the cold exchanger.

2. Describing the rotary design and computational approach

In a straight way, the magnetocaloric effect is the ability of a material to have its temperature changed by changing the applied magnetic field to this material. In order to characterize the MCE, two physical quantities called magnetocaloric potentials are used to quantify the effect: the adiabatic variation of temperature, $\Delta T$, and the isothermal variation of entropy, $\Delta S$. The potential $\Delta T$ can be direct measure. However, in real experiments it is somewhat difficult and complicated to measure temperature variations in small samples. From Maxwell relations [2], one can obtain these two potentials from magnetization data in function of temperature and applied magnetic field. In fact, both potentials depends on the temperature and on the applied magnetic field changing $\Delta H$. The $(-\Delta S)$ vs. $T$ and $\Delta T$ vs. $T$ curves have similar shapes and present a maximum when derivative of $M(T, H)$ is maximum. This is the reason why the search for new materials for applications around room temperature is focused on those presenting near-room-temperature transition.

The developed simulator needs a temperature increment as an entry. Based on the $\Delta T$ vs. $T$ shape and on the $\Delta T$ vs. $\Delta H$ at $T = T_C$, i.e. the $\Delta T$ values at magnetic transition [11], it was achieved $\Delta T$ vs. $T$ points due to $\Delta H = 2.5 kOe$. This is a mean magnetic field value of grade N48 commercial $(40 \times 40 \times 20)$ $mm^3$ NdFeB magnets used in simulations. Indeed, this approach agreed with some behavior find in literature [2,3,21]. With this purpose, it was chosen functions for the fitting in two regions: ferromagnetic ordered phase, when $T < T_C$, and the paramagnetic phase, when $T > T_C$. The result of these considerations can be seen in Figure 1.

The data in Figure 1 was correlated to exponential function $y(T) = Ae^{bt}$, as described above, leading to models with great adjust with correlation coefficient higher than $R = 0.99$. From this way, it was possible to introduce the magnetocaloric effect into the simulator. Still in Figure 1, it is possible to observe a peak in the temperature variation $\Delta T$ for a temperature near to $T = 19^0C$, very close to $T_C$. 

\[ y(T) = Ae^{bt} \]
Figure 1. The $\Delta T$ vs. $T$ calculated values of Gd metal and the fittings using functions with similar shapes. The full diamond symbols represent the temperature changing $\Delta T$ due to $\Delta H = 2.5 \, \text{kOe}$. The red line represents the fitting of $\Delta T < 19^0C$ and the blue line represents the fitting of $\Delta T > 19^0C$. Both fitting were performed using $y = Ae^{bt}$.

With the aim of implement the simulation, it was chosen the Brayton thermo-magnetic closed cycle [2,22]. The Brayton cycle consists to two isentropic processes, $A \rightarrow B$ and $C \rightarrow D$ in Figure 2, and two isofield processes, $B \rightarrow C$ and $D \rightarrow A$ also in Figure 2.

Figure 2. The magnetic Brayton Cycle used in the simulation. The processes $A \rightarrow B$ and $C \rightarrow D$ are isentropic, and $B \rightarrow C$ and $D \rightarrow A$ are isofield processes. Blue line is the $T$ vs. $S$ curve for $H = 0$ and the red line is for $H \neq 0$.

In this figure it is possible to observe entropy values $S$ as function of temperature. The blue line is the entropy $S_0(T)$ with no applied magnetic field and the red line is the entropy $S_H(T)$ with $H \neq 0$. 
Starting at state $A$, an magnetic field $H$ is applied in the regenerator material. Adiabatically, the system reaches state $B$. Keeping $H$ steady, heat is removed from the system until state $C$, then the field $H$ is vanished and the material reaches state $D$ without heat exchange. Finally, with no applied field, the system is taken to state $A$ receiving heat closing the cycle. The magnetic material can exchange heat in $B \rightarrow C$ and $D \rightarrow A$ processes. In rotary design, two or more samples magnetic materials can be placed with the aim of optimize these processes, which can be happen at the same time. Assuming a fluid as heat exchanger, one can see the flow diagram of the used in this work in T 3.

![Flow Diagram](image)

**T 3.** The water flow diagram showing the heat exchangers (Hot source and Cold source) and the synchronized Gd numbered sectors. The flow is generated by the Pump and then passing through the system, percolating the Gd sectors. The magnetized section is the shadow region as shown in the figure. The numbers in the circles indicate the entries and the exits in each stage of the process.

In figure 3, the sectors of Gd are numbered from 1 to 6. Sectors $n$ and $n + 3$ will be synchronized, as sector 1 and sector 4 shown in this figure. The water flow scheme is divided into six points. In sector 1, which is in a region where the magnets provide $H = 2.5 \text{ kOe}$, the fluid enters in point 1 and leaves in point 2 percolating the metal, doing the heat exchange with the Gd sector and performing the $D \rightarrow A$ isofield process. At the same time, sector 4 receives a flow in point 5 which exits in point 6 after heat exchanging performing the process $B \rightarrow C$. Adiabatic processes occur when the sectors are entering in ($A \rightarrow B$) and leaving from ($C \rightarrow D$) the region of applied magnetic field. The water flow is provided by a pump operating between points 2 and 3. In addition, the flow exchanges heat with the hot source and cold source allocated between points 3 and 4, and 7 and 8, respectively. As indicated, the Gd sectors forming a wheel operating clockwise and the heat exchanger fluid flows counterclockwise.

There are quite tries, studies and simulations about the magnets. Several magnet designs were tried in order to reach a maximum magnetic field intensity [23]. In fact, as cited before, many devices were built [10]. To provide the magnetic field, one can choose electromagnets or permanent magnets. Electromagnets used to be expensive and more complicated focusing in the domestic use. Permanent magnets do not allow set up the amplitude of the field. Therefore, to helping to find a better configurations of those permanent magnets, the finite elements method are one of the tools to simulate the magnetic field lines [3,17,18]. Though, the simulations performed in this work is inspired in a project for a magnetic refrigerator in progress at the IPRJ / UERJ. This kind of device scheme as shown in T 3 were applied in many devices already built [10,16,19], including other different regenerator materials [24]. To perform the simulations present here in this text, it was chose six tablet sectors forming the Gd wheel.

The simulations to calculate the temperatures of the fluid throughout the system have been done using a few approaches. In fact, there are limited software that can calculate some physical properties
[17,20]. However, it is common to find studies solving the partial differentials heat equations that can express the MCE [25–28]. Actually, the results that can be obtained by solving these equations are quite rich, but they have a computational cost besides not being a simple solution. A more simple way to deal with this problem is assuming the energy balance in the thermodynamic system heat exchange. The transient modeling approach for the fluid temperature corresponds to

\[ \rho_f c_{pf} V_f \frac{dT_f}{dt} = \dot{m} c_{pf} (T_{fin} - T_{fo}) + h_n A_n (T_s - T_{fo}) \]  

The equation (1) describe the fluid temperature \( T_f \) inside the heat exchangers, i.e. hot and cold source as well as inside the gadolinium (Gd) pore spaces. The physical quantities \( \rho_f, c_{pf}, V_f \) correspond to density, heat capacity and volume of the fluid. In the first term of right side of the equation (1), \( \dot{m} \) is the mass flow rate. The temperatures \( T_{fin} \) and \( T_{fo} \) are entrance and exit temperatures of the fluid in the heat exchangers which are related to heat flows \( q_u \) and \( q_l \). In the last term, \( h_n \) is the advection coefficient and \( A_n \) is the heat transfer area for hot / cold source. Finally, \( T_s \) corresponds to Gd temperature. The energy transient term results from the contribution of the energy transport along the borders plus the advection. In this model, it is considered an ideal uniform value of temperature along the fluid volume system in which the temperature at the exit is the same as at the interior of the system.

For the gadolinium energy balance model, the transient term is the contribution of the advection heat transfer as follow.

\[ \rho_s c_{ps} V_s \frac{dT_s}{dt} = -h_s A_s (T_s - T_{fo}) \]  

In the equation (2), the subscript refers to Gd, i.e. \( c_{ps} \) is the heat capacity of Gd while \( \rho_s \) and \( V_s \) are density and volume of Gd bulk sector, respectively. The following considerations were also assumed in the modeling: no heat loss along the pipes and a constant heat rate in the cold source of the heat exchanger. In order to facilitate the discussion about the behavior of temperatures in the points of the system shown in the T 3, they were labeled T1 to T8. Thus, the temperature at point 4 is the same at point 5, T4 = T5, as well T6 = T7, T1 = T8. As it was consider an ideal pump, T2 = T3.

Other important assumption is a stepwise approach. It means the magnetized section which allows the magnetization of the gadolinium porous bed completely as it moves in the clockwise direction. There is no partial magnetization of the gadolinium porous bed as it enters magnetic section in the clockwise direction.

The growing in the temperature were incorporated in the simulator using the exponential response in \( \Delta T \) due to the application of magnetic field to the metal Gd using the expressions cited before. The steps of magnetization and demagnetization, respectively, as

\[ T_s^{i+1} = T_s^i + \Delta T \]  

\[ T_s^{i+1} = T_s^i - \Delta T \]  

The inversion in heat transfer profiles along the process was used as a limit in the calculation of the maximum heat transfer absorption in the cold exchanger.

3. Results and discussion

In order for the simulations to be carried out, some physical parameters had to be assumed. In Table 1 it is possible to observe these input values. The volume and area values were chosen based on the cited project for a magnetic refrigerator in progress at the IPRJ / UERJ. In the same way, gadolinium pore space volume was 7.58 cm³. The used advection coefficients were assumed as an average value on
literature for water. Heat capacity value of Gd was considered as an average at transition temperature, which is around room temperature [11]. Finally, the step frequency to each sector in the magnetic field region was set up to 0.5 Hz. Other frequency values will be studied in future works. The time step considered in the simulator was $10^{-3}$ s.

| Table 1. The values of input parameters for the simulations performed. |
|---------------------------------------------------------------|
| Physical Quantities | Values                                      |
| $\rho_f$          | $1 \text{ g} \cdot \text{cm}^{-3}$         |
| $c_{pf}$          | $4.186 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ |
| $V_f$             | $30 \text{ cm}^3$                         |
| $h_e$             | $2000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ |
| $A_e$             | $0.88 \text{ m}^2$                        |
| $\rho_s$          | $7.63 \text{ g} \cdot \text{cm}^3$         |
| $c_{ps}$          | $0.2355 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ |
| $V_s$             | $22.75 \text{ cm}^3$                      |
| $h_s$             | $1000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ |
| $A_s$             | $0.22 \text{ m}^2$                        |

The approach chosen in this work allows a large number of analyzes. For a first one, it was chosen to verify how the mass flow rate $\dot{m}$ influences the described system. Thus, it was be possible to determine the dependency from this parameter.

In Figure 4 it is shown the flow temperature behavior of T2, T4, T6 and T8, i.e. in points 2, 3, 4 and 5 along time as described in T 3. As one can observe, T4 remains unchanged whatever mass flow rate $\dot{m}$, what it is expect because T4 is the temperature of exiting from hot source. From $t = 0$, in a very short time T2 and T6 change abruptly from $19^\circ \text{C}$ for all mass flow rates $\dot{m}$ values in this figure. The simulations were performed providing a heat power, $Q$ to the system. In fact, it is one of the parameters on interest of this study. When $Q = 20 \text{ W}$ and $\dot{m} = 20 \text{ g/s}$, Figure 4 (a), the systems reaches a steady state after 100 s. In this situation, the flux removes heat from cold source (T6 $\rightarrow$ T8) staying below initial temperature (19$^\circ \text{C}$). Likewise, it releases heat to the hot source (T2 $\rightarrow$ T4). This picture, the system behaves as a refrigerator as the temperature in the heat exchanger cold source stays below the $T_{300}$ (19$^\circ \text{C}$).

As the $\dot{m}$ rate is reduced, keeping all other parameters fixed, see Figure 4 (c) and Figure 4 (d), it can be seen that the temperatures T2, T6 and T8 in steady state rise. In fact, the difference between T2 and T4 rises. An interesting behavior can be noticed, a change in the process operation as the cold source temperature T6 equalizes the ambient temperature T4 (external temperature) which is obtained in Figure 4 (c). This point shows an inversion from refrigeration to heat pump operation as can be seen in Figure 4 (c) which indicates the cold source temperature T6 higher than the external temperature T6. Indeed, this behavior also depend on the heat power $Q$. In Figure 4 (c), from $t = 120$ s, T4 is around $19^\circ \text{C}$. In order to check under what conditions the system changes from cooler to heat pump- like, it was performed simulations using different $Q$ and $\dot{m}$ values. In Figure 4 (b), one can note T4 and T6 having the same trend after 100 s. There, the used values were $Q = 30 \text{ W}$ and $\dot{m} = 11.9 \text{ g/s}$. From Figure 4 it can be seen that increasing the mass flow rate leads to a reduction in the time to reach the steady state. It is worth noting that when the system reaches steady state, $Q = q_L = q_H$. 


Figure 4. The simulations of T2, T4, T6 and T8 and how they develop with time. The initial temperature is $T_i = 19^\circ C$ and the varying parameters are shown in the figure.

The Figure 5 shows the flow temperatures along the process positions in the stead state. As it can be seen the captured energy $q_L$ in the cold source (heat exchanger) is transferred as $q_H$ to the hot source (heat exchanger) in a closed cycle of energy balance in which the temperature at the initial point is equal to that at the final point. Thus, the points on the abscissa represent T1, T2, T3, T4, T5, T6, T7 and T8. There it was changed the mass flow rate $\dot{m}$ and heat power $Q$, as shown in the legend of the Figure 5. It is assumed no energy loss along the pipes so $T_2 = T_3$, $T_4 = T_5$, $T_6 = T_7$ and $T_8 = T_1$ for any parameter configurations, as described before. The temperature T4 is the initial temperature $T_i = 19^\circ C$, after hot source removes heat from the flow, so as T5. From T1 to T2 the magnetized Gd provides heat to the mass flow ($T_2 > T_1$). On the other hand, hot source removes heat from the flow, making $T_3 > T_4$, while the cold source provides heat to the flow, $T_8 > T_7$.

The changing from refrigerator to heat pump-like behaviour can be seen in the comportment of T6. Keeping fixed the heat power $Q$, a decreasing in the mass flow rate $\dot{m}$ causes an increasing in every temperatures, except T4 and T5. However, temperatures T6 and T7 can turn the behavior of the system. Around $\dot{m} = 10 \, g/s$, T6 takes values close to T5. When the flow decreases even more, T6 becomes greater than T5, making the system behave like a heat pump.

Beyond the time evolution of the fluid temperature, it was also possible to monitor the behaviour of the solid regenerator Gd. The Figure 6 shows how the temperature of the demagnetized Gd tablet sector between points 5 and 6 evolves over time, using $T_i = 19^\circ C$, $Q = 20 \, W$ and $\dot{m} = 20 \, g/s$ for this simulation. It is quite interesting an oscillating values indeed. Notwithstanding the time axis shows only values up to 50 s, this oscillatory behavior extends to longer times. The temperature values in function of time step of magnetized Gd tablet sector is similar.
Figure 5. The simulations of the temperatures in each point shown in the flow diagram (T1, T2, T3, T4, T5, T6, T7 and T8) after \( t = 300 \) s. The initial temperature is \( T_i = 19^\circ C \) and the varying parameters are in the legend.

![Temperature Simulation](image)

Figure 6. The simulation of the temperatures of the demagnetized Gd tablet sector between points 5 and 6 over time. The parameters used for this simulation are \( T_i = 19^\circ C \), \( Q = 20 W \) and \( m = 20 g/s \).

![Gd Temperature Simulation](image)

As indicated in Figure 4 (b), it were done some simulations changing both \( m \) and \( Q \), fixing the others parameters. The result can be seen in Figure 7.
Figure 7. The relation between mass flow rate $\dot{m}$ and the heat power $Q$ keeping the temperatures $T_4 = T_6$.

The linear trend of the data is very clear when looking at the points in this figure. It was confirmed by performing a fitting using the line equation, finding a very good agreement. The result provided $y(x) = 0.2573x + 4.2385$ and $R^2 = 0.9998$. For any pair of points above the line of equation $y(x)$, the thermodynamic system has a behavior of a refrigerator. On the other hand, any pair of points below the line of equation $y(x)$ takes the system to behave as a heat pump.

4. Conclusions

In this work, a simpler way of dealing with the temperature prediction problem in a thermodynamic system based on the magnetocaloric effect was presented. Instead of solving the partial differential equations to obtain the temperature field, the simulator present here was able to represent the transient aspects as well as the steady state conditions of the processes, considering both time performance and numerical stability, simplifying the phenomena of heat transfers. The approach chosen allows a large number of analyzes, but for a first study, it was possible to verify how the mass flow rate $\dot{m}$ affect the described system, determining the dependency from this parameter. Beyond, the calculations indicated that the system are very sensitive to the parameters changings. Elsewhere, it was observe a change from refrigerator to heat pump-like, that depends on a linear relationship between $\dot{m}$ and $Q$. Further studies will be done in order to characterize this system and even the approach.

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