Magnetic refrigeration at room temperature - from magnetocaloric materials to a prototype

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Abstract. Based on the magnetocaloric effect, magnetic refrigeration at room temperature has for the past decade been a promising, environmentally friendly new energy technology predicted to have a significantly higher efficiency than the present conventional methods. However, so far only a few prototype refrigeration machines have been presented worldwide and there are still many scientific and technological challenges to be overcome. We report here on the MagCool project, which spans all the way from basic materials studies to the construction of a prototype. Emphasis has been on ceramic magnetocaloric materials, their shaping and graded composition for technological use. Modelling the performance of a permanent magnet with optimum use of the flux and relatively low weight, and designing and constructing a prototype continuous magnetic refrigeration device have also been major tasks in the project.

1. Introduction

In 1881 Warburg reported on the discovery of the magnetocaloric effect [1], and in the 1920-ies Debye and Giaugue suggested it for achieving low temperatures for laboratory use [2, 3]. The magnetocaloric effect is caused by the fundamental thermodynamic property of entropy conservation under adiabatic conditions [4, 5]: In a simple picture describing a second order magnetic phase transition in a magnetic material undergoing magnetization, the magnetic order is increased and correspondingly the magnetic entropy part is decreased. The adiabatic constraint assures entropy conservation and therefore the lattice entropy must increase, causing a raise in temperature of the magnetic material. The process is reversible in second order materials meaning that a cycle of magnetization and demagnetization of the material will cause a corresponding temperature raise and drop of equal magnitude. An expression for the magnetocaloric effect in terms of the field and temperature dependent magnetization can be derived using the basic thermodynamic expression for the change in entropy $S$ of a given system as a function of the pressure $p$, the temperature $T$, and the applied magnetic field $H$,

$$dS(p, T, H) = \left( \frac{\partial S}{\partial p} \right)_{T,H} dp + \left( \frac{\partial S}{\partial T} \right)_{p,H} dT + \left( \frac{\partial S}{\partial H} \right)_{p,T} dH$$

(1)

together with the Maxwell relation

$$\left( \frac{\partial S}{\partial H} \right)_{p,T} = \left( \frac{\partial M}{\partial T} \right)_{p,H}.$$

(2)
In the simple case of a second order phase transition it can be assumed that the pressure is constant during magnetization, which leads to that the isothermal entropy change induced by a magnetic field change $H_1 \rightarrow H_2$ is

$$\Delta S_{H_1 \rightarrow H_2} = \int_{H_1}^{H_2} \left( \frac{\partial S}{\partial H} \right)_T \, dH. \quad (3)$$

Applying Maxwell’s relations for an adiabatic magnetic field change, i.e. $dS = 0$, gives the easier measurable expression in terms of the magnetization $M$

$$\Delta S_{H_1 \rightarrow H_2} = \mu_0 \int_{H_1}^{H_2} \left( \frac{\partial M}{\partial T} \right)_H \, dH, \quad (4)$$

where $\mu_0$ is the vacuum permeability. Applying the definition of the heat capacity at constant pressure $C_p$ and the second law of thermodynamics, leads to the expression for the related adiabatic temperature change

$$\Delta T_{ad,H_1 \rightarrow H_2} = -\mu_0 \int_{H_1}^{H_2} \frac{T}{C_p} \left( \frac{\partial M}{\partial T} \right)_H \, dH, \quad (5)$$

achieved by applying a magnetic field change $H_1 \rightarrow H_2$. Equations (4) and (5) describe well the characteristics of the magnetocaloric effect in terms of the directly measurable parameters $M$ and $T$. It should be noted that both $\Delta S$ and $\Delta T_{ad}$ exhibits an extremum for the maximum of $\partial M/\partial T$, e.g. for a ferromagnetic material that is around the Curie temperature $T_C$. Further, the heat capacity $C_p$ directly influences the adiabatic temperature change that can be achieved in a specific material.

The adiabatic temperature change that can be achieved in known magnetocaloric materials is only a few Kelvins [6]. However, in 1976 Brown demonstrated that by applying a regenerative cooling cycle a significant temperature gradient can be accumulated [7]. In Brown’s so-called active magnetic regenerator (AMR) a temperature gradient of 46K cooling from 319K was generated with Gd in a magnetic field change of 7T even though the adiabatic temperature change in Gd at 7T is only $\Delta T_{ad} \sim 14$K. It has been predicted that the cooling efficiency (COP) of magnetic refrigeration would result in at least 30% energy savings compared to conventional compressor based techniques working at room temperature [8]. Brown’s pioneering work combined with the discovery of the so-called giant magnetocaloric effect [9] made magnetic refrigeration using environmentally friendly and non-hazardous gasses and materials a promising alternative cooling technique at room temperature to the conventional compressor based techniques. Further, other technologies like heat pumps and air conditioning that are also responsible for a significant part of the global energy consuming could in the future be replaced by systems using the magnetocaloric effect.

The challenges for converting the principles of magnetic refrigeration into a commercially relevant technology of the future are many and closely coupled. They can be organized in four major topics:

- Materials for the AMR. Designing a commercially relevant material that shows a large enough adiabatic temperature change (i.e. $\Delta T_{ad} \sim 1$K) in the 250 K to 350 K region implying tunable magnetocaloric properties in this wide temperature span. The requirements to the materials are that they should be non-toxic, chemically stable, environmentally friendly, abundant, easy to fabricate and shape, recyclable, preferably not exhibit hysteresis effects that cause too significant losses, and last but not least cheap.
- Modelling of the thermodynamical and fluid dynamical properties of the AMR, so designs can be evaluated and optimal parameters predicted. This includes geometry of the AMR
with minimal pressure losses and optimum heat transfer between magnetocaloric material and heat transfer fluid. Also, modelling the temperature gradient and it’s coupling to the magnetocaloric properties of the AMR materials and the magnetic properties of the AMR materials under varying temperature close to the magnetic phase transition is an essential problem to be addressed.

- Modelling of the permanent magnet supplying the magnetic field in the magnetic refrigeration system. As large as possible magnetic fields are required in a region of closed flux. However, to achieve magnetic flux densities above 1 T is both costly and requires large amounts of magnetic material. Modelling of permanent magnet designs with an optimized balance between flux density and volume and volume of magnet material.

- Demonstration of the feasibility of the principles by a prototype magnetic refrigeration device.

In the MagCool project, funded by the Danish Council for Strategic Research, we are emphasizing that all four topics needs to be addressed in close collaboration. Therefore we have investigated a selection of commercially relevant magnetocaloric materials (discussed in section 2), combined the materials’ studies with modelling of both a permanent magnet and an AMR (briefly described in subsections 2.4 and 3.1) for finally designing a prototype magnetic refrigeration device (presented in section 3).

2. Commercially relevant magnetocaloric materials for room temperature magnetic refrigeration

Investigations of the magnetic properties of materials for magnetic refrigeration at room temperature have grown to an immense field of research and development. Materials candidates are found within both basic elements, alloys, and ceramics, among those are the well known Gd [7], Fe₄₀Rh₅₁ [10], the Gd₅Si₂Ge₂ and the related Gd₅(Si₁₋ₓGeₓ) series [9, 11], the Mn₆₋ₓSbx [12] series, and the LaFe₁₃₋ₓ₋ₙCoₙSiy series [13]. Gd has become the benchmark material for magnetic refrigeration at room temperature with an adiabatic temperature of 3.6 K at 1 T applied field change and a Curie temperature of 293 K. Fe₄₀Rh₅₁ has the so far largest known adiabatic temperature change of 5 K at 1 T. The latter materials are however, characterized by having only a relatively narrow working range of a few degrees due to the narrow magnetic transition. With the alloys of for instance Gd₅(Si₁₋ₓGeₓ) and Mn₆₋ₓSbx a relatively large temperature change (∆Tₐd ~2 K at 1 T), the giant magnetocaloric effect, is found for a wider range of working temperatures as the Curie temperature can be tuned by the exact materials composition. These materials’ magnetocaloric effect is related to several types of phase transitions inducing a 1st order magnetic phase transition, i.e. practical obstacles like hysteresis loses and volume changes are important. For commercialization both price, abundance, ease of production and shaping, and non-toxicity becomes highly relevant. By the newly developed industrial powder metallurgy methods [13] the LaFe₁₃₋ₓ₋ₙCoₙSiy series presenting a ∆Tₐd up to ~2.2 K at 1 T related to a second order phase transition could prove to be the magnetocaloric material of the future. Besides studying this materials series, we have during this project also focused on an alternative material candidate: the ceramic lanthanum manganite series (also known for the colossal magnetoresistance [14]), which also fulfill the requirements including a tunable TC in a wide range around room temperature, negligible hysteresis effects and in addition also robustness of the magnetocaloric effect.

2.1. La₀.₆₇Ca₀.₃₃₋ₓSrₓMn₁₀.₅₅O₃ - fine tuning TC by industrial production methods

La₀.₆₇Sr₀.₃₃MnO₃ is a perovskite material with a ferromagnetic to paramagnetic second order phase transition at TC = 354 K, and the corresponding La₀.₆₇Ca₀.₃₃MnO₃ has a first order magnetic (ferromagnetic to paramagnetic) and structural (orthorhombic to rhombohedral)
phase transition at $T_C = 260$ K [15]. Mixing compositions of La$_{0.67}$Ca$_{0.33-x}$Sr$_x$MnO$_3$ (for $0 < x < 0.33$) (LCSM) results in an LCSM compound with tunable Curie temperature and a second order magnetic phase transition with no observable hysteresis and an adiabatic temperature change up to 1.6 K at 0.7 T applied field change in the temperature range 260 K to 354 K [16]. The ferromagnetism of LCSM is caused by double exchange between the Mn$^{3+}$ and Mn$^{4+}$ ions mediated via the O$^{2-}$ ions. Therefore substituting Ca by Sr gradually increases the Mn-O-Mn bond angle and likewise increases the Curie temperature.

**Figure 1.** The magnetocaloric effect in La$_{0.67}$Ca$_{0.33-x}$Sr$_x$Mn$_{1.05}$O$_3$ for increasing $x$ (from left to right: $x = 0.0375$ to $x = 0.09$). The inset shows the corresponding adiabatic temperature change. $\Delta S$ has been determined indirectly by magnetization measurements and $\Delta T_{ad}$ has been measured directly, both are given for a 1 T applied field change.

LCSM can be prepared by for instance glycine-nitrate synthesis or solid state reaction. However, with industrial up-scaling in mind LCSM was prepared as a polycrystalline powder by spray pyrolysis (delivered by the company CerPoTech AS) and subsequently calcined and sintered (details of the materials fabrication will be published elsewhere [17]). Fig. 1 shows a predefined La$_{0.67}$Ca$_{0.33-x}$Sr$_x$Mn$_{1.05}$O$_3$ series (the series was prepared with a slight overstoichiometry of Mn to avoid dilution of the magnetization caused by understoichiometry) prepared by gradually increasing $x$ in the range $x = 0.0375$ to $x = 0.09$ to achieve a series of LCSM powders with $T_C$ in the range 274 K to 303 K, which is relevant for magnetic refrigeration at room temperature. The magnetic entropy change $\Delta S$ was measured indirectly by magnetization measurements in a Lakeshore 7407 vibrating sample magnetometer. These measurements were supplemented by $C_p$ measurements (not shown) by a custom built differential scanning calorimeter equipped with an in-house designed Halbach magnet [18] providing an adjustable magnetic field [19, 20]. Direct measurements of the adiabatic temperature change were also acquired by a custom built device using the Halbach magnet [20], these data are shown in the inset of Fig. 1.

The measured adiabatic temperature changes in a field change of 1 T are between 0.8 K and 1.5 K. The achieved $\Delta T_{ad}$ are qualitatively in good agreement with what has been determined indirectly using data for $\Delta S$ and $C_p$ [16]. However, the direct method eliminates the use of assumptions about the magnetic field dependence of $C_p$ and therefore gives a value for the adiabatic temperature change, which is closer to what would be achieved in the AMR.

The results in Fig. 1 demonstrates that it is indeed possible to fabricate large quantities (kilograms) of the LCSM material by industrial ceramic powder processing techniques with a precision good enough to tune the Curie temperature within a few degrees and achieving a practically usable $\Delta T_{ad}$. 

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2.2. La$_{0.75}$Ca$_{0.25}$Sr$_x$MnO$_3$ - a broad temperature range of $\Delta S$

As demonstrated above and by many other authors \[5, 8, 11, 12, 13\] tuning of the Curie temperature is a well known method to broaden the working range of the magnetocaloric materials, however, not the only possible one. For specific compositions of LCSM there will be co-existence of several phases, which may affect the magnetocaloric properties. The compound La$_{0.75}$Ca$_{0.25-\text{x}}$Sr$_\text{x}$MnO$_3$ ($x = 0.1$) lies close to the structural phase transition between the orthorhombic and rhombohedral regions \[21\] and may therefore exhibit such co-existence effects. We have prepared a series of La$_{0.75}$Ca$_{0.25-\text{x}}$Sr$_\text{x}$MnO$_3$ ($x = 0, 0.1, 0.25$) polycrystalline powders by solid state reaction and subsequently calcination and sintering. The powders were characterized structurally and the magnetocaloric properties were investigated as described above. Fig. 2 displays the entropy change for the $x = 0.1$ composition in magnetic field changes up to 1.6 T and a table-like magnetocaloric effect up to 1.2 J/kgK is observed in a broad temperature range between approximately 255 K and 315 K.

![Figure 2. The broad table-like magnetocaloric effect in La$_{0.75}$Ca$_{0.25-\text{x}}$Sr$_\text{x}$MnO$_3$ ($x = 0.1$) for increasing applied magnetic field changes (from bottom to top: 0.5 T, 1.2 T, 1.6 T). The cusps on the curves indicate that several mechanisms are at play broadening the phase transition. The inset shows the comparison of the table-like magnetocaloric effect (filled symbols) to the pure entropy change related to the magnetic phase transition (open symbols) at 1.6 T, observed after annealing the material.](image)

In the orthorhombic structure the dynamic Jahn-Teller effect plays a significant role in the magnetic properties. Due to the symmetry of the rhombohedral structure it is however not present in that structural phase. The competition between the structural and magnetic phases induces a so-called tri-critical point where an additional order parameter couples to the magnetic order parameter and a broad region of co-existence of several magnetic phases may occur. This is the origin of the table-like entropy change observed in Fig. 2.

The small cusps at the curves indicate the presence of competing phases. This co-existence of phases is induced by the structural phases and can be removed by annealing the La$_{0.75}$Ca$_{0.25-\text{x}}$Sr$_\text{x}$MnO$_3$ ($x = 0.1$) composition and the expected carrot-like entropy change is recovered (shown for comparison in the inset of Fig. 2). Though very complex, the nature of the table-like phase transition has shown to be of second order and not introducing hysteresis effects (detailed investigations of the mechanisms behind the table-like entropy is discussed in \[22\]).

Integration of the areas under the $\Delta S$-curves show that the areas related to the table-like and the carrot-like entropy changes are comparable, i.e. the same cooling effect is achieved but spread in a much broader temperature range. A $\Delta T_{ad} \sim$0.6 K at a magnetic field change of 1 T is achieved for the LCSM composition exhibiting the table-like magnetocaloric effect. This study illustrates the perspectives for tailoring $\Delta S$ and thereby also $\Delta T_{ad}$ by manipulating the interplay between several magnetic and structural phases.
2.3. \((La_{1-x}A_x)_{0.67}Ba_{0.33}Mn_{1.05}O_3\) - robustness of \(\Delta S\) against doping

For practical application of the magnetocaloric materials it is an advantage if the magnetocaloric effect is robust against impurities and that the tuning of \(T_C\) by doping does not significantly reduce \(\Delta S\) and \(\Delta T_{\text{ad}}\) as otherwise often observed [11, 13, 16]. We have studied the effect of substituting a part of the lanthanum in \(La_{0.67}Ba_{0.33}Mn_{1.05}O_3\) [23], this composition shows a Curie temperature of \(T_C = 347\, K\), a magnetic entropy change of \(\Delta S = 1.7\, J/kgK\) and a related adiabatic temperature change \(\Delta T_{\text{ad}} = 0.65\, K\) at 1 T applied magnetic field change. A \((La_{1-x}A_x)_{0.67}Ba_{0.33}Mn_{1.05}O_3\) series was prepared by glycine-nitrate synthesis with \(A\) being a mixture of lanthanides containing 66% La, 22% Nd, 8% Pr and 4% Ce to mimic some of the naturally occurring lanthanide compositions. The structural and magnetocaloric properties of a series of compositions with \(x = 0, 0.33, 0.67, 1\) was investigated, the entropy change in an applied magnetic field change of 1 T is shown in Fig. 3. In the \((La_{1-x}A_x)_{0.67}Ba_{0.33}Mn_{1.05}O_3\) series the reduction of \(T_C\) with increasing doping on \(A\) is caused by the ionic size mismatch, but there is no change from a second to a first order magnetic phase transition accompanied by a structural phase transition as found in the \(La_{0.67}Ca_{0.33-x}Sr_xMn_{1.05}O_3\) series. We suggest that the robust \(\Delta S\) is caused by a counter acting mechanism that compensates the effect of ionic size mismatch. Such a mechanism could be the increased internal stresses induced by the smaller ionic sizes, in turn causing a higher degree of lattice disorder that may again relax the internal stresses and thereby actually preserve the achieved entropy change independently of the impurity composition. This is discussed in detail in [23].

**Figure 3.** The magnetocaloric effect in \((La_{1-x}A_x)_{0.67}Ba_{0.33}Mn_{1.05}O_3\) \((x = 0, 0.33, 0.67, 1\) from right to left) acquired at 1 T field change. \(T_C\) is clearly reduced as \(x\) increases, whereas the corresponding \(\Delta S\) is observed to be unaffected by the doping with lanthanides.

2.4. Shaping of the AMR

Up to this point we have presented a family of material series that fulfill the requirements listed in the introduction of this section. However, for commercialization these polycrystalline ceramic powders also must be shaped into a form suited for an AMR by applying industrial techniques.

Shaping of the AMR is a very crucial point: an open structure that allows easy flow of the heat transfer fluid is required together with minimized pressure loss and an optimum contact area between the fluid and the magnetocaloric material. As a starting point we have chosen to work with a geometry of stacks of flat plates. These fulfill the criteria and can be modelled in great detail [24, 25]. We have applied tapecasting, sintering and subsequently laser cutting to fabricate thin and flat plates, an example is shown in Fig. 4. The thickness of the flat plates is \(\sim 0.3\, mm\). A characteristic feature of an AMR is the build-up of a temperature gradient, i.e. the optimum working temperature of the active magnetocaloric material changes gradually.
throughout the AMR in the direction of the heat transfer fluid flow. We have shown by modelling in [26] that tailoring the working temperature of the magnetocaloric material to the optimum working temperature in the AMR increases the achievable cooling power and COP by up to 30% when just grading the AMR with two in stead of one magnetocaloric material. For our prototype cooling machine modelling suggested that for optimal performance the LCSM plates should be graded with six materials with approximately 4 K difference between each $T_C$, an example of such a material set was shown in Fig. 1 and the principle of graded material is sketched in Fig. 5. For the tape casting slurries of each LCSM powder was prepared and a custom build multi compartment doctorblade was used for simultaneously tape casting all six (or up to ten) materials into one tape. The graded tape was subsequently dried and sintered and laser cut into narrow pieces prepared for stacking and mounting in the prototype [27]. An example of a graded plate with ten different LCSM compositions is shown in Fig. 5.

Stacking of individual plates for a complete AMR can become a cumbersome activity and therefore we have also studied other ways of industrial shaping. One successful example is shown in the inset of Fig. 4, where we have applied extrusion to fabricate a monolithic AMR with channels of square cross section. The extruded monolithic structure was afterwards cut into a cylindrical AMR of length 50 mm and diameter of 34 mm to fit into our test machine.
In conclusion we can apply industrial ceramic processing and shaping techniques to tailor the magnetocaloric properties of the materials for the AMR including combined materials with gradual change of the magnetocaloric properties. The lanthanum manganite series have proven perfectly tunable to an optimized working temperature range and in the special case of LBMO also robustness towards doping and impurities without significant reduction of the magnetocaloric effect.

3. The MagCool prototype

A fast increasing number of prototype magnetic refrigeration devices is presented each year, so far at least 42 systems have been published. A selection of the so far most promising systems include those by Zimm et al. [28], Tura and Rowe [29], Okamura et al. [30] and Tusek et al. [31]. All of those are based on a rotating system to achieve continuous movement and maximize the use of the magnetic field in the AMR. In the design of the MagCool prototype we have applied a two-step approach: firstly, a simple test machine with a linear parallel plate AMR that could be used for experiments under very flexible conditions and where the measurements could be modelled numerically in a feasible way was constructed [24]. Secondly, an optimized rotary magnetic refrigeration device was constructed [27] based on the results acquired by the test machine. For both systems the numerical modelling included optimization of the permanent magnet configuration [32] and of the thermodynamical and fluid dynamical parameters for the AMR [25].

The basic idea of the prototype device is a rotating cylindrical AMR enclosed by two concentric multipole permanent magnets with alternating regions of high and low field. The heat transfer fluid flow is parallel to the axis of the cylinder. For minimal pressure loss in the AMR a geometry of stacked plates was chosen. This geometry also minimizes the magnetostatic demagnetization field from the plates [33]. The prototype consists of four symmetrically alternating high and low field regions. By rotation of the AMR cylinder equal amounts of magnetocaloric material are entering and leaving the high field regions. Therefore the magnetic forces are balanced and the only work that needs to be supplied to rotate the AMR is caused by the small differences in magnetization due to the temperature profile throughout the AMR, and of course, the mechanical work related to friction in the external parts. While rotating the AMR, the heat transfer fluid flows along the plates in alternating directions in phase with the magnetization and demagnetization of the plates to generate the temperature gradient between the hot and the cold end. For construction reasons the AMR is divided into 24 compartments of stacks of parallel plates. Fig. 6 shows the inner and the outer design of the prototype.

The dimensions of the prototype where defined based on the numerical modelling with the target temperature difference between the hot and the cold end of 40 K and a continuous...
cooling power of 100 Watt using the benchmarking material Gd as magnetocaloric material. The prototype is currently in stage of final assembly. Future testing, also with the La\textsubscript{0.67}Ca\textsubscript{0.33}–xSr\textsubscript{x}MnO\textsubscript{3} and LaFe\textsubscript{13}–xCo\textsubscript{x}Si\textsubscript{y} series, will show how well these numbers can be reached in practice.

### 3.1. Permanent magnet configuration

For the test machine running with a linear parallel plate AMR, a permanent magnet with a Halbach configuration was constructed [18], but for the rotary prototype (see Fig. 6) a new permanent magnet had to be designed [34]. The performance of the magnet with regards to magnetic refrigeration can be evaluated using the $\Lambda_{\text{cool}}$ parameter [35], which is defined as

$$\Lambda_{\text{cool}} = \left( \langle B_{\text{high}}^{0.7} \rangle - \langle B_{\text{low}}^{0.7} \rangle \right) \frac{V_{\text{field}}}{V_{\text{mag}}} P_{\text{field}},$$

where $B_{\text{high}}$ and $B_{\text{low}}$ are the magnetic flux densities in the high and low field regions, respectively, and the $\langle \rangle$ denotes the average of the flux density. The flux density is evaluated to the power of 0.7 because this is the typical magnetic field dependence of the adiabatic temperature change for a second order magnetocaloric material at the Curie temperature [4]. The volume of magnet material $V_{\text{mag}}$ should be minimized as this is the most costly of all components in the prototype, and the corresponding volume of magnetic field $V_{\text{field}}$ should be maximized.

The prototype has a continuously rotating AMR with four alternating high and low magnetic field regions, and the magnetic field configuration was optimized to achieve the largest $\Lambda_{\text{cool}}$ using 3D finite element magnetostatic modelling [32]. The magnet has been designed to accommodate a cylindrical AMR with stacks of magnetocaloric plates filling the gap of 250 mm length and of 30 mm width. The result of the modelling and the final constructed permanent magnet is shown in Fig. 7.

![Figure 7. Modelling of the optimized magnetic field configuration for the continuously rotating prototype with 4 alternating regions of high (1.24 T) and low field (< 0.01 T). The two concentric cylindrical magnets measure 250 mm in length, the inner magnet has an inner diameter of 20 mm and an outer diameter of 140 mm, while the outer magnet has an inner diameter of 200 mm and an outer diameter of 270 mm.](image)

Evaluating the $\Lambda_{\text{cool}}$ parameter for the presented permanent magnet design shows a value of 0.21, which to the best knowledge of the authors matches the highest $\Lambda_{\text{cool}}$ published so far [34].

### 4. Conclusion

In conclusion, we have fulfilled three of our four goals set up in the introduction: Industrial relevant material series with tunable Curie temperature and even robustness of the entropy change against doping has been demonstrated by the lanthanum manganites. Modelling of both a concentric permanent magnet with flux closure and a continuously rotating parallel plate AMR
has resulted in a new improved design that is now being implemented as a prototype magnetic refrigeration machine. Only our last goal to demonstrate a running cooling machine is not yet achieved, though it will be in the near future.

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