

SUMMARY DESCRIPTION OF THE AMRR MODEL

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The current Active Magnetic Regenerative Refrigerator (AMRR) model developed at SEL is a one dimensional (1-D) thermodynamic model that solves the energy balance equations for the heat transfer fluid and the regenerator material of an AMRR cycle. The model uses cycle inputs such as the fluid mass flow rate and magnetic field profiles, fluid and regenerator material properties, and regenerator geometry properties to generate the cyclic steady state temperature profiles of the fluid and the regenerator. Using the temperature profiles, the cooling load produced by the AMRR system, the work input into the system (pump and magnetic) and the COP are evaluated. The MATLAB model takes into consideration the effects of magnetic hysteresis as a source of irreversibility where the rate of entropy generation is assumed to be proportional to the area swept by the hysteresis curve for one refrigeration cycle. The model only considers the magnetic regenerator and does not explicitly model the heat exchangers or other external hardware.

The model starts with initial guess values for the temperature profiles for the regenerator material and heat transfer fluid and steps forward in time using advanced numerical integration algorithms in MATLAB (i.e., the ode functions) until cyclic steady state is achieved. Once the solution is converged, the performance of the system is evaluated using the thermodynamic and magnetic properties of the working materials defined over a determined number of time and spatial steps for one AMRR cycle. Modeling parameters related to operating conditions, material properties, and geometry are determined by user-defined functions.

To make the model more user-friendly, a GUI application was developed at SEL by Abou Dbai that includes such components as the control parameter fields (e.g., applied field and mass flow rates), reset and stop buttons, pop-up menus for controlling magnetic hysteresis and selecting different types of heat transfer fluids. The GUI also provides a variety of output fields as described later. The interface was compiled using the deploy tool in MATLAB. The standalone application that is obtained in this fashion can be executed on computers that do not have MATLAB installed. However, a free MATLAB Compiler Runtime (MCR) must be downloaded from the Mathworks website for the application to run independently.

Figure 1 is a screen shot of the main panels of the Graphical User Interface. It shows the default input parameters, the pop-up menu for magnetic hysteresis, the different push buttons used to control the application, and the model output parameters.

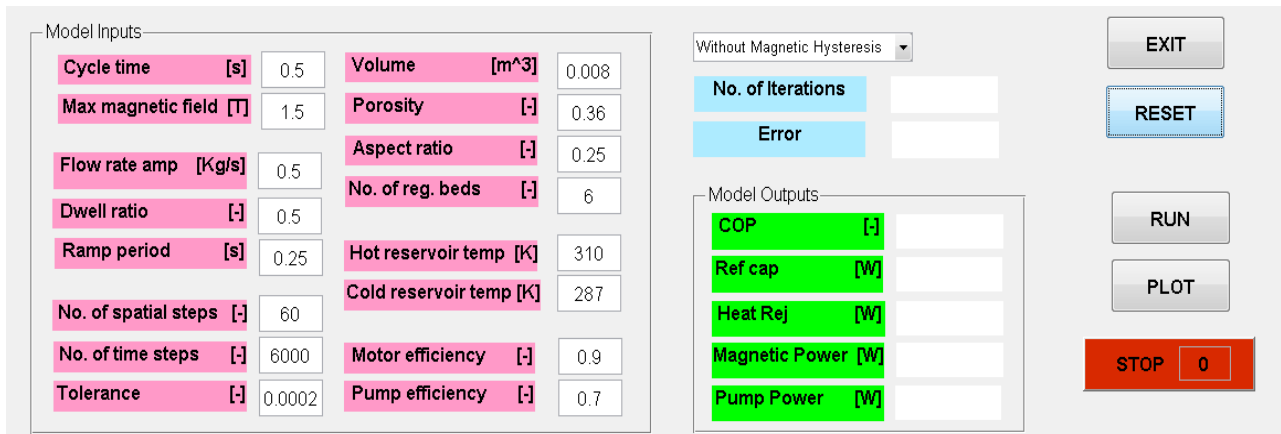


Figure 1 AMRR GUI application showing the default model input parameters, pop-up menu for magnetic hysteresis, push buttons, and the output fields

The model input parameters used in the AMRR Model are listed below in the same order as shown in Figure 1:

- refrigeration cycle time (τ)
- maximum externally applied magnetic field ($\mu_o H_{max}$)
- heat transfer fluid flow rate amplitude (\dot{m}_{amp})
- mass flow rate dwell ratio (dr)

- ramp period for fluid flow

- number of spatial steps (Nx)
- number of time steps (Nt)
- allowable tolerance for convergence (tol)

- total volume of the regenerator material (V)
- porosity of the regenerator bed packing (ϵ)
- aspect ratio of regenerator (AR)
- number of beds in the regenerator (n_{bed})
- cold side temperature of the regenerator (T_C)
- hot side temperature of the regenerator (T_H)

- electric motor efficiency (η_{motor})
- pump efficiency (η_{pump})

The main model outputs that are obtained from running the GUI application are listed below with the corresponding description:

- coefficient of performance (COP)
- refrigeration capacity (Q_C)
- heat rejection rate (Q_H)
- rate of magnetic work needed ($W_{magnetic}$)
- rate of pump work needed (W_{pump})

A Step-By-Step Guide to Install the AMRR application and Run a Base Case

The user will first need to download and install the Windows 64-bit version of the MATLAB Compiler Runtime (MCR) for R2012b. The compiler can be located on the Mathworks website at the following link: <http://www.mathworks.com/products/compiler/mcr/>

Once the MATLAB Compiler is installed, the user can then run the AMRR_Model.exe application and a GUI window will appear similar to Figure 1. The inputs, outputs and control buttons are distributed among the window as described below:

- 1- The top right section contains the user's control buttons
 - EXIT: closes the application
 - RESET: resets the model input parameters to the default values
 - RUN: runs the AMRR cycle until convergence is achieved
 - STOP: forces the application to stop iterating at any time
 - PLOT: plots different graphs of the model inputs and outputs

- 2- The top left and middle sections contain the model inputs and outputs respectively

- 3- The bottom section contains the plots generated by the application:
 - heat transfer fluid volumetric flow rate as a function of time
 - applied magnetic field as a function of time

 - magnetic material temperature variation as a function of time at the cold side, hot side and middle of the regenerator bed
 - heat transfer fluid temperature variation as a function of time at the cold side, hot side and middle of the regenerator bed
 - surface plot showing the temperature distribution of the Magnetocaloric material as a function of time and position

The error, the count number of iterations, and the fluid and solid temperature profiles are continuously updated after each iteration process.

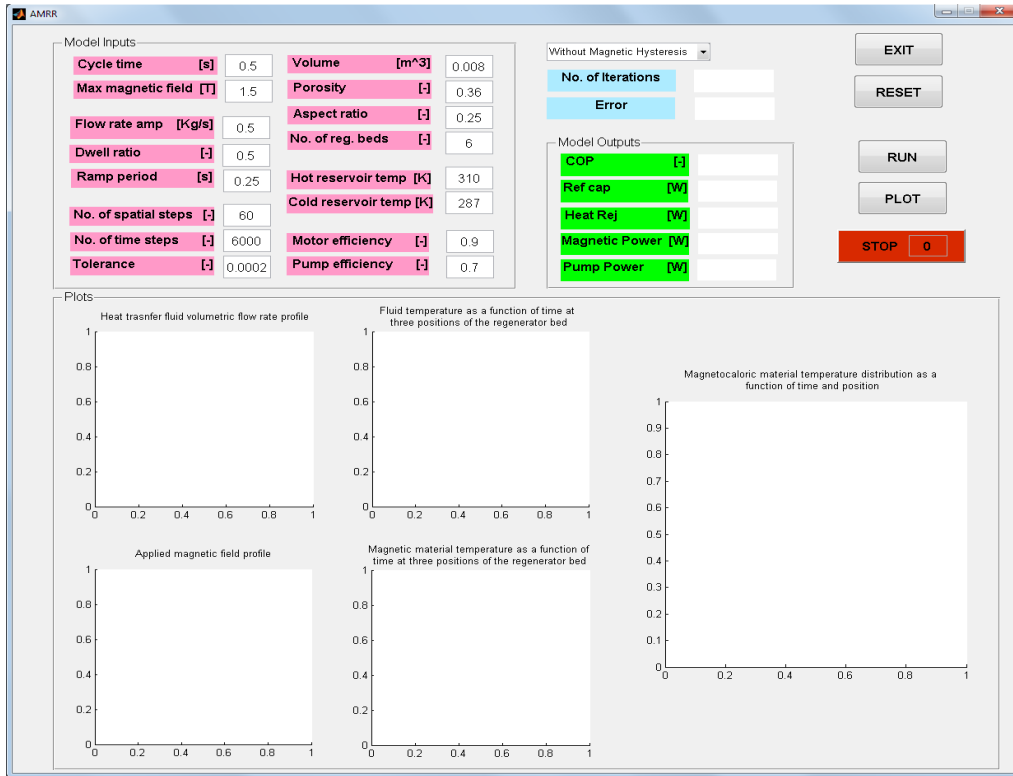


Figure 1 Screenshot of the AMRR_Model.exe application

Consider the following base case of an AMRR cycle operating at a cycle duration of 0.5 s. The regenerator material is made up of $\text{La}(\text{Fe}_{1-x}\text{Si}_x)_{13}\text{H}_y$ and has a total volume of 0.008 m^3 and an aspect ratio of 0.25. The porosity of the bed packing is 0.36. The heat transfer fluid is water and has a flowrate amplitude of 0.5 Kg/s with a dwell ratio of 0.5 and a ramp period of 0.25. The system is absorbing heat from a medium at 287 K and rejecting it to a constant temperature reservoir at 310 K. The pump and magnetic motor efficiency required to run the cycle are 90 and 70 % respectively.

Table 1 summarizes the different input parameters used in the AMRR model.

Table 1: Input parameters used in AMRR model for cycle performance study

Parameter	Value	Parameter	Value
cycle time (s)	0.5	porosity	0.36
max applied magnetic field (T)	1.5	hot reservoir temperature (K)	310
heat transfer fluid	H ₂ O	cold reservoir temperature (K)	287
fluid mass flow amplitude (Kg/s)	0.5	motor efficiency	0.9
dwel ratio	0.5	pump efficiency	0.7
ramp period for fluid flow (s)	0.25	aspect ratio	0.25
regenerator material	La(Fe _{1-x} Si _x) ₁₃ H _y	volume (m ³)	0.008

Next, the user is required to input the number of spatial and time steps and the error tolerance allowed for convergence. The default inputs are listed in the following table:

number of spatial steps	60
number of time steps	4000
convergence tolerance	0.0002

The user has also two options to run the AMRR cycle with or without magnetic hysteresis by selecting from the pop-up menu highlighted in Figure 2.

Figures 2-3 show the outputs generated by the AMRR application when running the cycle at the default input parameters and under the assumption of no magnetic hysteresis.

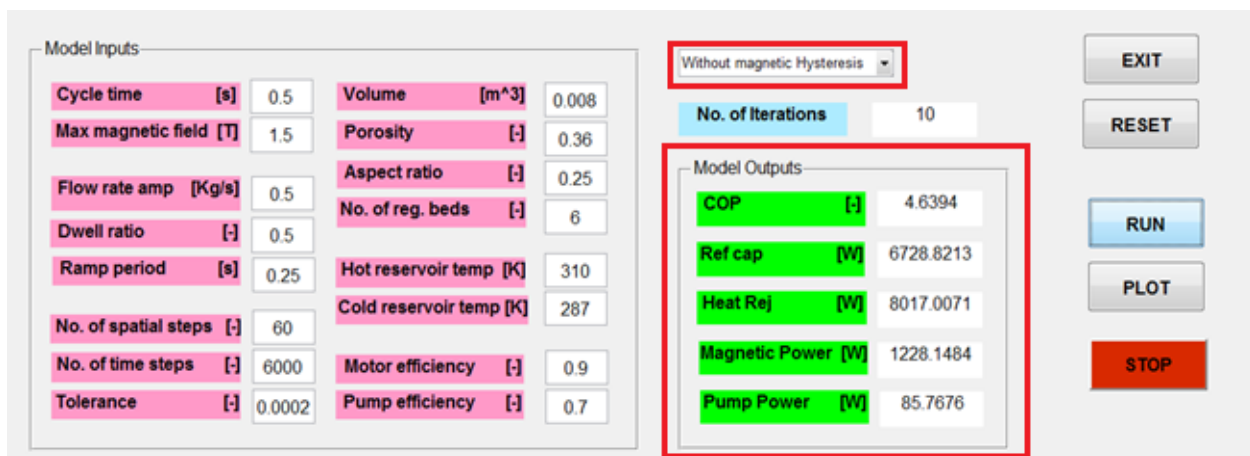


Figure 2 AMRR application outputs when running the AMRR cycle at the designated default input parameters and without magnetic hysteresis

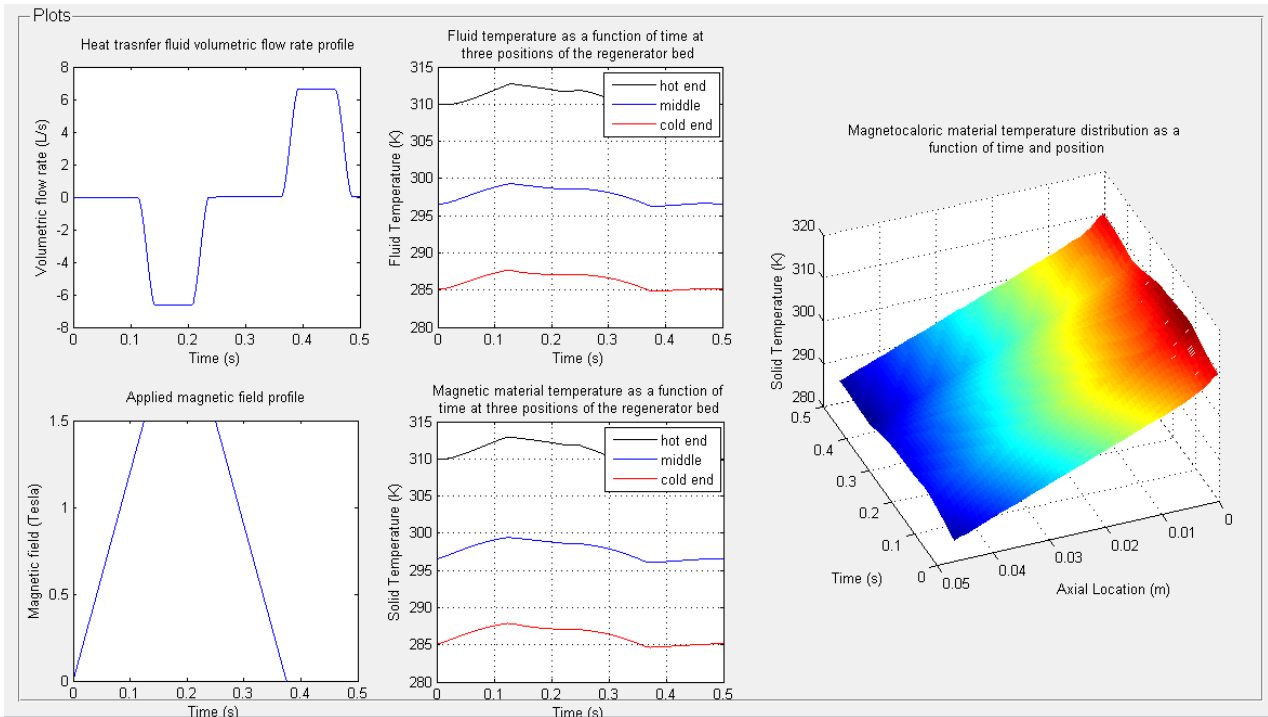


Figure 3 Generated plots from the application when running the AMRR cycle without magnetic hysteresis

Figure 6 show the outputs generated by the application when running the AMRR cycle at the default input parameters but with magnetic hysteresis included.

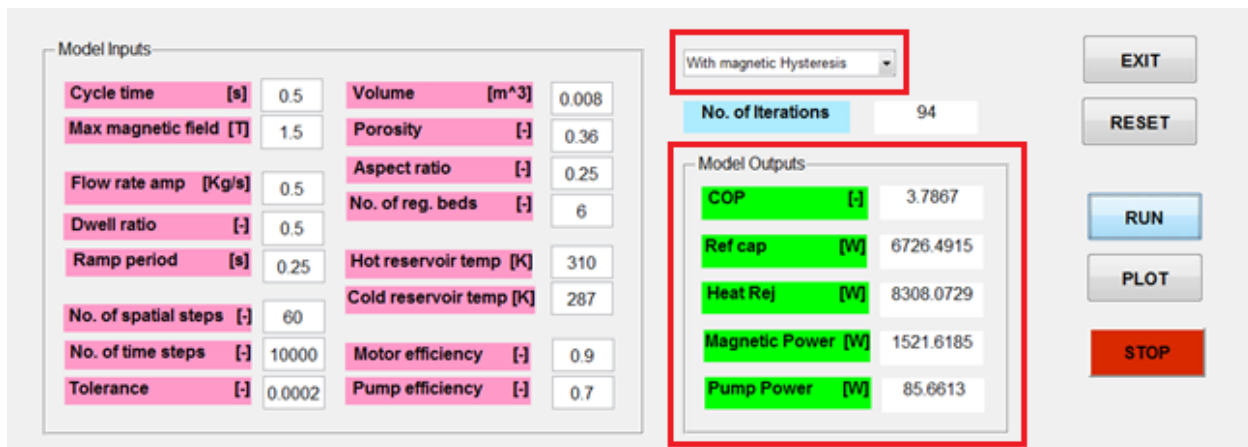


Figure 4 AMRR application outputs when running the AMRR cycle at the designated default input parameters and with magnetic hysteresis