Transient Response in Magnetocaloric Regeneration

Farhad Shir[1], Lawrence H. Bennett[1,2], *Senior Member, IEEE*, Edward Della Torre[1,2], *Fellow, IEEE*, Catherine Mavriplis[3], and Robert D. Shull[2], *Senior Member, IEEE*

[1]Institute for Magnetics Research, George Washington University, Ashburn, VA 20147 USA
[2]National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
[3]Mechanical and Aerospace Engineering Department, George Washington University, Washington, DC 20052 USA

We report on the first experimental demonstration of the details of the transient response in the four sequential processes of active magnetic regenerative refrigeration: magnetization, warm blow, demagnetization, and cold blow. The experimental results display the details of the gradual temperature divergence due to regeneration. The temperature change of the stationary solid bed is due to the magnetocaloric effect in a periodic field. The theory for the active magnetic regenerative refrigeration is applied to the transient processes in magnetocaloric regeneration. A time and spatial dependent model of temperature profile of the magnetization and demagnetization with thermal wave regenerative processes is developed.

***Index Terms*—Magnetic refrigeration, magnetocaloric effect, transient magnetic regenerative process.**

I. Introduction

EFFORTS have been made in recent years to develop cooling systems without chlorofluorocarbons (CFC) or their alternatives. Among such technologies, the most promising is the utilization of the magnetocaloric effect (MCE) for obtaining magnetic refrigeration [1]. MCE is the adiabatic conversion of a magnetically induced entropy change to the evolution or absorption of heat, with a corresponding rise or decrease in temperature. A magnetic refrigerator employs changes in the magnetic field of a solid magnetic material to control the temperature, as an alternative to conventional refrigeration which applies compression and expansion to a gas, thus substantially reducing energy loss and enhancing efficiency [2]. It has been used in gas liquefaction systems [3], cryogenic applications [4], and is a candidate for room-temperature commercial and industrial refrigeration and air conditioning processes [5].

Room-temperature magnetic refrigeration has reached a degree of maturity, as evidenced in recent claims of successful commercialization [6]. The transient process is important to the design and performance of a magnetic refrigeration system as it determines the temperature span across both ends of the refrigerant bed. In this paper, test results of temperature profile in an active magnetic regeneration (AMR) test bed and a theory of sequential processes in magnetocaloric regeneration during the transient period of its operation are discussed.

The AMR is a specific kind of heat exchanger, in which the magnetic material functions both as a refrigeration medium and as a heat regeneration medium, while the fluid flowing in the porous bed works as a heat transfer medium. The theory of the active magnetic regenerator [7] is similar to that of an ordinary regenerator except that the thermo-physical properties of the material are varied by the application and removal of a magnetic field.

An AMR operation consists of four processes: 1) bed magnetization, warming the magnetic material and the bed fluid by the MCE; 2) cold to hot exchange fluid flow through the bed, transferring heat to one end of the bed; 3) bed demagnetization, cooling the magnetic material and exchange fluid; and 4) hot to cold flow through the bed, absorbing heat at the opposite end of the bed [8]. Study of the fluid flow steps in an AMR system is related to the basic theory of thermal wave propagation [9], [10] in a refrigerant bed. Upon periodic change of the temperature in the solid refrigerant as the result of the MCE, the solid bed acts as a thermal regenerator system and after a transient time period, the refrigerant bed will reach its steady-state temperature span on both ends of the refrigerant bed. Although the temperature profile of the AMR in its steady-state operation has been investigated [11]–[15], the details of the transient response to the sequential processes have not been discussed previously.

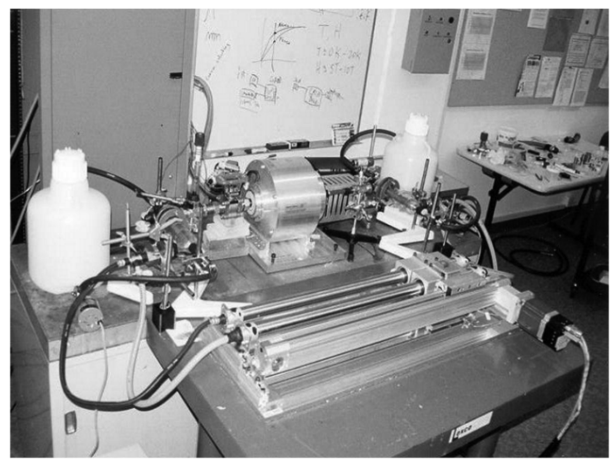

Fig. 1. The magnetic regenerative refrigeration test bed.

II. Experiment

An AMR test bed was used to evaluate the effect of the MCE in a regenerative porous bed of gadolinium (Gd) while helium, as the exchange gas, was flowing in a reciprocating pattern and a variable field was applied to the refrigerant bed. The test bed shown in Fig. 1 consists of four major parts as shown schematically in Fig. 2.

1) A commercial permanent adjustable-field magnet produced a magnetic field with a magnitude varying between 0

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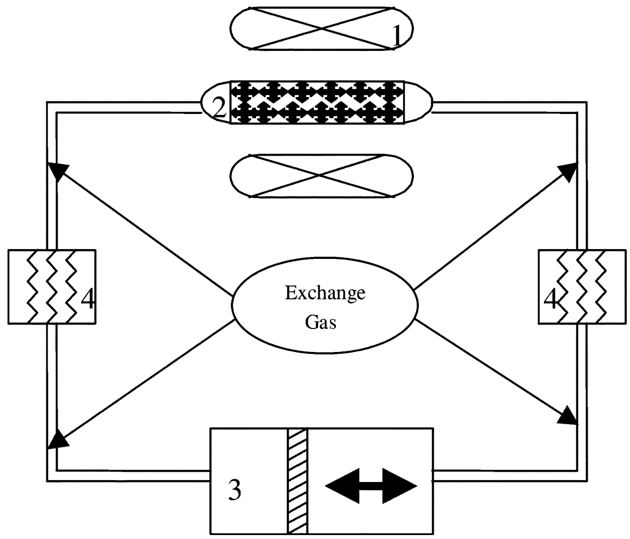

Fig. 2. Schematic of the basic operation of an AMR: 1: permanent magnet; 2: regenerative bed; 3: piston-cylinder displacer; and 4: heat exchanger.

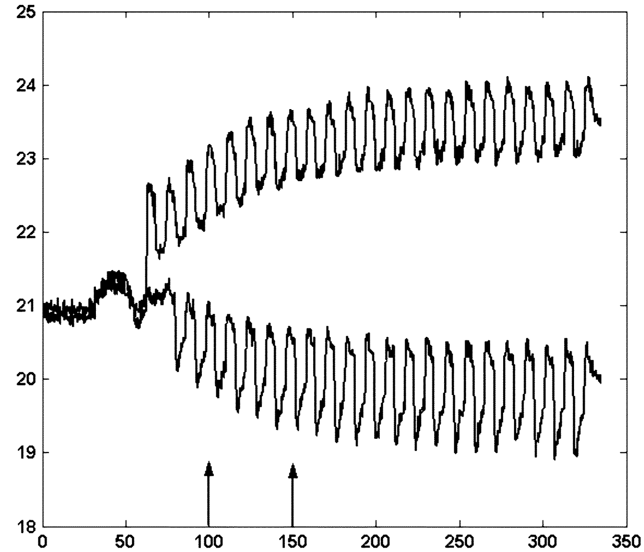

Fig. 3. Experimental temperature profile at the two ends of an AMR Gd test bed showing divergence with time.

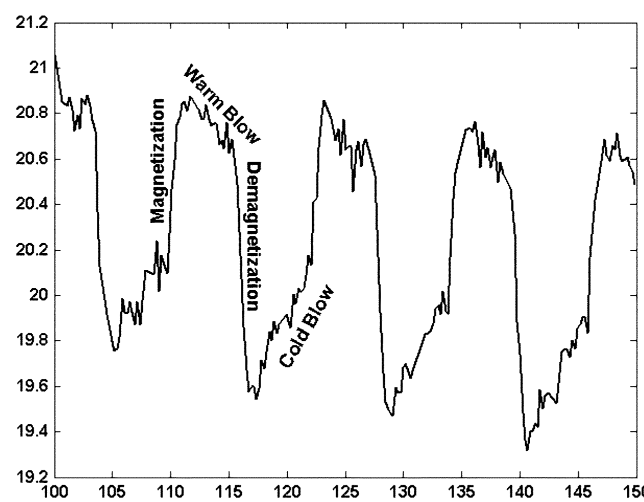

Fig. 4. Temperature profile in the cold end of the magnetic regenerative test bed, identifying the four sequential steps in each cycle.

and 2 T over a range of frequencies. Two nested permanent magnet cylinders generated the magnetic field, each of these producing 1 T. The outer cylinder was fixed; a stepper motor rotated the inner cylinder to vary the magnitude of the resulting rotating field. In our setup, the measured magnetic field showed sinusoidal time dependence.

2) The active regenerative porous bed consisted of impure Gd magnetocaloric material in the form of turnings inserted in the inner tube of the magnet that spanned the temperature difference between cold and hot ends of the refrigerant bed.
3) In order to move the exchange gas through the refrigerant bed and create a regenerative system to span the temperature on both ends of the bed, a gas displacer sealed rodless cylinder from Festo was used. At the time that the magnet was in the maximum field position, which corresponds to the refrigerant's hottest temperature, the piston moved in the direction to send the exchange gas to the hot reservoir through the bed. As soon as the magnet was in the lowest field position, which corresponds to the coldest temperature of the refrigerant material, the piston moved in the opposite direction, in order to transfer the exchange gas to the cold reservoir through the refrigerant bed. The test bed was vacuum-sealed and helium was used as the exchange fluid.
4) The warm and cold heat exchanger systems, which removed the thermal energy produced in the magnetization and demagnetization process. Water circulation in the inner tubes of the heat exchanger transfers energy to the cold and warm reservoirs.

This setup enables us to change different parameters and investigate their effects on the performance of the cycle. These parameters are: the nature of the magnetocaloric material; the shape and geometry of the refrigerant bed; the nature and speed of the exchange fluid; the cycle period and the intensity of the magnetic field.

Fig. 3 shows the temperature profiles at the two ends of the test bed as the AMR process proceeded, measured by thermocouples. These results are not précised as a result of thermal lag [16] and low performance of a thermocouple in measuring temperature in an alternating magnetic field [17]. We intend to improve our system in the future, e.g., by reducing heat losses, so that the magnitude of temperature change during magnetization and demagnetization steps and the overall temperature span on both ends of the bed will be improved in order to match the previously reported results [18]–[20] for steady-state or single-shot operation. Our goal was to give new insight into AMR transient behavior.

The temperature transient due to the periodic cycling of the AMR is shown in Fig. 3. During the transient, the difference in the mean temperature at the hot and cold ends of the bed increases, as does the peak-to-peak temperature variation of the quasi-periodic temperature cycle. When steady state is reached, the temperature cycle is periodic and the average temperature difference between the bed ends remains constant. The effect of regeneration is to change the rate of the temperature change at the two ends of the bed due to the transit time of the exchange gas down the bed.

Part of the data in Fig. 3 in the transient period for the cold end of the refrigerant bed is in expanded Fig. 4. This figure shows the

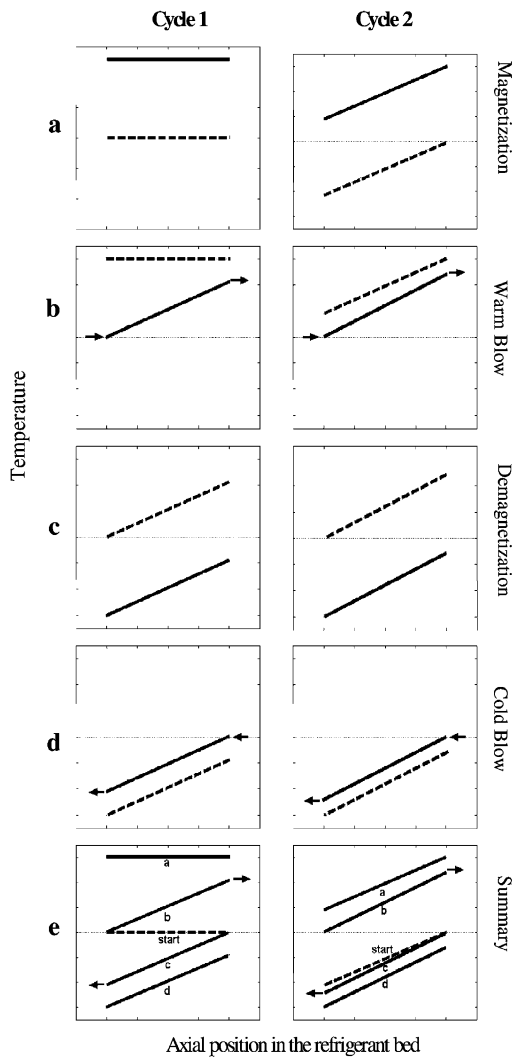

Fig. 5. Temperature of the bed versus axial position in the refrigerant for the four sequential processes in an AMR system for the first two consecutive transient cycles. The simplified linear temperature variation is assumed. The broken lines indicate the initial and the solid lines indicate the final state. Arrows indicate the direction of gas flow and the gas temperature at each end of the bed.

four sequential processes of the AMR cycle: bed magnetization, warming the magnetic material and the bed fluid by the MCE; cold to hot exchange fluid flow through the bed (warm blow), transferring heat to one end of the bed; bed demagnetization, cooling the magnetic material and exchange fluid; and hot to cold flow through the bed (cold blow), absorbing heat at the opposite end of the bed.

III. Theory

The theory of the four processes of an AMR cycle is well known [7], [8]. Fig. 5 demonstrates the temperature profile throughout the bed for the transient response of an AMR using these simplified assumptions: the MCE produces the same temperature change throughout the refrigerant bed in all locations; and the exchange gas enters the porous refrigerant bed at both ends at constant ambient temperature, i.e., the external heat exchangers effectively absorb the cold and hot energy from the exchange gas. As a result of these simplified assumptions, the schematic presentation of the temperature profile in this figure are not realistic, but this conceptual demonstration can be useful in developing a model for the transient response of the sequential processes in an AMR system. Consider an axial cross section of the magnetocaloric bed that is in equilibrium temperature with its surroundings as shown in the broken lines in the centerline of Fig. 5(a).

1) Adiabatic magnetization: Magnetic energy is transferred via the alignment of the magnetic dipoles in the increasing external magnetic field to the phonon system of the refrigerant lattice [21], thus increasing the refrigerant temperature uniformly through the bed as shown in Fig. 5(a).

2) Warm blow: Heat transfer fluid is forced to flow from the cold to the hot end of the regenerator while the magnetic field is kept constant. The exchange fluid absorbs heat from the hot refrigerant bed and exits the regenerator at a higher temperature as compared to its entrance temperature. As a result of this heat transfer, temperature of the magnetocaloric material decreases through the bed as shown in Fig. 5(b). The cold end of the refrigerant bed, which is closer to the entrance of the gas flow, cools faster than the hot end. Note, that as the exchange gas has cooled the refrigerant bed, its temperature has increased and finally the gas leaves the regenerator at a higher temperature compared to its entrance temperature in the bed. The initial condition for this process is the temperature distribution at the end of the previous (magnetization) phase. The important concept is the difference in the rate of cooling of the refrigerant bed along its length as the gas flows through the bed. This causes a temperature gradient at the end of the warm blow period in the refrigerant throughout its length.

3) Adiabatic demagnetization: Energy is transferred from the phonon system of the refrigerant lattice to the system of the magnetic dipoles, as their orientation becomes increasingly random in the decreasing magnetic field [Fig. 5(c)]. Starting with the temperature distribution at the end of the previous phase (warm blow), a lower temperature profile at thermodynamic equilibrium at the end of this phase will be achieved. As the MCE was assumed to produce the same temperature change through the refrigerant bed, the slope of the temperature profile curve along the bed should remain constant during this process.

4) Cold blow: Heat transfer fluid is forced to flow from the hot to the cold end of the regenerator while the magnetic field is kept constant. The exchange fluid loses heat to the cold refrigerant bed and leaves the regenerator at a lower temperature as compared to its entrance temperature. As a result of this heat transfer, temperature of the magnetocaloric material increases through the bed as depicted in Fig. 5(d). Starting with the new initial conditions at the end of the demagnetization process, the refrigerant bed temperature changes along its length with different rates as the exchange gas passes through the bed. The hot end of the refrigerant bed, which is closer to the entrance of the gas flow, warms up faster than the cold end. The diverse changes in temperature of the solid bed cause the final temperature profile to have a different slope compared to its previous phase as shown. The temperature distribution in the magnetic substance and the exchange gas at the end of the heat transfer indicates the initial condition for the following sequential cycle that starts with the magnetization as described in step 1.

The temperature profile in the first cycle of an AMR process is summarized in Fig. 5(e). This cycle has created a temperature profile along the refrigerant bed with a positive slope from the cold to the hot end of the regenerator. The magnitude of the slope of the final temperature profile in the cycle depends on the sequence of the processes, i.e., the AMR cycle process starts with magnetization or demagnetization, and also the direction of the exchange gas flow at the first stage of the regeneration steps. The exchange gas has been pumped out of the cycle at two ends of the bed during warm and cold blows as shown in the summary figure.

The second cycle follows using the initial conditions of the refrigerant bed from the temperature profile that was created at the last stage of the previous cycle. The same four sequential processes will cause a different temperature distribution with higher slope of temperature versus length throughout the bed at the end of the cycle [Fig. 5(e) in cycle 2] compared to cycle 1. As a result, the exchange gas leaves the warm end at a higher temperature and the cold end at a lower temperature in cycle 2 than in cycle 1.

This phenomenon of regeneration in combination with the periodic temperature change in the magnetocaloric refrigerant bed continues as the cycles proceed and higher temperature spans on both ends of the refrigerant bed are created during the transient period of the operation. After a certain time, depending on the exchange gas and solid bed physical and thermal-fluid properties, the solid refrigerant will reach its threshold ability to store heat or cold during the regenerative hot and cold blows at each location in the bed. At this steady-state mode, the hot gas leaves the refrigerant bed at the hot end of the bed with the same temperature (ideally) as the refrigerant bed and the cold gas is pumped out at the cold end of the bed at the same temperature as the cold end of the refrigerant. There is no further driving force between the exchange gas and the solid bed to exchange heat at this threshold thermal status and the cycles proceed with the same temperature span on both ends of the porous bed in a steady-state operation.

IV. MODEL

In order to analyze and design an optimum magnetic refrigeration system, it is important to model the magnetothermal behavior of the regenerative refrigerant bed during the four sequential processes of an AMR cycle. Based on the experimental data and the theory that was developed in the previous section, we can derive the governing equations of the temperature profile for the refrigerant bed and the exchange gas in transient process of an AMR. These equations relate the magneto thermal properties of the refrigerant bed to the thermo-fluid aspect of the regenerative process in a quantitative model for two nonflow magnetization and demagnetizations steps and two regenerative hot and cold blows processes.

The basic thermodynamics of the MCE is well known [22], [23]. To study the transient behavior, we have developed [16] a time-dependent model for magnetization and demagnetization processes of a magnetocaloric material. The magnetization dependence of the temperature profile for AMR system is

$$\frac{dT}{dt} = -\frac{T}{C_H}\mu_0 v \left(\frac{\partial M}{\partial T}\right)_H \frac{dH}{dt} \tag{1}$$

where v is the specific volume of the magnetocaloric material, μ_0 is the magnetic permeability of free space, C_H is the specific heat at constant applied field, H is the magnetic field strength, and M is the magnetization. For the two regenerative gas flow processes during warm and cold blows, Barclay [9] applied the basic governing equations of thermal wave propagation through a porous bed. The phenomenon of regeneration is complicated because of the transient nature of the heating or cooling of the gas and refrigerant material even though effects of the regenerator wall on the heat transfer are neglected. Conversely, the transient process is important in design and performance of an AMR system as it creates the temperature span in both ends of the refrigerant bed of the magnetocaloric material.

To derive the relations among the equations that describe the AMR process and develop a model to predict the behavior of a regenerative magnetic core during the regenerative gas blow steps in the cycle, the following assumptions can to be made: The axial conduction loss in the regenerative magnetic core is negligible, the magnetic core is perfectly insulated, and the physical parameters remain constant with time and temperature throughout the refrigerant bed. Based on these assumptions, energy balance for the exchange gas and the refrigerant regenerative bed can be performed, which results a pair of partial differential equations constitutes the dynamics of regeneration process in the model

$$\frac{\partial T_g}{\partial t} + v\frac{\partial T_g}{\partial x} = \frac{ha}{\rho_g C_g \varepsilon}(T_s - T_g) \tag{2}$$

$$\frac{\partial T_s}{\partial t} = \frac{ha}{(\rho_s C_s)(1-\varepsilon)}(T_g - T_s) \tag{3}$$

where T_g is the gas temperature, T_s is the solid refrigerant temperature, t is time, x is position, v is the interstitial velocity, h is convective heat transfer coefficient that connects to thermal-fluid characteristics of the exchange fluid [24], a is surface area per unit volume of the bed, ρ_s is the solid density, ρ_g is the gas density, C_s is the heat capacity of the solid, C_g is the heat capacity of the gas, and ε is the porosity.

The solution of (2) and (3) requires boundary conditions and initial conditions. In this system, we have two first-order time derivatives and one spatial derivative; therefore, we would need two initial conditions and one boundary condition. The governing equations then need to be nondimensionalized in order to solve them by analytical or numerical methods. In order to transfer (2) and (3) from Eulerian to Lagrangian coordinates, the following dimensionless parameters can be defined: the dimensionless length $z = (x)/(L)$, where L is the length of the regenerator; the nondimensional time $\tau = (t)/(t_r)$, where t_r is the mean transit time of the fluid within the bed; the dimensionless number for the solid refrigerant $\lambda_1 = (ha)/(\rho_g C_g \varepsilon)(L)/(v)$; the dimensionless number for the exchange fluid $\lambda_2 = (ha)/(\rho_s C_s(1-\varepsilon))(L)/(v)$; the dimensionless temperature of the gas $T_g^* = (T_g - T_{g0})/(T_{\text{in}} - T_{g0})$, where T_{in} is the temperature of the incoming gas to the refrigerant bed, and T_{g0} is the initial temperature of the gas in the regenerator; and the dimensionless solid refrigerant temperature $T_s^* = (T_s - T_{s0})/(T_{\text{in}} - T_{s0})T_{s0}$ is the initial temperature of the solid refrigerant in the regenerator.

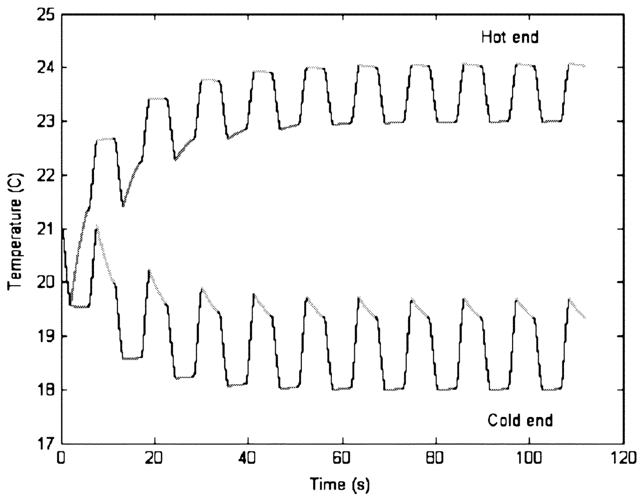

Fig. 6. Computed results of the temperature profile at both ends of magnetic regenerative refrigeration test bed.

Substituting these parameters in governing equations (2) and (3) produces (4) and (5), which are pair of normalized time and spatial dependent partial differential equations that evaluate temperature of the exchange fluid and the solid refrigerant in the regenerative processes of an AMR cycle

$$\frac{\partial T_g^*}{\partial \tau} + \frac{\partial T_g^*}{\partial z} = \lambda_1 (T_s^* - T_g^*) \tag{4}$$

$$\frac{\partial T_s^*}{\partial \tau} = \lambda_2 (T_s^* - T_s^*). \tag{5}$$

We used implicit finite-difference methods to solve (4) and (5) with their normalized boundary and initial conditions for regenerative warm and cold blows, and (1) for magnetization and demagnetization processes, which are bridges between the regenerative processes, to evaluate the temperature profile during the AMR process. The computed results on both ends of the refrigerant bed are shown in Fig. 6. This simulation was performed based on the experimental result depicted in Fig. 3, starting with the first process of demagnetization ($t = 50$ s) that divergence in temperature of both ends of the test bed begins to develop.

V. Conclusion

The temperature profile during the transient response of an AMR test bed of gadolinium in a magnetic field cycled between 0 and 2 T was measured. The observed four sequential processes and the temperature divergence due to regeneration were discussed. The theory for the AMR cycles was applied to the transient processes in magnetocaloric regeneration. We have presented new experimental results and the equations for a model for AMR system. Temporal- and spatial-dependent equations (1), (4), and (5) were used to solve for the temperature profiles of the magnetic regenerative refrigeration test bed. The results of calculations from a model based on these equations agree with the experimental behavior. These equations can also be useful in a model to evaluate the effects of applying various values for each parameter and its limit of applicability. Such results will be beneficial to design an optimum magnetic refrigeration system.

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