Hvis den private sektor virkelig mangler talent, så kom og hent det på universiteterne

The age at which Noble Prize research is conducted

Nobel Laureates are used as a proxy to study at what age scientists produce their most groundbreaking work. We determine the average age of Nobel Laureates at the time that their Prize-winning research was conducted. This is done using the Advanced Information document with scientific background information published by the Nobel Foundation for every awarded Nobel Prize since 1995 for physics and economics, 2000 for chemistry and 2006 for physiology or medicine. For all Laureates their average age when their Prize-winning research was conducted was $44.1\pm9.7$, with Laureates in physics generally being younger compared to the other fields. It is shown to be statistically significant that Laureates in physics have published their Nobel Prize winning works within a shorter span of years compared to the other fields, whereas Laureates in economics use a longer span of years. The number of papers cited by the Nobel Foundation for each Laureate was found to be $9.6\pm8.6$, with Laureates in physics having significantly fewer papers cited compared to the other fields, $5.4\pm4.8$, while Laureates in economics have significantly more, $17.3\pm11.5$. Finally, we find that Laureates wait an average of $22.3\pm10.8$ years between conducting their prize-winning research and receiving the Nobel Prize.
The demagnetization factor for randomly packed spheroidal particles
We investigate if the demagnetization factor for a randomly packed powder of magnetic spheroidal particles depend on the shape of the spheroidal particles and what the internal variation in magnetization is within such a powder. A spheroid is an ellipsoid of revolution, i.e. an ellipsoid with two semi-major axis being equal. The demagnetization factor is calculated as function of particle aspect ratio using two independent numerical models for several different packings, and assuming a relative permeability of 2. The calculated demagnetization factor is shown to depend on particle aspect ratio, not because of direct magnetic interaction but because the particle packing depend on the aspect ratio of the particles. The relative standard deviation of the magnetization across the powder was 3–8%, increasing as the particle shape deviates from spherical, while the relative standard deviation within each particle was relatively constant around 5%.

Unge forskere kritiserer strategi: Pionercentre favoriserer få forskere

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A topology optimized switchable permanent magnet system
The design of a magnetic field source that can switch from a high field to a low field configuration by rotation by 90°90° of a set of iron pieces is investigated using topology optimization. A Halbach cylinder is considered as the magnetic field source and iron inserts are placed in the air gap of the Halbach cylinder. The ideal shape of these iron inserts is determined as function of the field generated by the Halbach cylinder and as function of the size of the iron segments. The topology optimized structures are parabolic shaped pieces and have a difference in flux density between the high and low positions that is on average 1.29 times higher than optimized regular pole pieces. The maximum increase is a factor of 2.08 times higher than the regular pole pieces.

Freeze-casting to create directional micro-channels in regenerators for magnetic refrigeration
We present the engineering of directional porosity in the form of lamellar micro-channels in the magnetocaloric ceramic of La0.66Ca0.27Sr0.06Mn1.05O3 (LCSM) by freeze-casting. Freeze-casting is a templating technique based on the anisotropic growth of ice crystals in aqueous suspensions upon directional freezing, which, when applied to a suspension of LCSM results in hierarchical structures of aligned porosity in the form of micro-channels with widths of 5 μm to 20 μm. Channel sizes and tortuosity are measured and calculated from analysis of SEM images obtained at cross sections perpendicular and parallel to the freezing direction, respectively, while freezing conditions are monitored by temperature measurements. We propose that freeze-casting demonstrate apparent applicability within processing of ceramic materials for application as regenerator for magnetic refrigeration.
Topology Optimization of Segmented Thermoelectric Generators
The thermoelectric (TE) power output, $f_P$, and conversion efficiency, $f_\eta$, for segmented thermoelectric generators (TEGs) have been optimized by spatially distributing two TE materials (Bi$_2$SbTe and Skutterudite) using a numerical gradient-based topology optimization approach. The material properties are temperature-dependent, and the segmented TEGs are designed for various heat transfer rates at the hot and cold reservoirs. The topology-optimized design solutions are characterized by spike-shaped features which enable the designs to operate in an intermediate state between the material phases. Important design parameters, such as the device dimensions, objective functions and heat transfer rates, are identified, investigated and discussed. Comparing the topology optimization approach with the classical segmentation approach, the performance improvements of $f_P$ and $f_\eta$ design problems depend on the heat transfer rates at the hot and the cold reservoirs, the objective function and the device dimensions. The largest performance improvements for the problems investigated are $\approx 6\%$.

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Freeze-casting to create micro-channels in La$_{0.66}$Ca$_{0.33-x}$Sr$_x$Mn$_{1.05}$O$_3$
Influence of magnetization on the applied magnetic field in various AMR regenerators

The aim of this work is to assess the influence of a magnetic sample on the applied magnetic field inside the air gap of a magnetic circuit. Different magnetic sources including an electromagnet, a permanent magnet in a soft ferromagnetic toroidal yoke, as well as 2D and 3D Halbach cylinders are considered, using a numerical model. Gadolinium is chosen as magnetic material for the sample, due to its strong magnetocaloric properties and its wide use in magnetic refrigeration prototypes. We find that using uniform theoretical demagnetizing factors for cylinders or spheres results in a deviation of less than 2% in the calculation of internal magnetic fields at temperatures above the Curie point of gadolinium. Below the Curie point, a stronger magnetization of the cylinders and spheres leads to a larger deviation which can reach 8% when using uniform demagnetizing factors for internal magnetic field calculations.

Modeling a material from packing, through sintering and to the final microstructural properties

We present a combination of numerical models that can together simulate the initial packing of particles, followed by sintering and finally the resulting microstructural properties. For the latter we here focus on the magnetism of a sintered sample, and the associated coupling between heat and magnetism known as the magnetocaloric effect. We present a 3-dimensional time-dependent numerical model that spatially resolves samples down to the grain size, and includes the demagnetizing field, chemical inhomogeneity realized as a spatial variation of Curie temperature across the sample, local hysteresis and heat transfer. We can thus model how particle size, packing, sintering and chemical inhomogeneity affect the observed properties of magnetocaloric samples. For example, we show that even a modest distribution in Curie temperature (TC) across the sample results in a significant broadening and lowering of the total entropy change of the sample around TC. We discuss how clustering of grains with similar values of TC across the sample influences the results.
Operational test of bonded magnetocaloric plates

Bonded plates made by hot pressing $\text{La}_{0.85}\text{Ce}_{0.15}\text{Fe}_{11.25}\text{Mn}_{0.25}\text{Si}_{1.5}$H particles and resin have been tested as active magnetic regenerators in a small scale magnetocaloric device. Firstly, the plates were carefully characterised magnetically and thermally. The plates were prepared with 5 wt% resin, and from density measurements it was found that the volume ratio of the magnetocaloric material in the plates was 0.53, due to the resin and porosity. The best operating conditions for the plate regenerator were determined at which a temperature span of 6.4 K was measured along the plates.
Spatially resolved modelling of inhomogeneous materials with a first order magnetic phase transition
We present a numerical model that can simulate a magnetocaloric sample on the grain size level, including magnetostatics, heat transfer, local hysteresis and spatial variation of stoichiometry expressed as a variation in Curie temperature. Grain structure of a sample is realised as a number of regions each having a uniform and defined through a Voronoi-map. We show that demagnetising effects, caused by a finite sample size, and spatial variation in can account for the previously experimentally observed ‘virgin’ effects in the adiabatic temperature change and isothermal entropy change, respectively and first order reversal effect as a function of temperature. We conclude that even a very little variation in local stoichiometry of less than a percent, corresponding to a standard deviation in of for has a significant impact on the overall properties and history dependence of a sample.

The maximum theoretical performance of unconcentrated solar photovoltaic and thermoelectric generator systems
The maximum efficiency for photovoltaic (PV) and thermoelectric generator (TEG) systems without concentration is investigated. Both a combined system where the TEG is mounted directly on the back of the PV and a tandem system
where the incoming sunlight is split, and the short wavelength radiation is sent to the PV and the long wavelength to the TEG, are considered. An analytical model based on the Shockley-Queisser efficiency limit for PVs and the TEG figure of merit parameter zTs is presented. It is shown that for non-concentrated sunlight, even if the TEG operates at the Carnot efficiency and the PV performance is assumed independent of temperature, the maximum increase in efficiency is 4.5 percentage points (pp.) for the combined case and 1.8pp. for the tandem case compared to a stand alone PV. For a more realistic case with a temperature dependent PV and a realistic TEG, the gain in performance is much lower. For the combined PV and TEG system it is shown that a minimum zT value is needed in order for the system to be more efficient than a stand alone PV system.

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**Topology optimized permanent magnet systems**
Topology optimization of permanent magnet systems consisting of permanent magnets, high permeability iron and air is presented. An implementation of topology optimization for magnetostatics is discussed and three examples are considered. The Halbach cylinder is topology optimized with iron and an increase of 15% in magnetic efficiency is shown. A topology optimized structure to concentrate a homogeneous field is shown to increase the magnitude of the field by 111%. Finally, a permanent magnet with alternating high and low field regions is topology optimized and a ΛcoolΛcool figure of merit of 0.472 is reached, which is an increase of 100% compared to a previous optimized design.

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Active magnetic regenerator refrigeration with rotary multi-bed technology
Magnetic refrigeration is an emerging cooling technology with potential advantages over conventional vapor compression, the most important being higher efficiency. This thesis presents experimental and theoretical research into the possibilities of realizing this potential with actual active magnetic regenerator (AMR) prototypes. The starting point is the design and experiments with a rotary multi-bed prototype at the Technical University of Denmark. Promising results were obtained with this machine in terms of temperature span and cooling power. However, issues limiting the energy efficiency, mainly relating to heat leaks and flow system friction losses, have given rise to new ideas for taking the technology a step further. On this background, a second generation multi-bed prototype was designed, built and used in experimental investigations. A central feature of the new prototype is a novel system for handling the heat transfer fluid, providing a reciprocating flow inside the AMR beds while ensuring a continuous unidirectional flow in the surrounding flow circuit, communicating with the hot and cold reservoirs. With this system it is possible, via an arrangement of poppet valves and check valves, to control the flow rate versus rotational angle of the magnet system providing a time varying magnetic field in the beds with very minor losses compared to more traditional rotary valve based systems. Numerical AMR modeling capturing the variations in the azimuthal direction inside the beds has been used to investigate the effect of the shape of this flow profile, which confirms the importance of carefully optimizing it for the desired operating conditions. Numerical modeling and heat transfer calculations addressing heat leaks through the walls of the regenerator housing has revealed a necessary trade off between the amount of magnetocaloric material and an insulating air gap in the magnetized volume provided by the Halbach-like cylindrical permanent magnet system, when designing for high efficiency rather than maximum cooling power. The central part of the magnet system is a flux conducting iron core which was laminated for electrical and thermal insulation to minimize heat leaks and eddy current losses. Experimental investigations with different configurations of iron and insulation in the core focusing on the impact on temperature span and COP were conducted.
AMR experiments with the new prototype revealed strong impacts on COP and cooling power by minor adjustments of the individual valves controlling the flow in each bed. This effect, inherent to rotary multibed AMRs, is addressed with a numerical modeling approach and confirmed experimentally with the new prototype by carefully evening out the variations by the means of needle valves. An experimental performance analysis of the new prototype was carried out. A breakdown of the losses indicate pressure drop in external components and regenerator losses as the main contributors to entropy generation. While the former may be reduced by simple design improvements, the latter is non-trivial and requires detailed geometrical optimization assisted by numerical modeling and improved manufacturing techniques. Finally, possible applications are discussed and a concept of operating the AMR machine in combination with a thermal storage is introduced and demonstrated experimentally. Furthermore, a novel shunt valve technology, which was developed as a spin-off from the magnetic refrigeration research, is presented.

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An Analytical Model for the Influence of Contact Resistance on Thermoelectric Efficiency
An analytical model is presented that can account for both electrical and hot and cold thermal contact resistances when calculating the efficiency of a thermoelectric generator. The model is compared to a numerical model of a thermoelectric leg for 16 different thermoelectric materials, as well as to the analytical models of Ebling et al. (J Electron Mater 39:1376, 2010) and Min and Rowe (J Power Sour 38:253, 1992). The model presented here is shown to accurately calculate the efficiency for all systems and all contact resistances considered, with an average difference in efficiency between the numerical model and the analytical model of -0.07 ± 0.35pp. This makes the model more accurate than previously published models. The maximum absolute difference in efficiency between the analytical model and the numerical model is 1.14pp for all materials and all contact resistances considered.

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A thermoelectric power generating heat exchanger: Part I – Experimental realization

An experimental realization of a heat exchanger with commercial thermoelectric generators (TEGs) is presented. The power producing capabilities as a function of flow rate and temperature span are characterized for two different commercial heat transfer fluids and for three different thermal interface materials. The device is shown to produce 2 W per TEG or 0.22 W cm⁻² at a fluid temperature difference of 175 °C and a flow rate per fluid channel of 5 L min⁻¹. One experimentally realized design produced 200 W in total from 100 TEGs. For the design considered here, the power production is shown to depend more critically on the fluid temperature span than on the fluid flow rate. Finally, the temperature span across the TEG is shown to be 55–75% of the temperature span between the hot and cold fluids. © 2016 Elsevier Ltd. All rights reserved.

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A thermoelectric power generating heat exchanger: Part II – Numerical modeling and optimization

In Part I of this study, the performance of an experimental integrated thermoelectric generator (TEG)-heat exchanger was presented. In the current study, Part II, the obtained experimental results are compared with those predicted by a finite element (FE) model. In the simulation of the integrated TEG-heat exchanger, the thermal contact resistance between the TEG and the heat exchanger is modeled assuming either an ideal thermal contact or using a combined Cooper–Mikic–Yovanovich (CMY) and parallel plate gap formulation, which takes into account the contact pressure, roughness and hardness of the interface surfaces as well as the air gap thermal resistance at the interface. The combined CMY and parallel plate gap model is then further developed to simulate the thermal contact resistance for the case of an interface material. The numerical results show good agreement with the experimental data with an average deviation of 17% for the case without interface material and 12% in the case of including additional material at the interfaces. The model is then employed to evaluate the power production of the integrated system using different interface materials, including graphite, aluminum (Al), tin (Sn) and lead (Pb) in a form of thin foils. The numerical results show that lead foil at the interface has the best performance, with an improvement in power production of 34% compared to graphite foil. Finally, the model predicts that for a certain flow rate, increasing the parallel TEG channels for the integrated systems with 4, 8, and 12 TEGs enhances the net power per TEG with average values of 2.5%, 3% and 5%, respectively. © 2016 Elsevier Ltd. All rights reserved.

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Comparing superconducting and permanent magnets for magnetic refrigeration
We compare the cost of a high temperature superconducting (SC) tape-based solenoid with a permanent magnet (PM) Halbach cylinder for magnetic refrigeration. Assuming a five liter active magnetic regenerator volume, the price of each type of magnet is determined as a function of aspect ratio of the regenerator and desired internal magnetic field. It is shown that to produce a 1 T internal field in the regenerator a permanent magnet of hundreds of kilograms is needed or an area of superconducting tape of tens of square meters. The cost of cooling the SC solenoid is shown to be a small fraction of the cost of the SC tape. Assuming a cost of the SC tape of 6000 $/m² and a price of the permanent magnet of 100 $/kg, the superconducting solenoid is shown to be a factor of 0.3-3 times more expensive than the permanent magnet, for a desired field from 0.5-1.75 T and the geometrical aspect ratio of the regenerator. This factor decreases for increasing field strength, indicating that the superconducting solenoid could be suitable for high field, large cooling power applications.

Effects of flow balancing on active magnetic regenerator performance
Experiments with a recently constructed rotary multi-bed active magnetic regenerator (AMR) prototype have revealed strong impacts on the temperature span from variations in the resistances of the flow channels carrying heat transfer fluid in and out of the regenerator beds. In this paper we show through numerical modeling how unbalanced flow in the beds decreases the cooling power and COP for a dual bed device. Furthermore, it is shown how resistance variations in multi-bed devices give rise to unbalanced flow in the individual beds and how this decreases cooling powers and COPs of the
Exploring the efficiency potential for an active magnetic regenerator

A novel rotary state of the art active magnetic regenerator refrigeration prototype was used in an experimental investigation with special focus on efficiency. Based on an applied cooling load, measured shaft power, and pumping power applied to the active magnetic regenerator, a maximum second-law efficiency of 18% was obtained at a cooling load of 81.5 W, resulting in a temperature span of 15.5 K and a coefficient of performance of 3.6. A loss analysis is given, based on measured pumping power and shaft power together with theoretically estimated regenerator pressure drop. It is shown that, especially for the pressure drop, significant improvements can be made to the machine. However, a large part of the losses may be attributed to regenerator irreversibilities. Considering these unchanged, an estimated upper limit to the second-law efficiency of 30% is given by eliminating parasitic losses and replacing the packed spheres with a theoretical parallel plate regenerator. Furthermore, significant potential efficiency improvements through optimized regenerator geometries are estimated and discussed.
Generating the optimal magnetic field for magnetic refrigeration

In a magnetic refrigeration device the magnet is the single most expensive component, and therefore it is crucially important to ensure that an effective magnetic field as possible is generated using the least amount of permanent magnets. Here we present a method for calculating the optimal remanence distribution for any desired magnetic field. The method is based on the reciprocity theorem, which through the use of virtual magnets can be used to calculate the optimal remanence distribution. Furthermore, we present a method for segmenting a given magnet design that always results in the optimal segmentation, for any number of segments specified. These two methods are used to determine the optimal magnet design of a 12-piece, two-pole concentric cylindrical magnet for use in a continuously rotating magnetic refrigeration device.

Globally Optimal Segmentation of Permanent-Magnet Systems

Permanent-magnet systems are widely used for generation of magnetic fields with specific properties. The reciprocity theorem, an energy-equivalence principle in magnetostatics, can be employed to calculate the optimal remanent flux density of the permanent-magnet system, given any objective functional that is linear in the magnetic field. This approach, however, yields a continuously varying remanent flux density, while in practical applications, magnetic assemblies are realized by combining uniformly magnetized segments. The problem of determining the optimal shape of each of these segments remains unsolved. We show that the problem of optimal segmentation of a two-dimensional permanent-magnet assembly with respect to a linear objective functional can be reduced to the problem of piecewise linear approximation of a plane curve by perimeter maximization. Once the problem has been cast into this form, the globally optimal solution can be easily computed employing dynamic programming.
Optimally segmented magnetic structures

We present a semi-analytical algorithm for magnet design problems, which calculates the optimal way to subdivide a given design region into uniformly magnetized segments. The availability of powerful rare-earth magnetic materials such as Nd-Fe-B has broadened the range of applications of permanent magnets[1][2]. However, the powerful rare-earth magnets are generally expensive, so both the scientific and industrial communities have devoted a lot of effort into developing suitable design methods. Even so, many magnet optimization algorithms either are based on heuristic approaches[3], or are applicable only to analytically solvable geometries[4]. In addition, some questions remained fundamentally unanswered, such as how to segment a given design into N uniformly magnetized pieces. Our method calculates the globally optimal shape and magnetization direction of each segment inside a certain design area with an optional constraint on the total amount of magnetic material. The method can be applied to any objective functional which is linear respect to the field, and with any combination of linear materials. Being based on an analytical-optimization approach, the algorithm is not computationally intensive and provides the global optimum with respect to the considered problem without the need for a starting guess. The approach can be used in combination with finite element method calculations, and can therefore be applied also to problems for which an analytical solution to the magnetic field is not available. We will illustrate the results for magnet design problems from different areas, such as electric motors/generators (as the example in the picture), beam focusing for particle accelerators and magnetic refrigeration devices.

Optimally segmented permanent magnet structures

We present an optimization approach which can be employed to calculate the globally optimal segmentation of a two-dimensional magnetic system into uniformly magnetized pieces. For each segment the algorithm calculates the optimal shape and the optimal direction of the remanent flux density vector, with respect to a linear objective functional. We illustrate the approach with results for magnet design problems from different areas, such as a permanent magnet electric motor, a beam focusing quadrupole magnet for particle accelerators and a rotary device for magnetic refrigeration.
Performance of Halbach magnet arrays with finite coercivity

A numerical method to study the effect of finite coercivity on the Halbach cylinder geometry is presented. Despite the fact that the analytical solution available for this geometry does not set any limit to the maximum air gap flux density achievable, in real life the non-linear response of the magnetic material and the fact that the coercivity is not infinite will limit the attainable field. The presented method is able to predict when and where demagnetization will occur, and these predictions are compared with the analytical solution for the case of infinite coercivity. However, the approach presented here also allows quantification of the decrease in flux density and homogeneity for a partially demagnetized magnet. Moreover, the problem of how to realize a Halbach cylinder geometry using a mix of materials with different coercivities without altering the overall performance is addressed. Being based on a numerical approach, the presented method can be employed to analyze the demagnetization effects due to coercivity for any geometry, even when the analytical solution is not available.

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The lifetime cost of a magnetic refrigerator

The total cost of a 25 W average load magnetic refrigerator using commercial grade Gd is calculated using a numerical model. The price of magnetocaloric material, magnet material and cost of operation are considered, and all influence the total cost. The lowest combined total cost with a device lifetime of 15 years is found to be in the range $150-$400 depending on the price of the magnetocaloric and magnet material. The cost of the magnet is largest, followed closely by
the cost of operation, while the cost of the magnetocaloric material is almost negligible. For the lowest cost device, the optimal magnetic field is about 1.4 T, the particle size is 0.23 mm, the length of the regenerator is 40-50 mm and the utilization is about 0.2, for all device lifetimes and material and magnet prices, while the operating frequency vary as function of device lifetime. The considered performance characteristics are based on the performance of a conventional A+++ refrigeration unit. In a rough life time cost comparison between the AMR device and such a unit we find similar costs, the AMR being slightly cheaper, assuming the cost of the magnet can be recuperated at end of life.

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The magnetic properties of the hollow cylindrical ideal remanence magnet
We consider the magnetic properties of the hollow cylindrical ideal remanence magnet. This magnet is the cylindrical permanent magnet that generates a uniform field in the cylinder bore, using the least amount of magnetic energy to do so. The remanence distribution of this magnet is derived and the generated field is compared to that of a Halbach cylinder of equal dimensions. The ideal remanence magnet is shown in most cases to generate a significantly lower field than the equivalent Halbach cylinder, although the field is generated with higher efficiency. The most efficient Halbach cylinder is shown to generate a field exactly twice as large as the equivalent ideal remanence magnet.

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Comparing superconducting and permanent magnets for magnetic refrigeration

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Organisations: Department of Energy Conversion and Storage, Electrofunctional materials
Contributors: Bjørk, R., Nielsen, K. K., Bahl, C. R., Smith, A., Wulff, A. C.
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Design and experimental tests of a rotary active magnetic regenerator prototype
A rotary active magnetic regenerator (AMR) prototype with efficiency and compact design as focus points has been designed and built. The main objective is to demonstrate improved efficiency for rotary devices by reducing heat leaks from the environment and parasitic mechanical work losses while optimizing the utilization of the magnetized volume. Heat transfer calculations combined with 1D AMR modeling have revealed the necessity for an insulating air gap between magnet and regenerator when designing for high efficiency. 2D finite difference AMR modeling capturing the interplay between heat transfer fluid flow and an inhomogenous time-varying magnetic field in the individual regenerator beds has been used in the design process. For one operating point a COP of 3.1 at a temperature span of 10.2 K and a cooling power of 103W were measured. Major issues limiting the performance have been identified and improvements are outlined for future work. © 2015 Elsevier Ltd and IIR. All rights reserved.

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Direct measurements of the magnetic entropy change
An experimental device that can accurately measure the magnetic entropy change, $\Delta s$, as a function of temperature, $T$, and magnetic field, $H$, is presented. The magnetic field source is in this case a set of counter-rotating concentric Halbach-type magnets, which produce a highly homogeneous applied field with constant orientation. The field may be varied from 0 to 1.5 T in a continuous way. The temperature stability of the system is controlled to within ±10 mK and the standard range for the current setup is from 230 K to 330 K. The device is under high vacuum and we show that thermal losses to the ambient are negligible in terms of the calorimetric determination of the magnetic entropy change, while the losses cannot be ignored when correcting for the actual sample temperature. We apply the device to two different types of samples; one is commercial grade Gd, i.e., a pure second-order phase transition material, while the other is Gd$_5$Si$_2$Ge$_2$, a first order magnetic phase transition material. We demonstrate the device’s ability to fully capture the thermal hysteresis of the latter sample by following appropriate thermal resetting scheme and magnetic resetting scheme. © 2015 AIP Publishing LLC.

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Web of Science (2015): Indexed yes
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Direct_measurements_of_the_magnetic_entropy_change_postprint.pdf
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Research output: Contribution to journal › Journal article – Annual report year: 2015 › Research › peer-review

Experimental Studies with an Active Magnetic Regenerating Refrigerator
Experimental results for an active magnetic regenerator (AMR) are presented. The focus is on whether or not it pays off to partly substitute soft magnetic material with non-magnetic insulation in a flux-conducting core in the magnet system. Such a substitution reduces losses due to heat conduction and eddy currents, but also reduces the magnetic field. Two different cores were tested in the AMR system with different cooling loads and it is shown, that in the present case, replacing half of the iron with insulation lead to an average reduction in temperature span of 14%, but also a small decrease in COP, hence the substitution did not pay off. Furthermore, it is shown experimentally, that small imbalances in the heat transfer fluid flow greatly influence the system performance. A reduction of these imbalances through valve adjustments resulted in an increase in the temperature span from approximately 16 K to 27.3 K.

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Hybrid TEG-heat exchanger module for electrical power production

General information
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Modeling constrained sintering of bi-layered tubular structures
Constrained sintering of tubular bi-layered structures is being used in the development of various technologies. Densification mismatch between the layers making the tubular bi-layer can generate stresses, which may create processing defects. An analytical model is presented to describe the densification and stress developments during sintering of tubular bi-layered samples. The correspondence between linear elastic and linear viscous theories is used as a basis for derivation of the model. The developed model is first verified by finite element simulation for sintering of tubular bi-layer system. Furthermore, the model is validated using densification results from sintering of bi-layered tubular ceramic oxygen membrane based on porous MgO and Ce0.9Gd0.1O1.95-d layers. Model input parameters, such as the shrinkage kinetics and viscous parameters are obtained experimentally using optical dilatometry and thermo-mechanical analysis. Results from the analytical model are found to agree well with finite element simulations as well as measurements from sintering experiment.

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Research output: Contribution to journal › Journal article – Annual report year: 2014 › Research › peer-review
Modeling the Microstructural Evolution During Constrained Sintering
A numerical model able to simulate solid-state constrained sintering is presented. The model couples an existing kinetic Monte Carlo model for free sintering with a finite element model (FEM) for calculating stresses on a microstructural level. The microstructural response to the local stress as well as the FEM calculation of the stress field from the microstructural evolution is discussed. The sintering behavior of a sample constrained by a rigid substrate is simulated. The constrained sintering results in a larger number of pores near the substrate, as well as anisotropic sintering shrinkage, with significantly enhanced strain in the central upper part of the sample surface, and minimal strain at the edges near the substrate. All these features have also previously been observed experimentally.

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Modelling of thermoelectric generators for satellite application

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Organisations: Department of Energy Conversion and Storage, Electrofunctional materials, Aalborg University, Quick-Ohm Küpper & Co. GmbH
Contributors: Rezania, A., Wijesekara, W., Rosendahl, L., Van Nong, N., Bjørk, R., Katenbrink, N.
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Optimization of Permanent Magnet Assemblies

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Optimization of Permanent Magnet Assemblies

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Poster
Research output: Contribution to conference › Poster – Annual report year: 2015 › Research

Optimization of the Mechanical and Electrical Performance of a Thermoelectric Module

Finite element (FE) simulation of a thermoelectric (TE) module was conducted to optimize its geometrical dimensions in terms of mechanical reliability and performance. The TE module consisted of bismuth telluride, nand p-type legs. The geometrical dimensions of the module, i.e. leg length and leg cross-sectional area, were varied and the corresponding maximum thermal stress, output power and efficiency of the module was obtained. The optimal design of the module was then suggested based on minimizing the thermal stresses and maximizing the performance, i.e. power and efficiency. The optimal dimensions at a maximum von Mises stress of 75 MPa was a leg length of 2-2.5 mm, a leg width of 1.5-2 mm, which resulted in an efficiency of 7.2. Finally, the influence of solders, i.e. solder material between the leg, the interconnector and the top ceramic layer, on the induced thermal stresses and the module performance was investigated. The results revealed that transition from elastic to plastic deformation in the solder decreases the induced thermal stresses significantly. Moreover, beyond the elastic limit the stress magnitude is very much dependent on the magnitude and mechanism of the plastic deformation in the module. The present study provides a basis for unique and new optimization scheme of the TE modules in terms of endurance and performance.
Segmented Thermoelectric Oxide-Based Module for High-Temperature Waste Heat Harvesting

We report a high-performance thermoelectric (TE) oxide-based module using the segmentation of half-Heusler \( \text{Ti}_{0.3} \text{Zr}_{0.35} \text{Hf}_{0.35} \text{CoSb}_{0.8} \text{Sn}_{0.2} \) and misfit-layered cobaltite \( \text{Ca}_{3}\text{Co}_{4}\text{O}_{9+\delta} \) as the p-leg and 2% Al-doped \( \text{ZnO} \) as the n-leg. The maximum output power of a 4-couple segmented module at \( \Delta T=700 \) K attains a value of approximately 6.5 kWm\(^{-2}\), which is three times higher than that of the best reported non-segmented oxide module. The TE properties of individual legs, as well as the interfacial contact resistances, were characterized as a function of temperature. Numerical modeling was used to predict the efficiency and to evaluate the influence of the electrical and thermal losses on the performance of TE modules. Initial long-term stability tests of the module at the hot and the cold side temperatures of 1073 K and 444 K, respectively, showed a promising result with 4% degradation for 48 h operating in air.

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Organisations: Department of Energy Conversion and Storage, Electrofunctional materials, Johannes Gutenberg University, California Institute of Technology
Contributors: Le, T. H., Van Nong, N., Han, L., Bjørk, R., Pham, H. N., Holgate, T., Balke, B., Snyder, G. J., Linderoth, S., Pryds, N.
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The efficiency and the demagnetization field of a general Halbach cylinder

The maximum magnetic efficiency of a general multipole Halbach cylinder of order \( p \) is found as function of \( p \). The efficiency is shown to decrease for increasing absolute value of \( p \). The optimal ratio between the inner and outer radius, i.e. the ratio resulting in the most efficient design, is also found as function of \( p \) and is shown to tend towards smaller and smaller magnet sizes. Finally, the demagnetizing field in a general \( p \)-Halbach cylinder is calculated, and it is shown that demagnetization is largest either at \( \cos 2p \varphi = 1 \) or \( \cos 2p \varphi = -1 \). For the common case of a \( p=1 \) Halbach cylinder the maximum values of the demagnetizing field are either at \( \varphi = 0, \pi \) at the outer radius, where the field is always equal to the remanence, or at \( \varphi = \pm \pi/2 \) at the inner radius, where it is the magnitude of the field in the bore. Thus to avoid demagnetization the coercivity of the magnets must be larger than these values.

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The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system

The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system is examined using an analytical model for four different types of commercial PVs and a commercial bismuth telluride TEG. The TEG is applied directly on the back of the PV, so that the two devices have the same temperature. The PVs considered are crystalline Si (c-Si), amorphous Si (a-Si), copper indium gallium (di) selenide (CIGS) and cadmium telluride (CdTe) cells. The degradation of PV performance with temperature is shown to dominate the increase in power produced by the TEG, due to the low efficiency of the TEG. For c-Si, CIGS and CdTe PV cells the combined system produces a lower power and has a lower efficiency than the PV alone, whereas for an a-Si cell the total system performance may be slightly increased by the TEG.

The Total Lifetime Cost of a Magnetic Refrigerator

Abstract
The universal influence of contact resistance on TEG efficiency

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Contributors: Bjørk, R.
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Source-ID: 118916309
Research output: Chapter in Book/Report/Conference proceeding › Conference abstract in proceedings – Annual report year: 2015 › Research › peer-review

The Universal Influence of Contact Resistance on the Efficiency of a Thermoelectric Generator
The influence of electrical and thermal contact resistance on the efficiency of a segmented thermoelectric generator is investigated. We consider 12 different segmented p-legs and 12 different segmented n-legs, using eight different p-type and eight different n-type thermoelectric materials. For all systems, a universal influence of both the electrical and thermal contact resistance is observed on the leg's efficiency, when the systems are analyzed in terms of the contribution of the contact resistance to the total resistance of the leg. The results are compared with the analytical model of Min and Rowe. In order for the efficiency not to decrease by more than 20%, the contact electrical resistance should be less than 30% of the total leg resistance for zero thermal contact resistance, while the thermal contact resistance should be less than 20% for zero electrical contact resistance. The universal behavior also allowed the maximum tolerable contact resistance for a segmented system to be found, i.e., the resistance at which a leg of only the high-temperature thermoelectric material has the same efficiency as the segmented leg with a contact resistance at the interface. If, e.g., segmentation increases the efficiency by 30%, then an electrical contact resistance of 30% or a thermal contact resistance of 20% can be tolerated.

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Analysis of the internal heat losses in a thermoelectric generator

A 3D thermoelectric numerical model is used to investigate different internal heat loss mechanisms for a thermoelectric generator with bismuth telluride p- and n-legs. The model considers all thermoelectric effects, temperature dependent material parameters and simultaneous convective, conductive and radiative heat losses, including surface to surface radiation. For radiative heat losses it is shown that for the temperatures considered here, surface to ambient radiation is a good approximation of the heat loss. For conductive heat transfer the module efficiency is shown to be comparable to the case of radiative losses. Finally, heat losses due to internal natural convection in the module is shown to be negligible for the millimetre sized modules considered here. The combined case of radiative and conductive heat transfer resulted in the lowest efficiency. The optimized load resistance is found to decrease for increased heat loss. The leg dimensions are varied for all heat losses cases and it is shown that the ideal way to construct a TEG module with minimal heat losses and maximum efficiency is to either use a good insulating material between the legs or evacuate the module completely, and use small and wide legs closely spaced. (C) 2014 Elsevier Masson SAS. All rights reserved.

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Analysis_of_the_internal_heat_losses_in_a_thermoelectric_generator.pdf
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Design and initial testing of a compact and efficient rotary AMR prototype

MAGGIE, a new AMR prototype, is presented. It has been designed to produce a temperature span and cooling power relevant to commercial refrigeration applications combined with an attractive COP and a compact design. Concepts and design considerations are described. Initial non optimized tests show a COP of 3.6 at a temperature span of 7.2K with 103 W of cooling power.

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Design of thermoelectric modules for both mechanical reliability and performance using FE simulation

Thermo-mechanical modeling of the TE modules provides an efficient tool for assessing the mechanical strength of the modules against the induced thermal stresses and subsequently optimizing them in terms of the mechanical reliability. However, the design of TE modules in terms of mechanical reliability cannot be separated completely from the design for performance. These two objectives may conflict such that the improvement of the design parameters for one objective can deteriorate the other one. This trade-off can be seen particularly when the geometrical dimensions of a TE module is optimized for these two objectives.

The current study deals with FE simulation of the TE modules to optimize their geometrical dimension in terms of mechanical reliability and performance. First, FE simulation of a TE module consisting of bismuth telluride alloys is carried out and the induced thermal stresses, output power and efficiency of the module is calculated. Then, the geometrical dimensions of the module including the leg length and the cross sections of the TE elements are varied and the corresponding maximum thermal stresses, output power and efficiency of the modules are obtained. Based on the results, the geometrical dimensions of the TE elements for both mechanical reliability and performance are optimized to obtain a compromise design. The present work provides a basis for optimizing the TE modules in terms of their life time and performance.

Development and experimental results from a 1 kW prototype AMR

A novel rotary magnetic refrigeration device has been designed and constructed following the concepts recently outlined in Bahl et al. (2011). The magnet and flow system design allow for almost continuous usage of both the magnetic field and the magnetocaloric material in 24 cassettes, each containing an active magnetic regenerator (AMR) bed. The prototype design facilitates easy exchange of the 24 cassettes, allowing the testing of different material amounts and compositions. Operating with 2.8 kg of commercial grade Gd spheres a maximum no-span cooling power of 1010 W and a maximum zero load temperature span of 25.4 K have been achieved. For the purpose of actual operation, simultaneous high span and high performance is required. At a heat load of 200 W a high temperature span of 18.9 K has been obtained, dropping to a span of 13.8 K at the higher heat load value of 400 W.
Direct measurements of the magnetocaloric effect
We present an experimental setup recently developed at DTU Energy Conversion for measuring specific heat and direct isothermal entropy change in a varying magnetic field (DSC device) using calorimetry. The device operates in high vacuum (~1e-6 mbar) and measurements are fully automated with respect to magnetic field and temperature control. A magnetic field source comprised of two concentric Halbach type magnets that are fixed with respect to each other through a mechanical gear supply the applied magnetic field. The applied field range is 0.001 to 1.57 T with a minimum field step size smaller than 0.01 T. The magnet control is fully integrated in software allowing measurement scans to be automated. This device is an upgrade of an existing device where it is now possible to install a sample and then run temperature scans at different magnetic fields (specific heat measurement) as well as magnetic field scans under isothermal conditions (direct isothermal entropy change measurements).

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Publisher: International Institute of Refrigeration
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Finite element modeling of camber evolution during sintering of bi-layers
The need for understanding the mechanisms and optimization of shape distortions during sintering of bilayers is necessary while producing structures with functionally graded architectures. A finite element model based on the continuum theory of sintering was developed to understand the camber developments during sintering of bilayers composed of La0.85Sr0.15MnO3 and Ce0.9Gd0.1O1.95 tapes. Free shrinkage kinetics of both tapes were used to estimate the parameters necessary for the finite element models. Systematic investigations of the factors affecting the kinetics of distortions such as gravity and friction as well as the initial geometric parameters of the bilayers were made using optical dilatometry experiments and the model. The developed models were able to capture the observed behaviors of the bilayers’ distortions during sintering. Finally, we present the importance of understanding and hence making use of the effect of gravity and friction to minimize the shape distortions during sintering of bilayers.

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Web of Science (2014): Indexed yes
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Source: PublicationPreSubmission
Source-ID: 93521489
In situ characterization of delamination and crack growth of a CGO–LSM multi-layer ceramic sample investigated by X-ray tomographic microscopy

The densification, delamination and crack growth behavior in a Ce0.9Gd0.1O1.95 (CGO) and (La0.85Sr0.15)0.9MnO3 (LSM) multi-layer ceramic sample was studied using in situ X-ray tomographic microscopy (microtomography) to investigate the critical dynamics of crack propagation and delamination in a multilayered sample. Naturally occurring defects, caused by the sample preparation process, are shown not to be critical in sample degradation. Instead defects are nucleated during the debinding step. Crack growth is significantly faster along the material layers than perpendicular to them, and crack growth and delamination only accelerates when sintering occurs.

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Web of Science (2014): Indexed yes
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Research output: Contribution to journal › Journal article – Annual report year: 2014 › Research › peer-review

Modeling the microstructural evolution during constrained sintering
A mesoscale numerical model able to simulate solid state constrained sintering is presented. The model couples an existing kinetic Monte Carlo (kMC) model for free sintering with a finite element method for calculating stresses. The sintering behavior of a sample constrained by a rigid substrate is simulated, resulting in a larger number of pores near the substrate, which is also observed experimentally.

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Electronic versions:
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Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2015 › Research › peer-review
Modeling the microstructural evolution during constrained sintering

A numerical model able to simulate solid state constrained sintering is presented. The model couples an existing kinetic Monte Carlo (kMC) model for free sintering with a finite element model (FEM) for calculating stresses on a microstructural level. The microstructural response to the local stress as well as the FEM calculation of the stress field from the microstructural evolution is discussed. The sintering behavior of a sample constrained by a rigid substrate is simulated. The constrained sintering result in a larger number of pores near the substrate, as well as anisotropic sintering shrinkage, with significantly enhanced strain in the central upper part of the sample surface, and minimal strain near the edges near the substrate. These features are also observed experimentally.

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Contributors: Bjørk, R., Frandsen, H. L., Pryds, N.
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Multi-scale modeling of shape distortions during sintering of bi-layers

Models for deformational behaviors of porous bodies during sintering often rely on limited number of internal variables as they are formulated based on simplified or ideal microstructures. Considering realistic microstructures can improve the predictive capabilities of the already established theories like the continuum theory of sintering. A new multi-scale numerical approach for modeling of shape distortions during sintering of macroscopically inhomogeneous structures combined with a microstructure model is developed. The microstructures of the porous body are described by unit cells based on kinetic Monte Carlo (kMC) model of sintering. During the sintering process the shrinkage rate is calculated from the kMC model. With the help of computational homogenization, the effective viscosity of the powder compact is also estimated from a boundary value problem defined on the microstructures of unit cells simulated by the kMC model. Examples of simulation of sintering of bi-layers based on different material systems are presented to illustrate the multi-scale model. The approach can be considered as an extension to the continuum theory of sintering combined with the meso-scale kinetic Monte Carlo model. © 2014 Elsevier B.V. All rights reserved.

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Performance and stress analysis of oxide thermoelectric module architecture designed for maximum power output

Oxide thermoelectric materials are promising candidates for energy harvesting from mid to high temperature heat sources. In this work, the oxide thermoelectric materials and the final design of the high temperature thermoelectric module were developed. Also, prototypes of oxide thermoelectric generator were built for high temperature applications. This paper specifically discusses the thermoelectric module design and the prototype validations of the design. Here p type calcium cobalt oxide and n type aluminum doped ZnO were developed as the oxide thermoelectric materials. Hot side and cold side temperatures were used as 1100 K and 400 K respectively. Using analytical methods, the optimum thermoelement length and the thermoelements area ratio were explored in order to provide the maximum power output by the uni-couple and it is compared to methods reported in literature. Based on operating conditions of real thermoelectric uni-couples, the three-dimensional governing equations for the coupled heat transfer and thermoelectric effects were developed. Finite element simulations of this system were done using the COMSOL Multiphysics solver. Prototypes of the models were developed and the analytical and simulation results were validated. In addition, the thermal stress and the thermal expansion of the thermoelectric uni-couple were studied in this work.

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Performance-oriented Analysis of a Hybrid magnetic Assembly for a Heat-pump Magnetocaloric Device

Conventional active-regenerator magnetocaloric devices include moving parts, with the purpose of generating an oscillating magnetic field in the magneto-caloric material, placed inside the regenerator. In this work a different design is analyzed, for application in a magnetocaloric heat pump. In this design all the parts of the machine are static and the oscillating field is generated by varying the currents of electromagnets included in the hybrid magnetic assembly. The use of different permanent magnet materials is compared with the perspective of maximizing the coefficient of performance of the device.

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Strain in the mesoscale kinetic Monte Carlo model for sintering

Shrinkage strains measured from microstructural simulations using the mesoscale kinetic Monte Carlo (kMC) model for solid state sintering are discussed. This model represents the microstructure using digitized discrete sites that are either grain or pore sites. The algorithm used to simulate densification by vacancy annihilation removes an isolated pore site at a grain boundary and collapses a column of sites extending from the vacancy to the surface of sintering compact, through the center of mass of the nearest grain. Using this algorithm, the existing published kMC models are shown to produce anisotropic strains for homogeneous powder compacts with aspect ratios different from unity. It is shown that the line direction biases shrinkage strains in proportion the compact dimension aspect ratios. A new algorithm that corrects this bias in strains is proposed; the direction for collapsing the column is determined by choosing a random sample face and subsequently a random point on that face as the end point for an annihilation path with equal probabilities. This algorithm is mathematically and experimentally shown to result in isotropic strains for all samples regardless of their dimensions.
Finally, the microstructural evolution is shown to be similar for the new and old annihilation algorithms.

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**Demagnetization factor for a powder of randomly packed spherical particles**
The demagnetization factors for randomly packed spherical particle powders with different porosities, sample aspect ratios, and monodisperse, normal, and log-normal particle size distributions have been calculated using a numerical model. For a relative permeability of 2, comparable to room temperature Gd, the calculated demagnetization factor is close to the theoretical value. The normalized standard deviation of the magnetization in the powder was 6.0%-6.7%. The demagnetization factor decreased significantly, while the standard deviation of the magnetization increased, for increasing relative permeability. © 2013 AIP Publishing LLC

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Metamaterial anisotropic flux concentrators and magnetic arrays

A metamaterial magnetic flux concentrator is investigated in detail in combination with a Halbach cylinder of infinite length. A general analytical solution to the field is determined and the magnetic figure of merit is determined for a Halbach cylinder with a flux concentrator. It is shown that an ideal flux concentrator will not change the figure of merit of a given magnet design, while the non-ideal will always lower it. The geometric parameters producing maximum figure of merit, i.e., the most efficient devices, are determined. The force and torque between two concentric Halbach cylinders with flux concentrators is determined and the maximum torque is found. Finally, the effect of non-ideal flux concentrators and the practical use of flux concentrators, as well as demagnetization issues, is discussed. © 2013 AIP Publishing LLC.

Modeling Kinetics of Distortion in Porous Bi-layered Structures

Shape distortions during constrained sintering experiment of bi-layer porous and dense cerium gadolinium oxide (CGO) structures have been modeled. Technologies like solid oxide fuel cells require co-firing thin layers with different green densities, which often exhibit differential shrinkage because of different sintering rates of the materials resulting in undesired distortions of the component. An analytical model based on the continuum theory of sintering has been developed to describe the kinetics of densification and distortion in the sintering processes. A new approach is used to extract the material parameters controlling shape distortion through optimizing the model to experimental data of free shrinkage strains. The significant influence of weight of the sample (gravity) on the kinetics of distortion is taken into consideration. The modeling predictions indicate good agreement with the results of sintering of a bi-layered CGO system in terms of evolutions of bow, porosities and also layer thickness.
Modeling sintering of multilayers under influence of gravity

There is a tendency for multiple functional ceramic layers used in various applications to have increasing surface areas and decreasing thicknesses. Sintering samples with such geometry is challenging, as differential shrinkage of the layers causes undesired distortions. In this work, a model, which describes the combined effect of sintering and gravity of thin multilayers, is derived and later compared with experimental results. It allows for consideration of both uniaxial and biaxial stress states. The model is based on the Skorohod-Olevsky viscous sintering framework, the classical laminate theory and the elastic-viscoelastic correspondence principle. The modeling approach is then applied to illustrate the effect of gravity during sintering of thin layers of cerium gadolinium oxide (CGO), and it is found to be significant. © 2012 The American Ceramic Society.
Sintering of Multilayered Porous Structures: Part I—Constitutive Models

Theoretical analyses of shrinkage and distortion kinetics during sintering of bilayered porous structures are carried out. The developed modeling framework is based on the continuum theory of sintering; it enables the direct assessment of the cofiring process outcomes and of the impact of process controlling parameters. The derived "master sintering curve"-type solutions are capable of describing and optimizing the generic sintering shrinkage and distortion kinetics for various material systems. The approach utilizes the material-specific parameters, which define the relative kinetics of layer shrinkages such as the relative intensity of sintering, and employs the conversion between real and specific times of sintering. A novel methodology is also developed for the determination of the ratio of the shear viscosities of the layer's fully dense materials. This new technique enables the determination of all input parameters necessary for modeling sintering of bilayers using experimental techniques similar to optical dilatometry applied to each individual layer and to a symmetric trilayered porous structure based on the two-layer materials utilized in the bilayered system. Examples of sintering different porous bilayered systems are presented to justify the capability of the model in predicting and optimizing sintering kinetics.

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Sintering of Multilayered Porous Structures: Part II—Experiments and Model Applications

Experimental analyses of shrinkage and distortion kinetics during sintering of bilayered porous and dense gadolinium-doped ceria Ce0.9Gd0.101.95d structures are carried out, and compared with the theoretical models developed in Part I of this work. A novel approach is developed for the determination of the shear viscosities ratio of the layer fully dense materials. This original technique enables the derivation of all the input parameters for the bilayer sintering modeling from one set of optical dilatometry measurements, including the conversion between real and specific times of sintering, the layers' relative sintering intensity, and the shear viscosities ratio of the layer fully dense materials. These optical dilatometry measurements are conducted simultaneously for each individual layer and for a symmetric trilayered porous structure based on the two layers utilized in the bilayered system. The obtained modeling predictions indicate satisfactory agreement with the results of sintering of a bilayered cerium–gadolinium oxide system in terms of distortion and shrinkage kinetics.

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The effect of particle size distributions on the microstructural evolution during sintering

Microstructural evolution and sintering behavior of powder compacts composed of spherical particles with different particle size distributions (PSDs) were simulated using a kinetic Monte Carlo model of solid state sintering. Compacts of monosized particles, normal PSDs with fixed mean particle radii and a range of standard deviations, and log-normal PSDs with fixed mode and a range of skewness values were studied. Densification rate and final relative density were found to be inversely proportional to initial PSD width. Grain growth was faster during the early stages of sintering for broad PSDs, but the final grain sizes were smaller. These behaviors are explained by the smallest grains in the broader PSDs being consumed very quickly by larger neighboring grains. The elimination of the small grains reduces both the total number of necks and the neck area between particles, which in turn reduces the regions where vacancies can be annihilated, leading to slower densification rates. The loss of neck area causes grain growth by surface diffusion to become the dominant microstructural evolution mechanism, leading to poor densification. Finally, pore size was shown to increase with the width of PSDs, which also contributes to the lower densification rates.
Development and Experimental Results from a 1 kW Prototype AMR

A novel rotary magnetic refrigeration device has been designed and constructed following the concepts recently outlined in Bahl et al. (2011). The magnet and flow system design allow for almost continuous usage of both the magnetic field and the magnetocaloric material in 24 cassettes, each containing an active magnetic regenerator (AMR) bed. As outlined in Pryds et al. (2009) a small scale AMR test device has been used for materials choice and optimising operation, with each component being thoroughly characterised and tested before implementation. The prototype design facilitates easy exchange of the 24 cassettes, allowing the testing of different material amounts and compositions. Operating with 2.8 kg of commercial grade Gd spheres a maximum no-span cooling power of 1010 W and a maximum zero load temperature span of 25.4 K have been achieved. For the purpose of actual operation, simultaneous high span and high performance is required. At a heat load of 200 W a high temperature span of 18.9 K has been obtained, dropping to a span of 13.8 K at the higher heat load value of 400 W.

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Experimental results for a novel rotary active magnetic regenerator

Active magnetic regenerator (AMR) refrigerators represent an alternative to vapor compression technology and have great potential in realizing cooling devices with high efficiency, which are highly desirable for a broad range of applications. The technology relies on the magnetocaloric effect in a solid refrigerant rather than the temperature change that occurs when a gas is compressed/expanded. This paper presents the general considerations for the design and construction of a high frequency rotary AMR device. Experimental results are presented at various cooling powers for a range of operating conditions near room temperature. The device exhibited a no-load temperature span of over 25 K and can absorb a 100 W cooling load at a 20.5 K temperature span.

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Improved Modeling Approaches for Constrained Sintering of Bi-Layered Porous Structures

Shape instabilities during constrained sintering experiment of bi-layer porous and dense cerium gadolinium oxide (CGO) structures have been analyzed. An analytical and a numerical model based on the continuum theory of sintering has been implemented to describe the evolution of bow and densification kinetics in the sintering processes that consists of iso-rate and isothermal phases. The significant influence of weight of the sample (gravity) on the evolution of bow, especially in the isothermal sintering phase, is taken into account. The modeling predictions indicate good agreement with the results of sintering of a bi-layered cerium-gadolinium oxide system in terms of evolution of bow, porosity and thickness.

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Materials Challenges for High Performance Magnetocaloric Refrigeration Devices

Magnetocaloric materials with a Curie temperature near room temperature have attracted significant interest for some time due to their possible application for high-efficiency refrigeration devices. This review focuses on a number of key issues of relevance for the characterization, performance and implementation of such materials in actual devices. The phenomenology and fundamental thermodynamics of magnetocaloric materials is discussed, as well as the hysteresis behavior often found in first-order materials. A number of theoretical and experimental approaches and their implications are reviewed. The question of how to evaluate the suitability of a given material for use in a magnetocaloric device is covered in some detail, including a critical assessment of a number of common performance metrics. Of particular interest is which non-magnetocaloric properties need to be considered in this connection. An overview of several important materials classes is given before considering the performance of materials in actual devices. Finally, an outlook on further developments is presented.

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Modeling the microstructural evolution during constrained sintering

A numerical model able to simulate solid state constrained sintering of a powder compact is presented. The model couples an existing kinetic Monte Carlo (kMC) model for free sintering with a finite element (FE) method for calculating stresses on a microstructural level. The microstructural response to the stress field as well as the FE calculation of the stress field from the microstructural evolution is discussed. The sintering behavior of two powder compacts constrained by a rigid substrate is simulated and compared to free sintering of the same samples. Constrained sintering results in a larger number of pores near the substrate as well as a reorientation of the pores along the direction normal to the substrate. These features are also observed experimentally.

Properties of magnetocaloric materials with a distribution of Curie temperatures

The magnetocaloric properties of inhomogeneous ferromagnets that contain distributions of Curie temperatures are considered as a function of the width of such a distribution. Assuming a normal distribution of the Curie temperature, the average adiabatic temperature change, $\Delta T_{ad}$, the isothermal magnetic entropy change, $\Delta s$, and the heat capacity, $c_p$, in zero magnetic field and an applied magnetic field of $H$, have been calculated using the mean field model of ferromagnetism. Interestingly, both the peak position and amplitude of each of these parameters vary differently with the width of the distribution, explaining the observed mismatch of peak temperatures reported in experiments. Also, the field dependence of $\Delta T_{ad}$ and $\Delta s$ is found to depend on the width of the distribution.
The sintering behavior of close-packed spheres

The sintering behavior of close-packed spheres is investigated using a numerical model. The investigated systems are the body-centered cubic (bcc), face-centered cubic (fcc) and hexagonal close-packed spheres (hcp). The sintering behavior is found to be ideal, with no grain growth until full density is reached for all systems. During sintering, the grains change shape from spherical to tetrakaidecahedron, similar to the geometry analyzed by Coble [R.L. Coble, J. Appl. Phys. 32 (1961) 787].

Design concepts for a continuously rotating active magnetic regenerator

Design considerations for a prototype magnetic refrigeration device with a continuously rotating AMR are presented. Building the active magnetic regenerator (AMR) from stacks of elongated plates of the perovskite oxide material La0.67Ca0.33−xSrxMn1.05O3, gives both a low pressure drop and allows grading of the Curie temperature along the plates. This may be accomplished by a novel technique where a compositionally-graded material is tape cast in one piece. The magnet assembly is based on a novel design strategy, to create alternating high- and low magnetic field regions within a magnet assembly. Focus is on maximising the magnetic field in the high field regions but also, importantly, minimising the flux in the low field regions. The design is iteratively optimised through 3D finite element magnetostatic modelling.
A Monolithic Perovskite Structure for Use as a Magnetic Regenerator

A La0.67Ca0.26Sr0.07Mn1.05O3 (LCSM) perovskite was prepared for the first time as a ceramic monolithic regenerator used in a regenerative magnetic refrigeration device. The parameters influencing the extrusion process and the performance of the regenerator, such as the nature of the monolith paste and the influence of the sintering on the adiabatic temperature change, were investigated. Comparisons between the extruded monolithic structure before and after the sintering showed that an increase of the adiabatic temperature change was seen after the sintering. Furthermore, calculations show that the performance of the monolithic structure is potentially superior to a parallel plate regenerator, indicating the potential cost and structural benefit of using such structure, i.e. a mechanically stable ceramic thin wall structure, which can be produced in one processing step.

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Determing the minimum mass and cost of a magnetic refrigerator

An expression is determined for the mass of the magnet and magnetocaloric material needed for a magnetic refrigerator and these are determined using numerical modeling for both parallel plate and packed sphere bed regenerators as function of temperature span and cooling power. As magnetocaloric material Gd or a model material with a constant adiabatic temperature change, representing an infinitely linearly graded refrigeration device, is used. For the magnet a maximum figure of merit magnet or a Halbach cylinder is used. For a cost of $40 and $20 per kg for the magnet and magnetocaloric material, respectively, the cheapest 100 W parallel plate refrigerator with a temperature span of 20 K using Gd and a Halbach magnet has 0.8 kg of magnet, 0.3 kg of Gd and a cost of $35. Using the constant material reduces this cost to $25. A packed sphere bed refrigerator with the constant material costs $7. It is also shown that increasing the operation frequency reduces the cost. Finally, the lowest cost is also found as a function of the cost of the magnet and magnetocaloric material.
Improving Magnet Designs With High and Low Field Regions

A general scheme for increasing the difference in magnetic flux density between a high and a low magnetic field region by removing unnecessary magnet material is presented. This is important in, e.g., magnetic refrigeration where magnet arrays have to deliver high field regions in close proximity to low field regions. Also, a general way to replace magnet material with a high permeability soft magnetic material where appropriate is discussed. As an example, these schemes are applied to a two dimensional concentric Halbach cylinder design resulting in a reduction of the amount of magnet material used by 42% while increasing the difference in flux density between a high and a low field region by 45%.

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The ideal dimensions of a Halbach cylinder of finite length

In this paper the smallest or optimal dimensions of a Halbach cylinder of a finite length for a given sample volume and desired flux density are determined using numerical modeling and parameter variation. A sample volume that is centered in and shaped as the Halbach cylinder bore but with a possible shorter length is considered. The external radius and the length of the Halbach cylinder with the smallest possible dimensions are found as a function of a desired internal radius, length of the sample volume and mean flux density. It is shown that the optimal ratio between the outer and inner radius of the Halbach cylinder does not depend on the length of the sample volume. Finally, the efficiency of a finite length Halbach cylinder is considered and compared with the case of a cylinder of infinite length. The most efficient dimensions for a Halbach cylinder are found and it is shown that the efficiency increases slowly with the length of the cylinder.
The influence of the magnetic field on the performance of an active magnetic regenerator (AMR)

The influence of the time variation of the magnetic field, termed the magnetic field profile, on the performance of a magnetocaloric refrigeration device using the active magnetic regeneration (AMR) cycle is studied for a number of process parameters for both a parallel plate and packed bed regenerator using a numerical model. The cooling curve of the AMR is shown to be almost linear far from the Curie temperature of the magnetocaloric material. It is shown that a magnetic field profile that is 10% of the cycle time out of sync with the flow profile leads to a drop in both the maximum temperature span and the maximum cooling capacity of 20–40% for both parallel plate and packed bed regenerators. The maximum cooling capacity is shown to depend very weakly on the ramp rate of the magnetic field. Reducing the temporal width of the high field portion of the magnetic field profile by 10% leads to a drop in maximum temperature span and maximum cooling capacity of 5–20%. An increase of the magnetic field from 1 T to 1.5 T increases the maximum cooling capacity by 30–50% but the maximum temperature span by only 20–30%. Finally, it was seen that the influence of changing the magnetic field was more or less the same for the different regenerator geometries and operating parameters studied here. This means that the design of the magnet can be done independently of the regenerator geometry.
Designing a magnet for magnetic refrigeration

This thesis investigates the design and optimization of a permanent magnet assembly for use in a magnetic refrigeration device. The heart of magnetic refrigeration is the adiabatic temperature change in the magnetocaloric material which is caused by the magnetic field. In order to design an ideal magnet assembly the magnetocaloric materials and the refrigeration process itself and their properties and performance as a function of magnetic field are investigated. For the magnetocaloric materials it is the magnetization, specific heat capacity and adiabatic temperature that are investigated as functions of the magnetic field. Following this the process utilized by a magnetic refrigerator to provide cooling is investigated using a publicly available one dimensional numerical model. This process is called active magnetic regeneration (AMR). The aim is to determine the performance of the AMR as a function of the magnetic field in order to learn the properties of the optimal magnet assembly. The performance of the AMR as a function of the synchronization and width of the magnetic field with respect to the AMR cycle, the ramp rate and maximum value of the magnetic field are investigated. Other published magnet designs used in magnetic refrigeration devices are also evaluated, using a figure of merit based on the properties of the investigated magnetocaloric materials, to learn the properties of the best magnet designs to date. Following this investigation the Halbach cylinder, which is a hollow permanent magnet cylinder with a rotating remanent flux density, is investigated in detail as it forms the basis of many magnet designs used in magnetic refrigeration. Here the optimal dimensions of a Halbach cylinder, as well as analytical calculations of the magnetic field for a Halbach cylinder of infinite length, are presented. Once it has been determined which properties are desirable for a magnet used in magnetic refrigeration the design of a new magnet is described. This is a high performance cylindrical magnet for use in a new magnetic refrigeration device being built at Risø DTU. This magnet design must have alternating regions of high and low magnetic field. As a basis for the magnet design the concentric Halbach cylinder design is chosen. This design is then optimized by employing several developed optimization schemes that lower the flux density in a specific region and lower the amount of magnet material used in a given magnet assembly. These schemes are applied to a numerical model of the magnet design. Afterwards the magnet design is dimensioned and segmented to allow construction. This design has been constructed and the flux density measured. Finally, the magnetic forces internally in the magnet design and on the magnetocaloric material inside the magnet assembly have been analyzed.
An optimized magnet for magnetic refrigeration

A magnet designed for use in a magnetic refrigeration device is presented. The magnet is designed by applying two general schemes for improving a magnet design to a concentric Halbach cylinder magnet design and dimensioning and segmenting this design in an optimum way followed by the construction of the actual magnet. The final design generates a peak value of 1.24 T, an average flux density of 0.9 T in a volume of 2 L using only 7.3 L of magnet, and has an average low flux density of 0.08 T also in a 2 L volume. The working point of all the permanent magnet blocks in the design is very close to the maximum energy density. The final design is characterized in terms of a performance parameter, and it is shown that it is one of the best performing magnet designs published for magnetic refrigeration.
Comparison of adjustable permanent magnetic field sources
A permanent magnet assembly in which the flux density can be altered by a mechanical operation is often significantly smaller than comparable electromagnets and also requires no electrical power to operate. In this paper five permanent magnet designs in which the magnetic flux density can be altered are analyzed using numerical simulations, and compared based on the generated magnetic flux density in a sample volume and the amount of magnet material used. The designs are the concentric Halbach cylinder, the two half Halbach cylinders, the two linear Halbach arrays and the four and six rod mangle. The concentric Halbach cylinder design is found to be the best performing design, i.e. the design that provides the most magnetic flux density using the least amount of magnet material. A concentric Halbach cylinder has been constructed and the magnetic flux density, the homogeneity and the direction of the magnetic field are measured and compared with numerical simulation and a good agreement is found.

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Design Concepts for a Continuously Rotating Active Magnetic Regenerator
Design considerations for a prototype magnetic refrigeration device with a continuously rotating AMR are presented. Building the AMR from stacks of elongated plates of the perovskite oxide material La0.67Ca0.33-xSrxMn1.05O3, gives both a low pressure drop and allows grading of the Curie temperature along the plates. This may be accomplished by a novel technique where a compositionally graded material may be tape cast in one piece. The magnet assembly is based on a novel design strategy, to create alternating high- and low magnetic field regions within a magnet assembly. Focus is on maximising the magnetic field in the high field regions but also, importantly, minimising the flux in the low field regions. The design is iteratively optimised through 3D finite element magnetostatic modelling.

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Magnetocaloric properties of LaFe$_{13-x-y}$Co$_x$Si$_y$ and commercial grade Gd

The magnetocaloric properties of three samples of LaFe$_{13-x-y}$Co$_x$Si$_y$ have been measured and compared to measurements of commercial grade Gd. The samples have $(x=0.86, y=1.08)$, $(x=0.94, y=1.01)$ and $(x=0.97, y=1.07)$ yielding Curie temperatures in the range 276–288 K. The magnetization, specific heat capacity and adiabatic temperature change have been measured over a broad temperature interval. Importantly, all measurements were corrected for demagnetization, allowing the data to be directly compared. In an internal field of 1 T the maximum specific entropy changes were 6.2, 5.1 and 5.0 J/kg K, the specific heat capacities were 910, 840 and 835 J/kg K and the adiabatic temperature changes were 2.3, 2.1 and 2.1 K for the three LaFeCoSi samples respectively. For Gd in an internal field of 1 T the maximum specific entropy change was 3.1 J/kg K, the specific heat capacity was 340 J/kg K and the adiabatic temperature change was 3.3 K. The adiabatic temperature change was also calculated from the measured values of the specific heat capacity and specific magnetization and compared to the directly measured values. In general an excellent agreement was seen.

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Review and comparison of magnet designs for magnetic refrigeration

One of the key issues in magnetic refrigeration is generating the magnetic field that the magnetocaloric material must be subjected to. The magnet constitutes a major part of the expense of a complete magnetic refrigeration system and a large effort should therefore be invested in improving the magnet design. A detailed analysis of the efficiency of different published permanent magnet designs used in magnetic refrigeration applications is presented in this paper. Each design is analyzed based on the generated magnetic flux density, the volume of the region where this flux is generated and the amount of magnet material used. This is done by characterizing each design by a figure of merit magnet design efficiency parameter, $\Lambda_{\text{cool}}$. The designs are then compared and the best design found. Finally recommendations for designing the ideal magnet design are presented based on the analysis of the reviewed designs.

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Spatially resolved measurements of the magnetocaloric effect and the local magnetic field using thermography

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The demagnetizing field of a non-uniform rectangular prism
The effect of demagnetization on the magnetic properties of a rectangular ferromagnetic prism under non-uniform conditions is investigated. A numerical model for solving the spatially varying internal magnetic field is developed, validated and applied to relevant cases. The demagnetizing field is solved by an analytical calculation and the coupling between applied field, the demagnetization tensor field and spatially varying temperature is solved through iteration. We
show that the demagnetizing field is of great importance in many cases and that it is necessary to take into account the non-uniformity of the internal field, especially for non-constant temperature distributions and composite magnetic materials.

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**Detailed numerical modeling of a linear parallel-plate Active Magnetic Regenerator**
A numerical model simulating Active Magnetic Regeneration (AMR) is presented and compared to a selection of experiments. The model is an extension and re-implementation of a previous two-dimensional model. The new model is extended to 2.5D, meaning that parasitic thermal losses are included in the spatially not-resolved direction. The implementation of the magnetocaloric effect (MCE) is made possible through a source term in the heat equation for the magnetocaloric material (MCM). This adds the possibility to model a continuously varying magnetic field. The adiabatic temperature change of the used gadolinium has been measured and is used as an alternative MCE than mean field modeling. The results show that using the 2.5D formulation brings the model significantly closer to the experiment. Good agreement between the experimental results and the modeling was obtained when using the 2.5D formulation in combination with the measured adiabatic temperature change.

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Magnetic cooling at Risoe DTU

Magnetic refrigeration at room temperature is of great interest due to a long-term goal of making refrigeration more energy-efficient, less noisy and free of any environmentally hostile materials. A refrigerator utilizing an active magnetic regenerator (AMR) is based on the magnetocaloric effect, which manifests itself as a temperature change in magnetic materials when subjected to a varying magnetic field. In this work we present the current state of magnetic refrigeration research at Risoe DTU with emphasis on the numerical modeling of an existing AMR test machine. A 2D numerical heat-transfer and fluid-flow model that represents the experimental setup is presented. Experimental data of both no-heat load and heat load situations are compared to the model. Moreover, results from the numerical modeling of the permanent magnet design used in the system are presented.

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Numerical modeling in magnetic refrigeration

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Optimization and improvement of Halbach cylinder design
In this paper we describe the results of a parameter survey of a 16 segmented Halbach cylinder in three dimensions in which the parameters internal radius, rin, external radius, rex, and length, L, have been varied. Optimal values of rex and L were found for a Halbach cylinder with the least possible volume of magnets with a given mean flux density in the cylinder bore. The volume of the cylinder bore could also be significantly increased by only slightly increasing the volume of the magnets, for a fixed mean flux density. Placing additional blocks of magnets on the end faces of the Halbach cylinder also improved the mean flux density in the cylinder bore, especially so for short Halbach cylinders with large rex. Moreover, magnetic cooling as an application for Halbach cylinders was considered. A magnetic cooling quality parameter, Lambdacool, was introduced and results showed that this parameter was optimal for long Halbach cylinders with small rex. Using the previously mentioned additional blocks of magnets can improve the parameter by as much as 15% as well as improve the homogeneity of the field in the cylinder bore. ©2008 American Institute of Physics

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Projects:

Micromagnetism and permanent magnets
Poulsen, E. B., PhD Student, Department of Energy Conversion and Storage
Bjørk, R., Main Supervisor
Insinga, A. R., Supervisor
Nielsen, K. K., Supervisor
01/04/2019 → 31/03/2022
Project: PhD

Harvesting Energy with Levitating Magnets
Imbaquingo Muñoz, C. E., PhD Student, Department of Energy Conversion and Storage
Bjørk, R., Main Supervisor
Bahl, C., Supervisor
Insinga, A. R., Supervisor
01/01/2019 → 31/12/2021
Project: PhD
Getting the most out of magnetocaloric materials for high efficiency refrigeration
Erbesdobler, F., PhD Student, Department of Energy Conversion and Storage
Nielsen, K. K., Main Supervisor
Bahl, C., Supervisor
Bjørk, R., Supervisor
Forskningsrådsfinansiering
01/01/2018 → 31/12/2020
Award relations: Getting the most out of magnetocaloric materials for high efficiency refrigeration
Project: PhD

Freeze casting to create micro-channel structures
Christiansen, C. D., PhD Student, Department of Energy Conversion and Storage
Bjørk, R., Main Supervisor
Nielsen, K. K., Supervisor
Forskningsrådsfinansiering
01/01/2017 → 31/12/2019
Award relations: Freeze casting to create micro-channel structures
Project: PhD

Active Magnetic regenerator refrigeration with rotary multi-bed technology
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Engelbrecht, K., Main Supervisor
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Palm, B., Examiner
Kitanovski, A., Examiner
Technical University of Denmark
01/04/2016 → 20/09/2016
Award relations: Active Magnetic regenerator refrigeration with rotary multi-bed technology
Project: PhD

Modeling of shape instabilities occurring during sintering
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Frandsen, H. L., Main Supervisor
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Pryds, N., Supervisor
Hattel, J. H., Examiner
Bordia, R. K., Examiner
Raether, F., Examiner
Forskningsrådsfinansiering
15/07/2011 → 30/09/2014
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Project: PhD

Modeling and development of permanent magnets for magnetic refrigeration at room temperature
Bjørk, R., PhD Student, Risø National Laboratory for Sustainable Energy
Pryds, N., Main Supervisor
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Smith, A., Supervisor
Hendriksen, P. V., Examiner
Coey, J. M. D., Examiner
Rowe, A., Examiner
Forskningsrådsfinansiering
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Optimised Hybrid Magnets
Insinga, A. R., PhD Student, Department of Energy Conversion and Storage
Activities:

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Rasmus Bjørk (Lecturer)
Department of Energy Conversion and Storage
Electrofunctional materials

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