Preface

This book provides the basis for engineering a new, alternative form of technology, i.e., magnetocaloric energy conversion. It has been written for postgraduate students, engineers and researchers, especially those working in the areas of refrigeration and heat pumping, power generation and heat transfer. The aim of the book is to provide the reader with a theoretical basis supported by practical examples, facilitate the understanding, design and construction, and to introduce new solutions to engineering problems in future magnetocaloric energy-conversion devices.

The global energy demand for refrigeration and air conditioning is rapidly increasing. Nearly 20 % of all energy is wasted in existing cooling or air-conditioning devices. Here, vapour-compression air-conditioning and refrigeration technologies have dominated the market for more than 100 years.

As the capacity per unit mass of vapour-compression technology has improved over time their dominant position has become even stronger by lowering the manufacturing costs and improving efficiency. However, the trends of the converging S-curve of development show that vapour compression has become a mature technology, having only a small potential for some significant improvements in efficiency.

There is a continuous quest to find new, environmentally friendly refrigerants for vapour compression. Many of the alternative substances are related to a lower energy efficiency, high pressures, flammability or even explosive hazards.

Based on the adopted Kyoto Protocol, the chlorofluorocarbons CFCs, which had an important impact on the ozone layer (with high ozone depletion potential (ODP)), were phased out in the 1990s. Another group of refrigerants, the hydrochlorofluorocarbons (HCFSs) will be phased out by 2020. Despite this, the majority of remaining refrigerants possess a global warming potential (GWP). Moreover, most of the electricity production is based on fossil fuels. In order to reduce the amount of their use, one way is certainly to increase the use of renewable energy sources. On the other hand, one should take care of reducing energy consumption throughout the whole energy chain—from production to consumption. The last is also associated with the efficiency of energy conversion.

Therefore, any improvement in the efficiency of energy-conversion technologies will drastically influence the global energy demand as well as reduce the harmful environmental impacts. Vapour compression represents an important part of the world's energy consumption. Since it represents a mature technology, it is therefore obvious to think about alternative technologies. One such example is magnetocaloric energy conversion, i.e., magnetic refrigeration, magnetic heat pumping, and magnetic power generation, respectively.

Magnetocaloric energy conversion is a technology that is based on the exploitation of the magnetocaloric effect (MCE). The MCE is a physical phenomenon that occurs in magnetic materials under the influence of a varying magnetic field, i.e., magnetization and demagnetisation. Instead of a gas-refrigerant as the working substance, magnetocaloric devices employ a solid magnetic material.

Magnetocaloric materials have a GWP and an ODP equal to zero. In analogy with the polytropic compression and isenthalpic expansion of the gas-refrigerant, the processes of magnetization and demagnetization of some magnetocaloric materials are nearly isentropic. This is why the magnetocaloric energy conversion, as an alternative, offers improvements in efficiency. Note that the earliest prototypes have already demonstrated an exergy efficiency higher than that of existing vapour-compression technologies. Moreover, silent operation without vibration makes this technology attractive for a large number of applications. It is therefore not a coincidence that different technology foresights have characterized magnetocaloric energy conversion as one of the most promising alternatives for future air conditioning and refrigeration.

In 1843, James Prescott Joule observed that heat is evolved in iron samples under an applied magnetic field. In 1860, William Thomson (Lord Kelvin) knew that ferromagnetic materials lose their magnetic properties when heated above a certain temperature (known today as the Curie temperature). Twenty years later in 1881 Emil Warburg published his work explaining magnetic hysteresis. A year later, in 1882, James Alfred Ewing discovered the same phenomenon and was the first to name it "hysteresis". Later in 1917–1918, the physicists Pierre Weiss and Auguste Piccard announced the discovery of the "novel magnetocaloric phenomenon".

In parallel with the discovery of the MCE, scientists were creating ideas to apply the MCE in energy-conversion devices. Towards the end of the 19th century Jožef Stefan had the first ideas that ferromagnetic materials could be applied in power generation. Some years later, but still in the 19th century, Nikola Tesla and Thomas Alva Edison patented ideas about thermomagnetic motors. In 1926 Peter Joseph William Debye and in 1927 William Francis Giauque independently discussed the application of the MCE for cryogenic temperatures under 1 K. The experimental proof came in 1933 from W.F. Giauque and D.P. MacDougall. The first magnetic refrigerator ever built for room-temperature applications was constructed and tested by G.V. Brown in 1976. In 1982, John A. Barclay and William A. Steyert introduced the idea of an active magnetic regenerator (AMR), which is today widely applied.

An important milestone in the development of magnetocaloric energy conversion is the discovery of the so-called giant MCE, which was announced in 1997 by Karl A. Gschneidner, Jr. and Vitalij K. Pecharsky. Since then, there has been an exponential increase in patents, articles, conference contributions as well as individual chapters in a number of different books.

Among the books that concern *Magnetocaloric Energy Conversion*, it is important to mention that on *Ferrohydrodynamics* by Ronald E. Rosensweig, which was published in 1985. Although this book could be taken as the bible for ferrohydrodynamics, a large part of it was dedicated to magnetocaloric energy conversion, not only by providing the basic theory, but also by encouraging researchers to enter the engineering of this particular domain.

Another important work was published by Alexander M. Tishin and Yuri I. Spichkin in 2003. The book *The Magnetocaloric Effect and its Applications* was actually the first that was strictly focused on magnetocalorics, by giving a comprehensive description of magnetocaloric materials and their properties, as well as by pointing out different potential applications.

A very large number of different publications on magnetocaloric materials and systems have been provided in the proceedings of the International Conferences on Magnetic Refrigeration at Room Temperature—THERMAG. Since starting in 2005 in Montreux, Switzerland, these conferences have been organized in 2007 in Portorož, Slovenia, in 2009 in Des Moines, Iowa, USA, in 2010 in Baotou, Inner Mongolia, China, in 2012 in Grenoble, France, and in 2014 in Victoria, British Columbia, Canada.

For the continuous organization of the first five THERMAG events under the umbrella of the *IIR—International Institute of Refrigeration*, we have to thank Peter William Egolf, who in 2004 established the *IIR Magnetic Cooling Working Party* and led it until 2012. Without his efforts and also the efforts of all the contributors to such conferences, the magnetocaloric community would be missing an important part, which led to closer collaborations between engineers, physicists and material scientists as well as leading to better transfer of knowledge.

With about 60 prototypes being developed all over the world, and the involvement of different industries, magnetocaloric energy conversion is today on its way towards the first market applications. For these, strong interdisciplinary engineering knowledge is required. The authors of this book have recognised that there exists no such complete work that would provide the required basis for engineering.

The aim of this book is therefore to provide the most important information for students, engineers and researchers to help them understand the physics behind magnetocaloric energy conversion, and to provide sufficient basis, which will serve for the design and construction of future magnetocaloric energy-conversion devices. Moreover, by adding the latest results in research and completing them with new ideas and concepts, this book should be helpful for researchers and their industrial partners in finding and developing new magnetocaloric market applications.

The first seven chapters provide the fundamentals and practical examples on *Magnetocaloric Energy Conversion* and its various sub-domains. Chapters 8 and 9 provide potential solutions to engineering problems supported by new concept proposals, and economic aspects of magnetocaloric energy conversion. The last chapter is dedicated to other, analogous, alternative technologies of solid-state energy conversion, which might also have a potential for future market applications.

In Chap. 1 on the *Thermodynamics of Magnetocaloric Energy Conversion*, the basic magnetocaloric thermodynamic potentials are presented and described. The state of the art gives an overview of the existing theoretical and experimental approaches to magnetocaloric thermodynamic cycles. Design issues related to different thermodynamic refrigeration cycles are shown as well, described through basic thermodynamic equations, as well as definitions of the coefficient of performance (COP), the exergy efficiency and the theoretical maximum cooling capacity.

Chapter 2 on *Magnetocaloric Materials for Freezing, Cooling and Heat-Pump Applications* introduces different magnetocaloric materials in terms of engineering and their applications. Among those, the most promising magnetocaloric materials are highlighted and presented with their basic thermodynamic properties.

Magnetic Field Source represents one of the most important and also most expensive parts of the magnetocaloric device. Therefore, the optimal design of a magnetic field source is crucial for obtaining a cost-effective and energy-efficient device. In this chapter we briefly describe some of the most important issues that relate to magnetic field sources. Despite the fact that different magnetic field sources with respect to their application in magnetocaloric energy conversion can be applied, the main emphasis of Chap. 3 is on permanent magnets and their assemblies. However, brief information is also provided about electric resistive magnets and superconducting magnets, including their cryogenic parts. A review supported by drawings of different permanent-magnet assemblies is given in the chapter, which includes basic information about their characteristics.

Chapter 4 deals with *Active Magnetic Regeneration*. Note, most of the existing prototype devices and studies are based on applying magnetocaloric materials with the principle of active magnetic regeneration (AMR). In the first part of the chapter, the operation of an AMR within different thermodynamic cycles is explained. Comprehensive information about numerical modelling of an AMR is given, supported by a review of this particular research, and by the necessary mathematical models required for modelling. The impact of the operating conditions (mass-flow rate and operating frequency) and geometrical characteristics on AMR are presented. In addition, results on numerical and experimental investigations of the different AMR thermodynamic cycles are shown, and guidelines for future research on AMR thermodynamic cycles are given. The impact of the heat-transfer fluid on the characteristics of the AMR is discussed. Brief information about some processing and manufacturing techniques is provided. The end of the chapter provides brief information on the practical limitations for the application of AMR cycles.

A special case of magnetocaloric energy conversion relates to *Magnetocaloric Fluids*. These can be further divided into ferrofluids (nanofluids) and magneto-rheological particle suspensions. In Chap. 5, this book provides important information on rheologic constitutive models of magnetic fluids, and introduces the basic governing equations, which relate to the thermo-magneto-fluid dynamics of ferrofluids. The review on existing studies and applications of magnetocaloric fluids is given. The chapter provides a discussion and guidelines for the potential design of devices that concern magnetocaloric energy conversion with magnetocaloric fluids. Since other magnetic fluids can also be successfully applied in magnetocaloric energy conversion, their various potential uses are outlined in the chapter.

The existing practical limitations of AMR principles relate to the power density of magnetocaloric devices. This is associated with the number of thermodynamic cycles performed in a unit of time. Therefore, in the past few years, some research groups have started a serious investigation of the potential in other mechanisms, which led them to research on *Special Heat Transfer Mechanisms—Active and Passive Thermal Diodes*. The thermal diode (heat "semiconductor", thermal switch, heat valve, thermal rectifier) is a physical phenomenon, mechanism or device in which it is possible to manipulate and control the direction of the heat flux and sometimes also the intensity of the heat flux. Chapter 6 presents different kinds of mechanisms and devices that can be applied as thermal diodes. These can be further divided into two main areas: solid-state thermal diodes and microfluidic thermal diodes, respectively. The characteristics of such thermal diodes are compared and presented with respect to different potential applications. A review of existing research with regard to magnetic refrigeration is given and the potential configurations of thermal diodes in magnetic refrigeration as guidelines for future applications are shown.

Chapter 7 provides an *Overview of Existing Magnetocaloric Prototype Devices*. Generally, two different types of such devices have been exploited—linear and rotary devices. Based on information from the literature, as well as due to the help of the magnetocaloric community, the majority of these prototypes are presented in this chapter. The information is supported by drawings, photographs as well as the main operating characteristics. To this we also add contact details of the institutes and people, which may be used for collaboration, potential investments in the technology or industrial development. At the end of the chapter, the summary of all prototypes is given in tables.

As a continuation of Chap. 7, the Chap. 8 on *Design Issues and Future Perspectives for Magnetocaloric Energy Conversion* gives comprehensive information on the different possible designs for particular types of magnetic refrigerators and heat pumps. Whereas some of the configurations were already applied in research, Chap. 8 also provides information about new solutions, which are based on the author's research experiences and which might be applied in future studies and related devices. In addition, a note on power generation is added, with a brief review of the existing work in this particular domain. By pointing out the most successful design approaches, this chapter also serves as a future guideline on magnetic refrigeration and heat pumping.

The commercialization of the presented technology requires analyses of the *Economic Aspects of the Magnetocaloric Energy Conversion*. In Chap. 9, we address the cost issues that relate to magnetic field sources and magnetocaloric materials. With supporting information on global market prices, we have also added a simple calculation of the costs for the magnetocaloric refrigerator. This is followed by a review of the different economic studies covering magnetic refrigeration, including some of the ecological aspects that are related to the carbon footprint and lifecycle analyses (LCAs).

The last chapter in this book is dedicated to other *Alternative Solid-State Energy Conversion* technologies. Because of the analogy with magnetocaloric energy conversion, these “ferroic”, solid-state technologies can be applied by engineers having a knowledge of magnetocalorics. The chapter is divided into three sections, which regard the electrocaloric (pyroelectric), barocaloric and elastocaloric energy conversion technologies. In each section, the physical principle behind the technology is presented with an overview of the existing materials and their physical properties. Furthermore, different possibilities for how to design an energy-conversion device using these materials are reviewed (especially for electrocalorics). Since the technology based on these three effects is in an early stage of development, only a few prototypes of energy-conversion devices, as the state of the art, have been presented.

With the presented knowledge and engineering solutions we hope that this book will well serve the reader in exploiting alternative possibilities of energy conversion by learning and designing future magnetocaloric devices for refrigeration, air-conditioning, heating and power generation.

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