Progress in Materials Science 93 (2018) 112–232

Contents lists available at ScienceDirect

Progress in Materials Science

journal homepage: www.elsevier.com/locate/pmatsci

Magnetocaloric effect: From materials research to refrigeration devices

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ARTICLE INFO

Article history:
Received 6 April 2017
Received in revised form 25 October 2017
Accepted 26 October 2017
Available online 8 November 2017

Keywords:
Magnetocaloric effec
Magnetic refrigeration
Thermomagnetic properties

ABSTRACT

The magnetocaloric effect and its most straightforward application, magnetic refrigeration, are topics of current interest due to the potential improvement of energy efficiency of cooling and temperature control systems, in combination with other environmental benefits associated to a technology that does not rely on the compression/expansion of harmful gases. This review presents the fundamentals of the effect, the techniques for its measurement with consideration of possible artifacts found in the characterization of the samples, a comprehensive and comparative analysis of different magnetocaloric materials, as well as possible routes to improve their performance. An overview of the different magnetocaloric prototypes found in literature as well as alternative applications of the magnetocaloric effect for fundamental studies of phase transitions are also included.

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https://doi.org/10.1016/j.pmatsci.2017.10.005
0079-6425/

1. Introduction

Energy efficiency and sustainability are priority topics for most research funding agencies worldwide and are recurrent topics in different mass media. In fact, according to data from Laurence Livermore National Laboratory 61% of the estimated USA energy consumption in 2015 corresponds to rejected energy, while only the remaining 39% is actually employed in energy services. Values are comparable for other developed countries, like 63% rejected energy in 2011 in UK or Spain. These data indicate that it is not only necessary to focus on the primary energy source and avoid our dependence on non-renewable energy sources but also to dedicate large research efforts for improving the efficiency of energy conversion. In particular, most renewable energy sources have to be converted into electricity before their final use, and in USA 67% of the conversion process in 2015 resulted in wasted energy [1]. In many cases, magnetic materials play a relevant role in energy conversion into electricity. This constitutes a driving force for the improvement of magnetic materials for energy applications [2], with some current examples covered in a recent Viewpoint Set of Scripta Materialia [3].

Among the different final uses of energy in the residential and commercial sectors, refrigeration and air conditioning account for a relevant fraction of electricity use, with numbers varying from country to country due to their different climate. Recent data from EIA [4] estimate that 87% of USA households are furnished with air-conditioners and ~114 million units account for an annual energy demand of 186 billion kWh of electricity. There is no doubt that our way of life relies on our capability of cooling food and controlling the temperature of our living and working environments. If developing countries adopt similar trends in cooling habits, there can be a 50-fold increase in the demand of air conditioners [5]. In the European Union, heating and cooling in buildings and industry account for half of the EU's energy consumption and in order to fulfil the EU's climate and energy goals, the heating and cooling sector must drastically reduce their energy consumption and cut their use of fossil fuels [6]. Magnetic refrigeration can play a relevant role in this effort to improve the energy efficiency of temperature and climate control. It is expected that these refrigerators based on magnetocaloric effect (MCE) will be energetically more efficient than the current ones based on the compression and expansion of gasses.

In fact, magnetic refrigeration is a timely topic of research. The discovery of magnetic materials that exhibit a remarkable change in their temperature when they are adiabatically magnetized close to room temperature [7] has produced a surge in the number of publications on MCE in the last two decades. Simultaneously, as these materials enable the possibility of designing magnetic refrigerators with operation temperatures close to room temperature, there has been a noticeable increase in the development of magnetic refrigerator prototypes [8]. This scientific and technological interest is mainly