**DTU Library**

# The influence of the solid thermal conductivity on active magnetic regenerators

**Nielsen, Kaspar Kirstein; Engelbrecht, Kurt**

# The influence of the solid thermal conductivity on active magnetic regenerators

**K.K. Nielsen and K. Engelbrecht**
**DTU Energy Conversion**
**Technical University of Denmark**
**Frederiksborgvej 399, DK-4000 Roskilde, Denmark**
**kaki@risoe.dtu.dk**

**Abstract.**   The influence of the thermal conductivity of the regenerator solid on the performance of a flat plate active magnetic regenerator (AMR) is investigated using an established numerical AMR model. The cooling power at different (fixed) temperature spans is used as a measure of the performance for a range of thermal conductivities, operating frequencies, a long and short regenerator, and finally a regenerator with a low and a high number of transfer units (NTU) regenerator. In this way the performance is mapped out and the impact of the thermal conductivity of the solid is probed.

Modeling shows that under certain operating conditions, the AMR cycle is sensitive to the solid conductivity. It is found that as the operating frequency is increased it is not only sufficient to have a high NTU regenerator but the regenerator performance will also benefit from increased thermal conductivity in the solid. It is also found that a longer regenerator is generally better performing than a shorter one under the otherwise exact same conditions. This suggests that the thermal conductivity of candidate magnetocaloric materials should be considered when selecting them for use in a device.

Keywords: Active magnetic regenerator; thermal conductivity; parallel plate heat exchanger; magnetocaloric effect; magnetic refrigeration

## 1. Introduction

Magnetic refrigeration is an emerging technology that may improve energy efficiency of refrigeration devices in general and in particular significantly reduce the release of refrigerant gases with large global warming potentials [1]. A magnetic refrigerator that works at room temperature is based on the active magnetic regenerator (AMR) principle. During the AMR cycle one or multiple solid magnetic materials are periodically magnetized/demagnetized thus increasing/decreasing their temperature due to the magnetocaloric effect (MCE). This is synchronized with an oscillating flow of a heat transfer fluid that removes excess heat and rejects it to the ambient at one end of the system (denoted the hot end) and absorbs a cooling load at the other (cold) end [2].

The MCE is related to the change of magnetic entropy when the magnetic field applied to a magnetic material is varied. It may manifest itself as an adiabatic temperature change or an isothermal entropy change [3] depending on the condition under which the field is applied. For practical AMR devices applied magnetic fields of between one and two Tesla are considered viable (these may be generated by practical permanent magnets) [4], which result in an adiabatic temperature change of the order of a few Kelvin. The magnetocaloric solid material is therefore organized as a thermal regenerator matrix. In this way a temperature span several times greater than the adiabatic temperature change may be obtained.

The application of the MCE as both the active refrigerant and as a thermal regenerator results in significant demands on many different properties of the solid material. Other than the MCE properties, which are studied in great detail in the literature [1, 5], these include mechanical and shaping properties and the thermal properties mass density, $\rho_s$, specific heat, $c_s$, and thermal conductivity, $k_s$, with subscript s denoting solid.

An efficient thermal regenerator should generally be able to transfer heat from the interior of the solid to the heat transfer fluid at a sufficient rate as well as minimize conduction losses due to the temperature gradient in the axial direction caused by the temperature difference between the hot and cold ends. This means that an ideal regenerator solid material should have an infinite thermal conductivity transverse to the direction of the flow and zero thermal conductivity in the direction of the flow (in the following denoted the axial direction). Such an extremely anisotropic material hardly exists and it is therefore quite relevant to investigate the influence of a finite, and isotropic, thermal conductivity of the solid.

The operating frequency of an AMR device is generally considered to be critical for the overall performance [4]. At higher frequencies the cooling power density has been shown to increase [6], [7] as long as the regenerator is efficient at transferring heat between the solid and fluid. At lower frequencies the heat transfer is less important whereas the power density decreases and the axial conduction will have a more significant impact. These trends are quantified in the following using a previously published 2-dimensional numerical AMR model that numerically resolves the thermal conduction in

the axial direction and perpendicular to the direction of the flow [8]. A simplified model magnetocaloric material is assumed [9] so that the only varied material parameter is the thermal conductivity.

The influence on heat transfer performance of the thermal conductivity of a single sphere was investigated in Ref. [10]. The heat transfer characteristics of the sphere were found to be highly dependent on cycle frequency and solid conduction, however, the study was used to develop a correction factor for 1D regenerator models to account for temperature gradients in the solid material and did not predict AMR performance. A correction to the convective heat transfer coefficient, $h$, based on the Fourier and Biot numbers was suggested in line with the earlier work presented in Refs. [11, 12].

## 2. Numerical AMR model

In order to study the influence of the solid thermal conductivity a 2-dimensional AMR is applied. The model was published in Ref. [8] and simulates a parallel flat plate regenerator. The model solves the unsteady partial differential heat transfer equations in two dimensions. These may be expressed as

$$\frac{\partial T_\mathrm{s}}{\partial t} = \frac{k_\mathrm{s}}{\rho_\mathrm{s} c_\mathrm{s}} \nabla^2 T_\mathrm{s} + \dot{Q}_\mathrm{MCE} \tag{1}$$

$$\frac{\partial T_\mathrm{f}}{\partial t} = \frac{k_\mathrm{f}}{\rho_\mathrm{f} c_\mathrm{f}} \nabla^2 T_\mathrm{f} - \mathbf{u} \cdot \nabla T_\mathrm{f}, \tag{2}$$

where $T$ is temperature, $t$ is time, $\dot{Q}_\mathrm{MCE}$ is the magnetic work term, $\mathbf{u}$ is the flow velocity field, $k$ is the thermal conductivity, $\rho$ is the mass density and $c$ the specific heat. Subscript f indicates the fluid domain and s indicates the solid domain. The AMR cycle is divided into four steps. Firstly, the magnetocaloric material is magnetized, thus increasing the temperature. This is implemented as a step-change for simplicity. Thus, the magnetic work term in Eq. 1 is only non-zero twice per cycle (once for magnetization and once for demagnetization). Secondly, the heat transfer fluid is moved from the cold to the hot end through the regenerator. This is the cold to hot blow period. Thirdly, the material is demagnetized thus decreasing the temperature. Finally, the heat transfer fluid is moved from the hot to the cold side.

During the AMR cycle heat is rejected at the hot end, $\dot{Q}_\mathrm{hot}$, at the hot side temperature $T_\mathrm{hot}$, and a cooling load is absorbed at the cold end, $\dot{Q}_\mathrm{cold}$, at a fixed temperature $T_\mathrm{cold}$. The AMR cycle is repeated until cyclic steady state is reached. This is defined as the point when the relative change of both $\dot{Q}_\mathrm{hot}$ and $\dot{Q}_\mathrm{cold}$ from the previous cycle to the current one is less than $10^{-6}$. Details about the numerical implementation may be found in Ref. [8].

### 2.1. Magnetocaloric and thermal properties

A set of thermal properties are necessary as input to the model. The present work is focused on the influence of the thermal conductivity of the solid and the remaining

**Table I.** The thermal properties of the solid and fluid applied in the model.

| Property | $k$ [W/mK] | $\rho$ [kg/m$^3$] | $c$ [J/kgK] |
|:---:|:---:|:---:|:---:|
| Solid | 1-100 | 7900 | 300 |
| Fluid | 0.6 | 1000 | 4200 |

**Table II.** Thermal conductivity of magnetocaloric materials currently applied in various AMR devices. The values are reported at room temperature.

| Material | $k$ [W/mK] | Ref. |
|:---:|:---:|:---:|
| LaCaSrMnO | 1 | [17] |
| LaFeCoSi | 8 | [18] |
| Gd, GdEr, GdTb | 10 | [19] |

parameters have therefore been chosen to be constant and similar to those of gadolinium (for the solid) and water (for the fluid). Table I gives the properties used in this investigation.

Magnetocaloric materials that are currently being used in experimental devices typically have conductivities from 1 to about 10 W/mK. Reported in literature these are the following series LaCaSrMnO [13, 14], LaFeCoSi and LaFeSiH [14, 6] and gadolinium [15, 16]. Their thermal conductivities are provided in Table II. For the present study is was decided to cover this range of thermal conductivity and extent it somewhat so that it ranges from 1 to 100 W/mK.

The magnetocaloric effect is simplified significantly in this study. A constant adiabatic temperature change $\Delta T_{\mathrm{ad}} = 3$ K is assumed and the specific heat in zero magnetic field is likewise constant with a value of 300 J/kgK. In order to be thermodynamically self-consistent the specific heat while magnetized is found by combining the constant adiabatic temperature change and specific heat in zero field through the defining relation

$$s(T, H = H_1) = s(T + \Delta T_{\mathrm{ad}}(T), H = H_2). \tag{3}$$

Here, $H_1$ and $H_2$ are the initial and final magnetic fields, respectively, and in particular the initial field is assumed to be zero. The specific entropy is denoted $s$. This is found by integrating $c/T$ at constant field with respect to temperature. The specific entropy in field is then used to derive the specific heat in field that is then a function of temperature, albeit only slightly varying. A very similar model material was considered in Ref. [9] and is useful for this investigation as it eliminates variables associated with experimental MCE data such as temperature dependence and experimental uncertainty. The magnetic field change is assumed constant and homogeneous throughout the entire magnetic plate such that demagnetizing effects are ignored.

**Table III.** Operating and geometric parameter variations.

| Parameter | Value range |
|---|---|
| $L$ [m] | 0.05 and 0.2 |
| $H_\mathrm{f}$, $H_\mathrm{s}$ [mm] | 0.2, 0.3 and 0.4, 0.6 |
| $f$ [Hz] | 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 |
| $T_\mathrm{cold}$ [K] | 265-295, steps of 5 K |
| $T_\mathrm{hot}$ [K] | 295 |

### 2.2. Model cases

In the following the various parameter variations (or model cases) are described and justified. A summary is given in Table III.

*2.2.1. Regenerator length* The major variation in this investigation is obviously that of the thermal conductivity of the solid. It is, however, quite relevant to consider this variation for different AMR cases. Two values of the length, $L$, of the regenerator are considered, 0.05 and 0.20 m, respectively. These are denoted as short and long regenerators. A longer regenerator is expected to have fewer losses due to axial conduction than a shorter one. This will be quantified in the results section. In all cases modeled here, the total regenerator volume is held constant, so a long regenerator will have a smaller cross-sectional area for fluid flow.

*2.2.2. Regenerator effectiveness* A common way of classifying the heat transfer effectiveness of a thermal regenerator is to consider the number of transfer units defined as

$$\mathrm{NTU} = \frac{hA_\mathrm{HT}}{\dot{m}_\mathrm{f}c_\mathrm{f}}$$

$$= \frac{\mathrm{Nu}k_\mathrm{f}A_\mathrm{HT}}{2f\varphi m_\mathrm{s}c_\mathrm{s}d_h} \tag{4}$$

$$\varphi = \frac{\dot{m}_\mathrm{f}c_\mathrm{f}}{2fm_\mathrm{s}c_\mathrm{s}}. \tag{5}$$

Here, the heat transfer surface area, mass flow rate of the heat transfer fluid, Nusselt number of the regenerator, operating frequency, mass of the solid, and the hydraulic diameter have been introduced and are denoted by $A_\mathrm{HT}$, $\dot{m}_\mathrm{f}$, Nu, $f$, $m_\mathrm{s}$ and $d_h$, respectively. The thermal utilization, $\varphi$, has also been introduced. This ratio describes the ratio of the thermal mass of the moved fluid to the thermal mass of the regenerator solid.

Generally, as the NTU increases the regenerator effectiveness increases [20]. For a parallel plate regenerator with an incompressible laminar flow, which is considered here, the Nusselt number is roughly constant [21]. The only geometric parameter that can change the regenerator effectiveness is therefore the hydraulic diameter, which for parallel plates is $d_h = 2H_\mathrm{f}$ where $H_\mathrm{f}$ is the flow channel thickness. A smaller channel

thickness thus yields a more effective regenerator. Two cases are therefore considered: one with $H_\mathrm{f} = 0.2$ mm and one where $H_\mathrm{f} = 0.4$ mm. These are called high and low NTU regenerators, respectively, in the following.

The porosity of the regenerator is defined as

$$\epsilon = \frac{H_\mathrm{f}}{H_\mathrm{f} + H_\mathrm{s}}, \tag{6}$$

where $H_\mathrm{s}$ is the solid plate thickness. Keeping this value fixed at 0.4 and the thermal utilization, defined in Eq. 5, constant at 0.5 in all model cases implies that the plate thickness should follow the flow channel thickness. Se Tab. III for details.

*2.2.3. Operating frequency* It is clear that the operating frequency, $f$, of an AMR device is very important for the resulting performance. A higher frequency means that the MCE is magnetized and demagnetized more often per unit time, increasing the potential for cooling power. At the same time, the fluid flow rate must also increase to maintain the utilization, which reduces the NTU. A low frequency may yield a cooling power density that is too low and parasitic losses may become dominating. On the other hand, a high frequency operation can reduce regenerator efficiency as the fluid velocity becomes too high for efficient regeneration. The operating frequency is therefore varied from 0.25 Hz to 4 Hz in this study, which corresponds to recently published devices [22].

*2.2.4. Temperature span and cooling power* The model is used in a mode where the cold and hot side temperatures are prescribed. The hot side is at all times $T_\mathrm{hot} = 295$ K and the cold side varies from $T_\mathrm{cold} = 295$K down to 265 K in steps of 5 K. The resulting $\dot{Q}_\mathrm{cold}$ as a function of the temperature span, defined as $\Delta T \equiv T_\mathrm{hot} - T_\mathrm{cold}$, is then found.

The results presented in the following section are then given as normalized cooling powers (ranging from 0 to 1) at a fixed temperature span.

This means that the resulting cooling power from the model (in units of W/kg) has been divided by the maximum cooling power within the relevant parameter space. The relevant parameter space includes the range of operating frequency, solid thermal conductivity, regenerator length and regenerator effectiveness given in Table III but is at a fixed temperature span. The results given in Figures 1–3 are thus scaled with the same number (230 W/kg) and are thus directly comparable.

The results given in Figs. 4–5 are scaled with a number different from that in the previous figures and the results between the two sets of figures are therefore not directly comparable. The reason for this is the difference in the fixed temperature spans in the two cases that makes direct comparison irrelevant.

In this way it is straightforward to probe the impact of the variations in the parameters on the cooling power of the regenerator, since all the results may be compared directly (for a given fixed $\Delta T$).
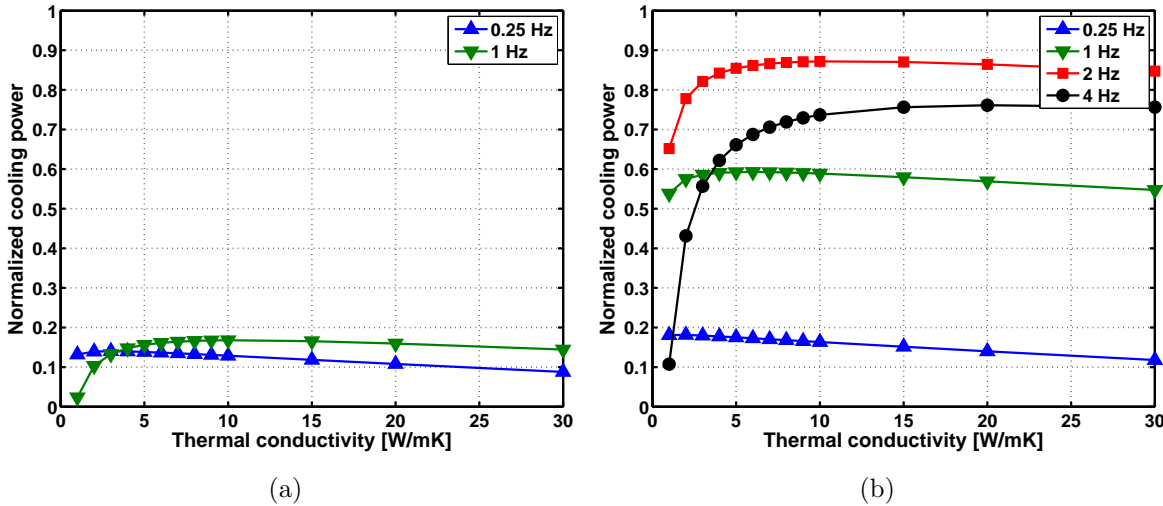
**Figure 1.** (Color online) The normalized cooling power as a function of the solid thermal conductivity for a short regenerator ($L = 0.05$ m). The normalization is done using the maximum cooling power of 230 W/kg. (a) The NTU is low ($H_{\mathrm{f}} = 0.4$ mm). (b) The NTU is large ($H_{\mathrm{f}} = 0.2$ mm). The legend indicates AMR operating frequencies.

## 3. Results and discussion

### 3.1. Fixed temperature span of 10 K

In Fig. 1 the normalized cooling power for the short regenerator is given. Two plots are shown: one where the NTU is low (Fig. 1(a)) and one where it is large (Fig. 1(b)). In both plots the normalized cooling power as a function of the solid thermal conductivity is given at different AMR operating frequencies. The low-NTU regenerator is not able to maintain a sufficient temperature span above 1 Hz (see Fig. 1(a)) and negative cooling powers are not plotted. The temperature span is fixed at 10 K.

As the frequency increases it is quite clear that the sensitivity of the performance to the solid thermal conductivity becomes more pronounced. At low conductivities the normalized cooling power is a very steep function of the thermal conductivity (Fig. 1(b)). This is due to the fact that as the frequency increases the required heat transfer rate from the internal part of the solid to its surface, and thus contact with the heat transfer fluid, also has to increase in order for the performance to be maintained.

It is also evident from Fig. 1 that an optimal solid conductivity exists. When the thermal conductivity becomes too high the regenerator performance is reduced due to the effect of axial conduction. At higher frequencies this effect is less pronounced, albeit still present (see Fig. 1(b)). If the thermal conductivity is too low, the solid cannot transport the magnetic work from its interior to the fluid. It is also evident from Fig. 1 that materials with low conductivity provide the best results for low frequency operation when the regenerator is relatively short.

The normalized cooling power as a function of thermal conductivity of the solid in the case of a long regenerator is given in Fig. 2. The results are similar to those of the
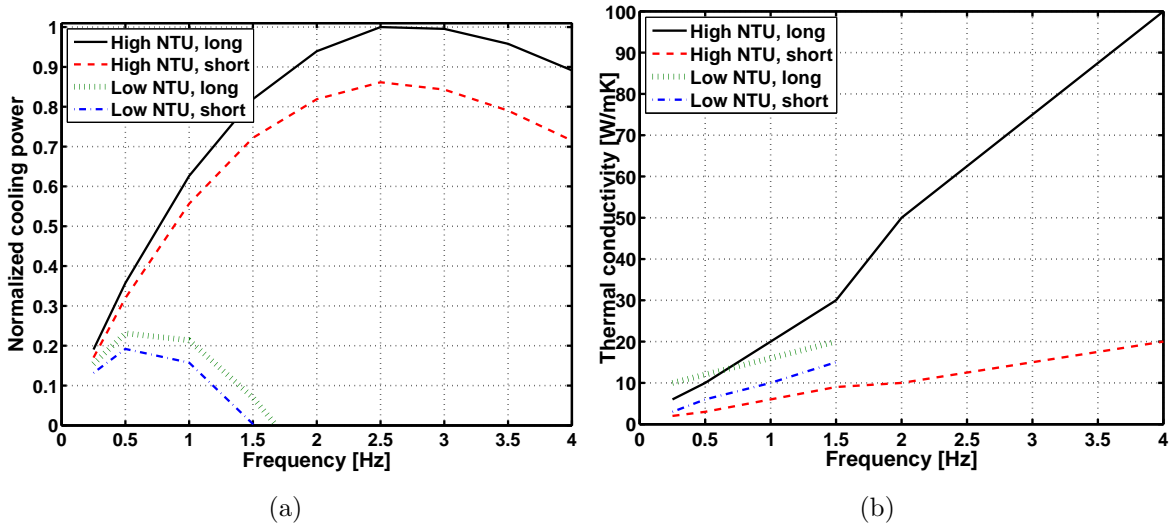
(a)                   (b)
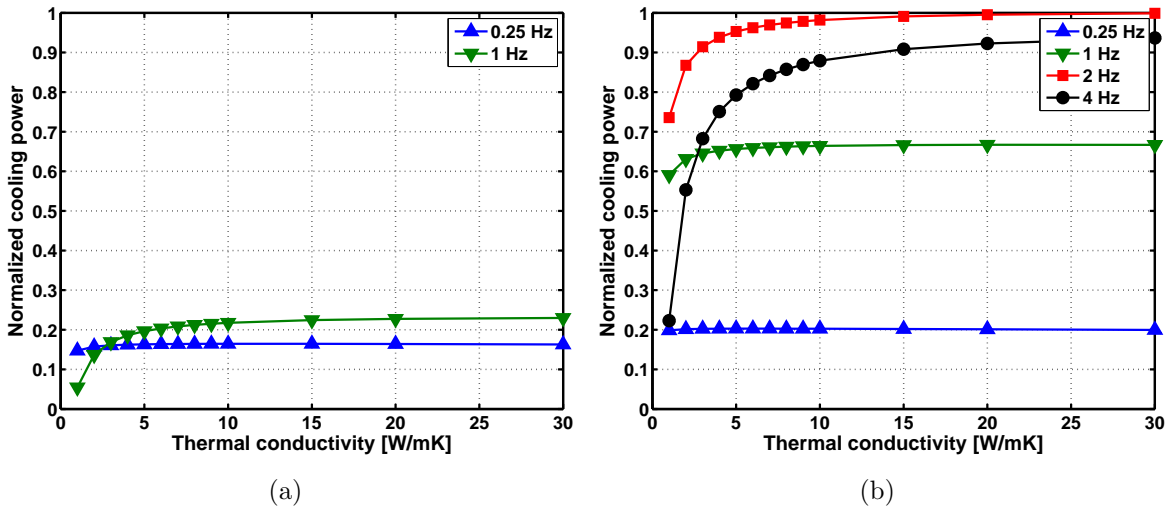
**Figure 2.** (Color online) The normalized cooling power as a function of solid thermal conductivity for a long regenerator ($L = 0.2$ m). The normalization is done using the maximum cooling power of 230 W/kg. (a) The NTU is small ($H_\mathrm{f} = 0.4$ mm). (b) The NTU is large ($H_\mathrm{f} = 0.2$ mm). The legend indicates AMR operating frequencies.

short regenerator, although one clear difference is observed. As the thermal conductivity of the solid increases the cooling power generally also increases or becomes constant as opposed to the short regenerator case (Fig. 1) where the cooling power decreases at high conductivities due to the axial conduction losses. Since the temperature span in both cases is the same, the axial conduction is reduced in the long regenerator simply because of the increased conduction path.

It is also clear from Fig. 2 that the overall performance, at a given frequency and conductivity, is better than for the short case (Fig. 1). It is therefore clear that a longer flat plate regenerator is generally better than a shorter one under the same operating conditions. This is, however, from a strictly AMR point of view and not taking into account external factors such as the design of permanent magnets. It should also be kept in mind that these results are for parallel plates. When considering packed sphere regenerators, where the pressure drop is significantly larger, a longer regenerator may be difficult to realize.

Figure 3(a) shows the normalized maximum cooling power with respect to the thermal conductivity as a function of operating frequency for the four cases of different regenerator geometries (still at a fixed temperature span of 10 K). Figure 3(b) shows the corresponding values of the thermal conductivities at the maximum cooling powers. The cooling power clearly has a maximum as a function of operating frequency, which is dependent on the NTU of the regenerator. The longer regenerators are also seen to be superior to the shorter regenerator, which was also concluded from Figs. 1-2.

The solid thermal conductivity at which the maximum cooling power occurs increases with increasing operating frequency. It may thus be concluded that AMR devices operating at higher frequencies would benefit from an MCM with higher thermal

**Figure 3.** (Color online) (a) The maximum cooling power as a function of operating frequency at a fixed temperature span of 10 K. (b) The corresponding solid thermal conductivity at which the maximum occurs. The legend describes the four different geometries considered.
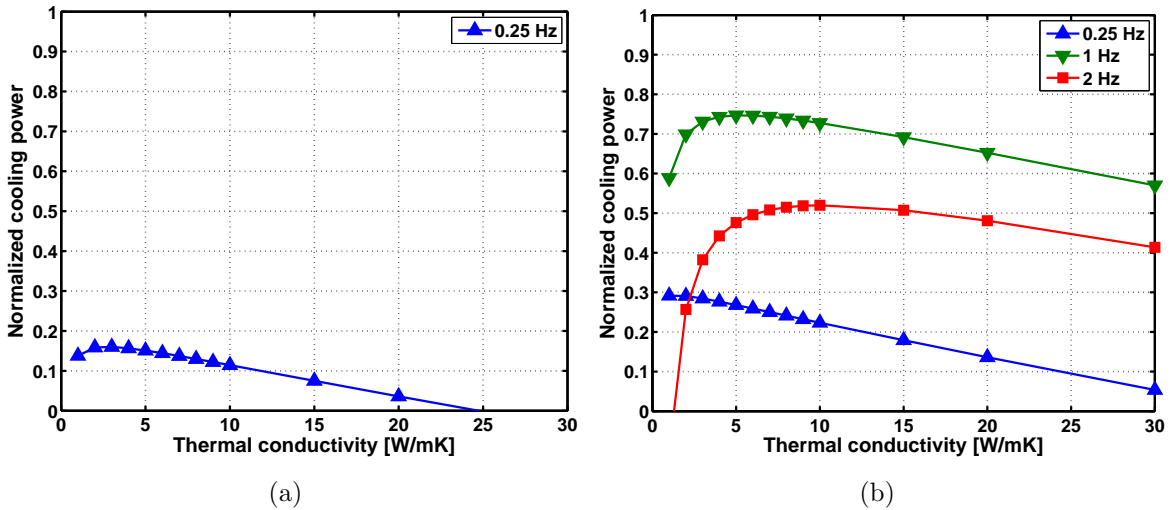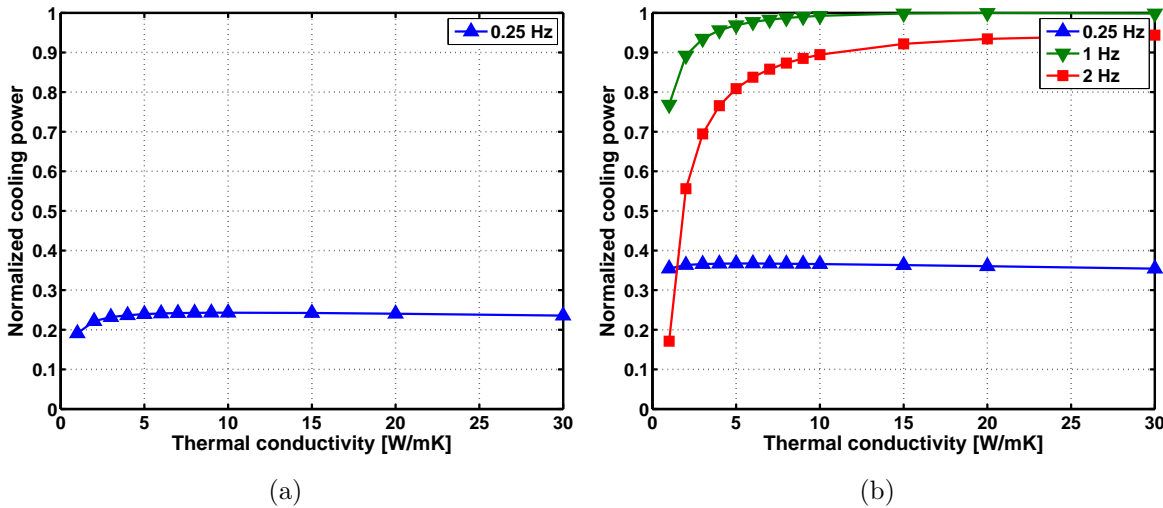


**Figure 4.** (Color online) The normalized cooling power as a function of solid thermal conductivity for a short regenerator ($L = 0.05$ m) at a fixed temperature span of 20 K. The normalization is done using the maximum cooling power of 115 W/kg. (a) The NTU is small. (b) The NTU is large.

conductivity. Again, this is due to the increased demand on the heat conduction through the solid transverse to the axial direction at higher frequencies.

### 3.2. Fixed temperature span of 20 K

As the temperature span is increased the axial conduction will also increase. Furthermore, the requirement of the regenerator effectiveness is also increased. Figure

(a)  (b)

**Figure 5.** (Color online) The normalized cooling power as a function of solid thermal conductivity for a long regenerator ($L = 0.2$ m) at a fixed temperature span of 20 K. The normalization is done using the maximum cooling power of 115 W/kg. (a) The NTU is small. (b) The NTU is large.

4 gives the cooling power as a function of the solid thermal conductivity for the short regenerator (at the small and large values of the NTU, respectively) and Fig. 5 for the long regenerator. The normalization is done for the present parameter space at a temperature span of 20 K and the results may therefore not be compared directly to those presented in Figs. 1-2.

It is clear that since the plate and channel thicknesses are held constant, the possible range of operating frequencies with a positive cooling power is decreased as the imposed temperature span is increased. That is to be expected from basic AMR theory since the time for heat transfer decreases as the frequency increases and thus the number of transfer units will decrease. Imposing a larger temperature span therefore significantly decreases the availability of cooling power in the regenerator.

What is of greater interest is the fact that in the case of the short regenerator (Fig. 4) the dependence of the cooling power on the solid thermal conductivity is more pronounced. At the higher operating frequencies a clear optimum exists, which also increases as a function of the frequency, as was the case for the smaller temperature span.

For the long regenerator (Fig. 5) it is seen that it is still beneficial to increase the thermal conductivity at higher frequencies. It is, however, also apparent that at an operating frequency of 2 Hz, the dependency on the thermal conductivity is much greater when the temperature span is 20 K (Fig. 5(b)) rather than 10 K (Fig. 2(b)). However, at low frequency operation the performance remains only slightly dependent on solid thermal conductivity.

It should be noted that at an operating frequency of 4 Hz none of the considered regenerators are able to produce a positive cooling power at the fixed temperature span

of 20 K and these curves are therefore not plotted in Figs. 4-5.

## 4. Conclusion

A 2-dimensional numerical AMR model was applied in order to study the effect of the solid thermal conductivity on the performance of flat plate active magnetic regenerators. Several operating frequencies, regenerator effectivenesses and regenerator lengths were considered. It is found that the AMR performance may be highly sensitive to the thermal conductivity depending on the operating conditions, but only a limited parameter space was considered. Modeling showed that there exists an optimum solid thermal conductivity for a given geometry and operating condition that balances thermal transport from the MCM to the heat transfer fluid and axial conduction losses.

It was shown that performance can be greatly affected by the regenerator length, which is directly related to axial conduction losses. The importance of the solid thermal conductivity was shown to depend on the operating frequency of the device. Generally, if the AMR device is operated at a high frequency, the sensitivity of the performance to variations in the thermal conductivity is increased. The model predicted that for a long regenerator a conductivity of 50 W/mK is necessary to achieve maximum cooling power for 2 Hz operation, which is significantly higher than current high performance MCMs have. For flat plate regenerators, modeling showed that longer regenerators performed better, as the increased conduction path reduced axial conduction losses associated with the higher solid conductivity.

It is also concluded that when operating the AMR at low frequencies ($< 1$Hz), the thermal conductivity has little impact on the performance and that the trend is that a smaller conductivity is better. This is due to the fact that axial conduction losses are relatively larger for lower operating frequencies since the cooling power density is smaller than at higher frequencies.

## References

[1] V. K. Pecharsky and K.A. Gschneidner. Advanced magnetocaloric materials: What does the future hold? *International Journal of Refrigeration*, 29:1239–1249, 2006.
[2] J. A. Barclay. Theory of an active magnetic regenerative refrigerator. *NASA Conference Publication*, pages 375–387, 1983.

[3] V. K. Pecharsky and K. A. Gschneidner Jr. Magnetocaloric effect and magnetic refrigeration. *Journal of Magnetism and Magnetic Materials*, 200(1-3):44–56, 1999.

[4] A. Rowe. Configuration and performance analysis of magnetic refrigerators. *International Journal of Refrigeration*, 34(1):168 – 177, 2011.

[5] E. Bruck, O. Tegus, D.T.C. Thanh, N.T. Trung, and K.H.J. Buschow. A review on Mn based materials for magnetic refrigeration: structure and properties. *International Journal of Refrigeration*, 31(5):763–770, 2008.

[6] S. Russek, J. Auringer, A. Boeder, J. Chell, S. Jacobs, and C. Zimm. The performance of a rotary magnet magnetic refrigerator with layered beds. In P. W. Egolf, editor, *Fourth International Conference on Magnetic Refrigeration at Room Temperatur.* Interna, 2010.

[7] A. Tura and A. Rowe. Permanent magnet magnetic refrigerator design and experimental characterization. *International Journal of Refrigeration*, 34(1):628 – 639, 2011.

[8] K. K. Nielsen, C. R. H. Bahl, A. Smith, R. Bjørk, N. Pryds, and J. Hattel. Detailed numerical modeling of a linear parallel-plate active magnetic regenerator. *International Journal of Refrigeration*, 32(6):1478–1486, 2009.

[9] K. Engelbrecht and C.R.H. Bahl. Evaluating the effect of magnetocaloric properties on magnetic refrigeration performance. *Journal of Applied Physics*, 108(12):123918, 2010.

[10] K. L. Engelbrecht, G. F. Nellis, and S. A. Klein. The effect of internal temperature gradients on regenerator matrix performance. *Journal of Heat Transfer*, 128(10):1060–1069, 2006.

[11] C. P. Jeffreson. Prediction of breakthrough curves in packed beds. *American Institute of Chemical Engineers*, 18(2):409–20, 1972.

[12] H. Hausen. *Heat Transfer in Counterflow, Parallel-Flow and Cross-flow.* McGraw-Hill Co., 1983.

[13] A. R. Dinesen, S. Linderoth, and S. Mørup. Direct and indirect measurement of the magnetocaloric effect in $La_{0.67}Ca_{0.33-x}Sr_xMnO_3 \pm \delta$ ($x \in [0; 0.33]$). *Journal of Physics: Condensed Matter*, 17(39):6257–6269, 2005.

[14] K. Engelbrecht, C.R.H. Bahl, and K.K. Nielsen. Experimental results for a magnetic refrigerator using three different types of magnetocaloric material regenerators. *International Journal of Refrigeration*, 34(4):1132–1140, 2011.

[15] A. Rowe and A. Tura. Experimental investigation of a three-material layered active magnetic regenerator. *International Journal of Refrigeration*, 29:1286–1293, 2006.

[16] C. Zimm, A. Boeder, J. Chell, A. Sternberg, A. Fujita, S. Fujieda, and K. Fukamichi. Design and performance of a permanent-magnet rotary refrigerator. *International Journal of Refrigeration*, 29(8):1302–1306, 2006.

[17] D. W. Visser, A. P. Ramirez, and M. A. Subramanian. Thermal conductivity of manganite perovskites: Colossal magnetoresistance as a lattice-dynamics transition. *Phys. Rev. Lett.*, 78(20):3947–3950, May 1997.

[18] S. Fujieda, Y. Hasegawa, and A. Fujita. Thermal transport properties of magnetic refrigerants $La(Fe_xSi_{1-x})_{13}$ and their hydrides, and $Gd_5Si_2Ge_2$ and MnAs. *Journal of Applied Physics*, 95(5):2429–2431, 2004.

[19] P. Jacobsson and B. Sundqvist. Thermal conductivity and electrical resistivity of gadolinium as functions of pressure and temperature. *Physical Review B*, 40(14):9541–9551, 1989.

[20] G. D. Dragutinovic and B. S. Baclic. *Operation of Counterflow Regenerators*, volume 4 of *International Series on Developments in Heat Transfer.* Computational Mechanics Publications, 1 edition, 1998.

[21] M. Nickolay and H. Martin. Improved approximation for the Nusselt number for hydrodynamically developed laminar flow between parallel plates. *International Journal of Heat and Mass Transfer*, 45(15):3263–3266, 2002.

[22] B. Yu, M. Liu, P. W. Egolf., and A. Kitanovski. A review of magnetic refrigerator and heat pump prototypes built before the year 2010. *International Journal of Refrigeration*, 33(6):1029–1060, 2010.