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The lifetime cost of a magnetic refrigerator

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ABSTRACT

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 lifetime cost comparison between the magnetic refrigeration device and such a unit, we find similar costs, the former being slightly cheaper, assuming the cost of the magnet can be recuperated at end of life.

Le coût d'un réfrigérateur magnétique sur sa durée de vie

Mots clés : Régénérateur d'un réfrigérateur magnétique ; Champ magnétique ; Coût ; Prix ; Compresseur

1. Introduction

Magnetic refrigeration is a promising, efficient and environmentally friendly technology based on the magnetocaloric effect. A substantial number of scientific magnetic refrigeration devices have been published (Kitanovski et al., 2015; Yu et al., 2010), but so far the technology has yet to be commercialized. The main challenge for this is the relatively small magnetocaloric effect present in currently used magnetocaloric materials; the benchmark magnetocaloric material, Gd, has an adiabatic temperature change of less than 4 K in a magnetic field of 1 T (Bjørk et al., 2010a; Dan'kov et al., 1998), depending on purity. Therefore, a regenerative process, called active magnetic regeneration (AMR), is used to produce the desired temperature span (Barclay, 1982).

An important aspect in the commercialization of magnetic refrigeration is proving the often mentioned (potentially) high efficiency of magnetic refrigeration devices. Furthermore, it is crucial to show that these devices will have a lower lifetime cost than vapor compression based devices. Magnetic refrigeration devices will have a larger construction cost than vapor compression devices, due to the permanent magnet material needed to provide the magnetic field in the device. However, if the

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Nomenclature

Variables

$\dot{m}$	mass flow rate [kg s^{-1}]
a	specific surface area [m^{-1}]
A_c	cross sectional area [m^2]
d_{par}	particle size [m]
f	frequency [Hz]
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
H	magnetic field [A m^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length of regenerator [m]
M	magnetization [A m^{-1}]
m	mass [kg]
M^*	magnet efficiency parameter (-)
N	demagnetization factor [-]
Q	cooling power [W]
s	entropy [J K^{-1}]
T	temperature [K]
t	time [s]
u	velocity [m s^{-1}]
ΔT	temperature span [K]

Greek

ε	porosity [-]
μ_0	permeability of free space [m kg s^{-2} A^{-2}]
ρ	density [kg m^{-3}]
φ	utilization [-]

operating cost is significantly lower than compression based devices, then magnetic refrigeration devices may be overall cheaper. Determining the operation and construction costs of a magnetic refrigeration device is the purpose of this paper.

The total construction cost of a magnetic refrigeration unit has previously been considered by a number of authors. Rowe (2011) defined a general performance metric for active magnetic regenerators, which included the cost and effectiveness of the magnet design as a linear function of the volume of the magnet and the generated field. A figure of merit used to evaluate the efficiency of the magnet design was introduced in Bjørk et al. (2008), not taking the performance of the actual AMR system into account. The optimal AMR system design, i.e. ignoring the magnet, has been considered by Tusek et al. (2013b).

The building cost of a magnetic refrigeration device was considered by Bjørk et al. (2011), for a device with a given temperature span and cooling power calculated using a numerical model. Both a Halbach cylinder and a "perfect" magnet were considered, as well as both parallel plates and packed sphere regenerators. Assuming a cost of the magnet material of \$40 per kg and of the magnetocaloric material of \$20 per kg, the cheapest packed sphere bed refrigerator with Gd that produces 50 W of continuous cooling at a temperature span of 30 K using a Halbach magnet was found to use around 0.15 kg of magnet, 0.04 kg of Gd, having a magnetic field of 1.05 T and a minimum cost of \$6. The cost is dominated by the cost of the magnet. However, this calculation assumed magnetocaloric properties as predicted by the mean field theory, which is known to overestimate magnetocaloric properties compared to commercial grade Gd (Bahl et al., 2012). Also, the operating cost of the device was not considered.

The model presented by Tura and Rowe (2014) determined the total cost and optimal geometry and operating conditions for a dual-regenerator concentric Halbach configuration using a simple analytical model of an AMR. The magnetocaloric material was taken to be ideally graded, i.e. the adiabatic temperature change was defined as a linear function of temperature throughout the AMR and with a constant specific heat equal to that of Gd at the Curie temperature. Furthermore, a single particle size of 0.3 mm was considered. Both the manufacturing and the operating costs were considered and the lowest cost device was found as a function of the desired cooling power and effectiveness of the magnetocaloric material for a fixed temperature span of 50 K. For a cooling power of 50 W, the system with the lowest cost had a magnetic field of 1 T, a frequency around 4.5 Hz, a utilization of 0.35 and a COP of 2. The capital costs are around \$100 and \$40 for the magnet and the magnetocaloric material, respectively, while the cost of operation is \$0.004 h^{-1}.

In this paper we will consider not only the construction cost of the magnetic refrigeration device, but also the operating cost. Based on these, we will calculate the overall lowest cost of the magnetic refrigeration device based on the price of the magnet material, the price of the magnetocaloric material and the expected lifetime of the device.

2. Required device performance

In order to get relevant cooling performance values, we chose as a benchmark for this study a refrigerator appliance in the energy class A^{+++} (EU-label system), specifically a well insulated appliance with a 350 L inner volume. As vapor compression devices operate differently from magnetocaloric devices, it can be hard to find a fair way of making a direct comparison between the two. Thus, the intention of this paper is to identify a magnetocaloric unit with an output performance resembling that experienced from the vapor compression unit.

According to the calculation scheme of EU-directive 1060/2010, the average electrical power consumption must not exceed 8.6 W (Mrzyglod and Holzer, 2014). At a coefficient of performance of about 3.2, which is the operating COP for an A^{+++} appliance (Mrzyglod and Holzer, 2014), this is equivalent to an average cooling power of about 24 W, assuming an ambient temperature of 25 °C. However, door openings, loading and periods of increased ambient temperature will result in an increase in the cooling power demand. In general, the compressor in the device will be dimensioned for loads well above the average, and be operated in an on/off manner at times of lower cooling power demand.

Taking the values from Mrzyglod and Holzer (2014), the magnetocaloric device considered in the following will be dimensioned to deliver a maximum cooling power of $Q_{high} = 50$ W for 10% of the time and $Q_{low} = 22$ W for the remaining 90% of the time. This gives an average cooling power of $Q_{av} = 24.8$ W, close to that of the considered A^{+++} appliance. Thus, the AMR must be large enough to deliver 50 W, but operate most of the time at a much lower load. This will be compared to a device continuously operating at a cooling power of 24.8 W, using a volume