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Potential for cost effective magnetocaloric air conditioning systems

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Abstract

Magnetic refrigeration is an emerging technology that exploits the magnetocaloric effect found in solid-state refrigerants. The combination of solid-state refrigerants, water-based heat transfer fluids, and high efficiency will lead to environmentally desirable products with minimal contributions to global warming. Among the numerous applications of refrigeration technology, air conditioning applications provide the largest aggregate cooling power and use the greatest quantity of electric energy. The primacy of the air conditioning application makes the establishment of cost targets for this application an essential feature of the R&D plan for magnetic refrigeration technology. A preliminary assessment of the permanent magnet costs and magnetocaloric material costs indicates that, for suitably chosen materials and operating conditions, these costs lay well below the total manufactured costs for vapor compression based air conditioners.

Keywords: Magnetic refrigerator; Air conditioning; Survey; Cost effectiveness

Perspectives des systèmes de conditionnement d'air magnétocaloriques et de leurs coûts

Mots clés : Réfrigérateur magnétique ; Conditionnement d'air ; Enquête ; Amortissement économique

1. Introduction

Refrigeration is critical to our health and the global economy. Consumer applications include air conditioning, food preservation, air dehumidification, beverage dispensing, and ice making. Industrial, commercial, and military applications include chilling of process fluids for food, metals, chemicals, industrial gases, electronics, and pharmaceutical production, refrigerated transport of commercial and medical goods, and cooling of computers and electronics. Current refrigeration systems, based on century old vapor compression technology, consume within the United States of America over 25% of residential electric demand and over 15% of commercial electric demand to meet space cooling and refrigeration needs [1]. Although comparable data are not available for global energy use, the Japan Refrigeration and Air Conditioning Industry Association [2] projects that 80% of the growth in air conditioning systems will come from Asia. Clearly, air conditioning and refrigeration applications will become an ever increasing consumer of electric

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Nomenclature

Symbols

B	magnetic flux density (T)
B_r	remnant magnetization (T)
C_{bed}	bed heat capacity (J m^{-3} K)
C_{fluid}	fluid heat capacity (J m^{-3} K)
C_{MCM}	MCM heat capacity (J m^{-3} K)
f	cycle frequency (Hz)
MCMCost	magnetocaloric material cost (US\$ kW$_c^{-1}$)
MCMPrice	magnetocaloric material price (US\$ kg^{-1})
NdFeBPrice	magnetic material price (US\$ kg^{-1})
Q_c	cooling power (W)
PMCost	Permanent magnet cost (US\$ kW$_c^{-1}$)
T_c	Curie temperature (K)
V_{PMM}	permanent magnet material volume (m^3)
V_{MF}	magnet field volume (m^3)
ΔT_a	magnetocaloric material adiabatic temperature change (K)
ΔT_{bed}	bed adiabatic temperature change (K)
ε	bed porosity
λ	magnetocaloric material latent heat (J m^{-3})
ρ_{MCM}	magnetocaloric material density (kg m^{-3})
ρ_{NdFeB}	permanent magnet material density (kg m^{-3})

Subscripts

a	adiabatic
c	cooling, Curie
bed	bed
fluid	fluid
MCM	magnetocaloric material
MF	magnetic field
NdFeB	neodymium iron boron
PMM	permanent magnet material

energy and a concomitant indirect producer of carbon dioxide.

Although vapor compression refrigeration has been improved, it is mature, with only incremental energy efficiency improvements anticipated in the future. Furthermore, conventional refrigeration systems use ozone depleting and global warming gases leading to undesirable environmental impacts. Although the global refrigeration and air conditioning industry are eliminating the use of ozone depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants with more environmentally benign hydrofluorocarbon (HFC) and hydrocarbon (HC) refrigerants, these replacement refrigerants are of growing concern due to their global warming potential as well as safety concerns in some applications.

Magnetic refrigeration is an emerging technology that exploits the magnetocaloric effect found in solid-state refrigerants. These solid-state refrigerants have no vapor pressure and so have zero ozone depletion potential and zero global warming potential. New designs of magnetic refrigeration components and systems have evolved recently that allow for compact devices which use water-based heat transfer fluids. Efficiency improvements of 20–30% compared to currently available vapor compression based systems are envisioned once technology development is complete. The combination of solid-state refrigerants, water-based heat transfer fluids, and high efficiency will lead to environmentally desirable products with minimal contributions to global warming.

2. Basic principles of magnetic refrigeration

Magnetic refrigeration technology is based upon the magnetocaloric effect, an intrinsic property of magnetic materials near their magnetic ordering temperature (e.g. Curie temperature, T_c, for ferromagnets). In the case of a ferromagnet, such as gadolinium, it is the reduction of entropy as the magnetic moments of the atoms are aligned upon application of a magnetic field and the increase of entropy when the magnetic moments become randomly oriented on removing the field which lead, respectively, under adiabatic conditions, to an increase or decrease in the temperature of the material, i.e., the adiabatic temperature change, ΔT_a. Gadolinium, a typical magnetocaloric material, has a maximum ΔT_a of 2.5 °C (4.5 °F) at the Curie temperature in a 1 T field (Fig. 1a). The Curie temperature, and thus the temperature of the peak ΔT_a, may be moved by adjusting the magnetocaloric material composition. This variation is shown for the Gd–Er solid solution alloy in Fig. 1b [3]. A number of interesting magnetocaloric materials, with compositionally tunable Curie temperatures and magnetocaloric properties [4–7] have been under investigation in recent years and have opened a pathway to devices with improved temperature span and efficiency.

The response of a magnetocaloric material to a magnetic field is similar to the response of a gas to compression and expansion. This analogy between a vapor compression refrigeration cycle and a magnetic refrigeration cycle is depicted in Fig. 2. In a vapor cycle refrigerator the refrigerant gas is compressed increasing its temperature, the compressed gas then rejects heat to the environment or hot sink, the refrigerant gas is then expanded decreasing its temperature, the expanded gas then absorbs heat from the source or space to be cooled and the cycle begins again. In a magnetic refrigerator the magnetocaloric material is magnetized increasing its temperature, the magnetized magnetocaloric material then rejects heat to the environment or hot sink, the magnetocaloric material is then demagnetized