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Research Paper

# Impacts of configuration losses on active magnetic regenerator device performance

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## HIGHLIGHTS

- A sinusoidal mesh is more effective than uniform mesh.
- A simple resistance network model can simulate external losses with good accuracy.
- External heat leaks significantly impact performance at higher temperature spans.
- Mass-flow weighted fields (step change model) can be used instead of full waveform.
- Efficiency can exceed 70% for low net loads.

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## ABSTRACT

A one dimensional, time dependent model is used to study the performance of an active magnetic regenerator. Parameters related to device configuration such as external heat leaks and demagnetization effects are included. Performance is quantified in terms of cooling power and second law efficiency for a range of displaced fluid volumes and operating frequencies. A sinusoidal meshing technique is employed and the model is validated against experimental measurements using gadolinium spheres. For the cases studied, sinusoidal mesh reduced the simulation time up to 70% compared to uniform meshing technique. Simulation results show that step change model for applied field can be effectively used instead of full field wave form if the flow weighted average low and high field values are used. It is found that external losses have a significant impact on measured AMR performance. Calculating the maximum temperature span of a typical system without considering the loss mechanisms external to the regenerator can overestimate actual performance.



## 1. Introduction

Magnetic refrigeration (MR) is a cooling technology based on the magnetocaloric effect (MCE). In recent years, research has focused on the design and construction of prototypes that use both first and second order magnetocaloric materials (MCM) in active magnetic regenerator (AMR) cycles [1–3]. The objectives of current system research is to create an active regenerator using multiple MCMs, providing useful cooling powers with high efficiency. Some of the main challenges of designing a high performance AMR system and how different design choices impact the performance of a system are discussed in [4]. The main technical challenge is related to the magnitude and temperature distribution of the magnetocaloric effect. Layering materials in an AMR with different phase transition temperatures is one way to create a wider range of operating temperatures [5]. To develop refrigerators with higher cooling power, different thermodynamic cycles are studied [6]. Some researchers are combining magnetic refrigeration with other refrigeration technologies [7]. The development of numerical tools to study and understand the behavior of layered beds is needed as material preparation, device development and experimental study is expensive and time consuming. Numerical models of layered AMRs at cryogenic and room temperature have recently been reported [8,9].

The combined effects of non-linear material properties, varying magnetic field, and time-dependent heat transfer and fluid flow make an AMR a complicated system to model. Parameters related to system design such as fluid flow unbalance which can negatively impact the performance of an AMR [10], also add to the complexity of performance modeling. Nielsen et al. review numerical models proposed for room temperature AMR systems [11]. Including more

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**Nomenclature**

| | |
|---|---|
| $A$ | area, m$^2$ |
| $B$ | applied field, T |
| $c$ | specific heat, J kg$^{-1}$ K$^{-1}$ |
| $C$ | volumetric specific heat, J m$^{-3}$ K$^{-1}$ |
| $h$ | convection coefficient, W m$^{-2}$ K$^{-1}$ |
| $H$ | magnetic field, A m$^{-1}$ |
| $K$ | thermal conductance, W K$^{-1}$ |
| $L$ | length, m |
| $m$ | mass, kg |
| $M$ | magnetization, A m$^2$ kg$^{-1}$ |
| $Q$ | heat transfer, net enthalpy flux, W |
| $R$ | thermal mass ratio, – |
| $T$ | temperature, K |
| $t$ | time coordinate, s |
| $V$ | volume, m$^3$ |
| $x$ | non-dimensional spatial coordinate, – |
| *Greek* | |
| $\alpha$ | porosity, – |
| $\eta$ | efficiency, – |
| $\mu$ | dynamic viscosity, N s m$^{-2}$ |
| $\rho$ | density, kg m$^{-3}$ |
| $\tau$ | period, s |
| *Subscript* | |
| 0 | ambient, – |
| $B$ | constant magnetic field, ($\mu_0 H$), or blow, – |
| $C$ | cold, – |
| $eff$ | effective, – |
| $f$ | fluid, – |
| $H$ | hot or high-field, – |
| $M$ | magnetic, – |
| $s$ | solid, – |
| *Superscript* | |
| $'$ | per unit length, – |
| $*$ | normalized value, – |
| $\cdot$ | per unit time, – |

detail in a model is usually at the expense of robustness and speed of solution. One of the challenges for numerical analysts is to find a suitable balance of detail and range of physical interactions to consider [12]. Experimental studies of AMR cycles always include system effects beyond the regenerator [13]; as a result, higher resolution regenerator models may be no better than simpler ones if these are not considered. An analytic model was shown to replicate device performance over a broad range of conditions when demagnetization and device heat leaks were included [14,15].

The development of efficient refrigeration and heat pumping systems is one of the main objectives of research activities [16]. Meeting this objective requires both system and AMR optimization – the AMR being the primary focus at this stage of development [12,17]. To do so, validated numerical models of both AMRs and systems are needed; however, in practice, it is difficult to separate the two. AMR modeling has received most of the focus to date, but validation of AMR models requires experimental data where system impacts are decoupled from regenerator impacts. In this regard, experimental AMR devices can be considered as imperfect measurement instruments when measuring only the AMR performance is the goal. The objective of this paper is to quantify system impacts on overall device performance, and, thereby, improve our understanding of actual AMR behavior.

In this paper we use a one-dimensional transient numerical model to study the behavior of an AMR system. The performance of a permanent magnet active magnetic regenerator test apparatus is analyzed using gadolinium. The effects of device related losses such as demagnetization, heat leaks between the hot reservoir and cold reservoir, and imperfect thermal isolation between the cold end and environment are considered. After validating the model against data from experimental measurements, we determine performance metrics of the AMR such as efficiency, COP and magnetic work for a range of operating conditions. The impacts of configuration losses on measured performance are quantified.

## 2. Configuration losses

An active magnetic device consists of several parts besides the regenerators themselves: fluid flow system, magnets, heat exchangers, piping, and insulation. Many different designs exist and design choices tend to weight some losses higher than others. Part of the engineering challenge is to quantify the trade-offs for a system configuration and to optimize the system as a whole. Here we define *configuration losses* as mechanisms *external* to the active regenerator that impact performance.

Fig. 1(a) represents a model of possible configuration losses external to the regenerator. Depending upon the operating temperature span of the regenerator, the aspect ratio, and the design of the casing holding the regenerator, heat leaks through the surrounding structure can lead to decreases or increases in performance [18]. While not often considered, imperfect thermal isolation may actually help a device obtain a larger temperature span when operating above the environmental temperature. Other configuration losses can arise from dead volumes and heat exchanger ineffectiveness. Finally, a configuration may be selected which minimizes thermal leaks, but results in situation where demagnetization is significant. This cannot be shown in the schematic as a resistor; instead, it acts as a reduction in the effective variation in magnetic field which is the driving force for magnetic work.

Fig. 1(b) shows a simplified model where only two thermal loss mechanisms related to configuration are considered: heat leaks

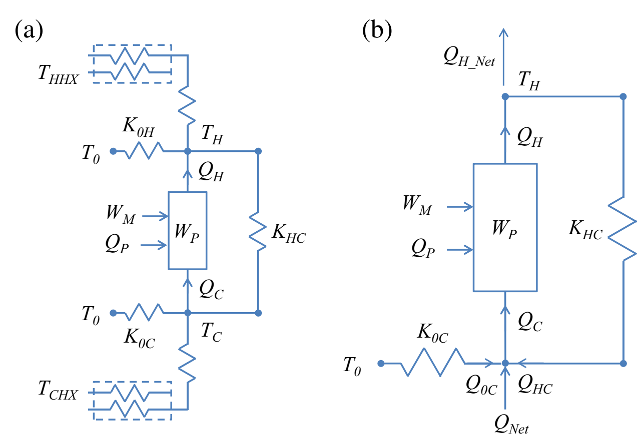


**Fig. 1.** (a) A schematic of heat transfer losses in an AMR system, and (b) a simplified model which considers only two main configuration related loss mechanisms: heat leaks to the cold section from the environment and the hot side.