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Rotary magnetic chillers with permanent magnets

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ABSTRACT

In this article a technical–economic analysis of rotary magnetic liquid chillers is presented. The technical part comprises studies on different magnetocaloric regenerator geometries and different operating parameters. The results are presented by correlations of the Coefficient of Performance (COP) and the cooling capacity of a magnetic chiller. The analysis is based on applications with two different working fluids. The results reveal that magnetic chillers can be more efficient than conventional compressor-based chillers. However, the investment costs for magnetic chillers are higher. A discussion on the cost break-down and possible cost reductions is outlined. Some ideas for future R&D in the field of magnetic refrigeration are given.

Refroidisseurs magnétiques rotatifs équipés d'aimants permanents

Mots clés : réfrigérateur magnétique ; refroidisseur d'eau ; froid ; refroidissement ; économie d'énergie ; COP

1. Introduction

With the discovery of the "giant magnetocaloric effect" (Pecharsky and Gschneidner, 1997) the development of magnetic refrigeration gained increased momentum. Since then, the number of papers published in international journals has grown exponentially. The number of patents in this area is also increasing and approximately forty-five prototype refrigerators have been built up to 2012 (compare also Yu et al., 2010). Simultaneously, a large number of studies on the simulation and optimization of magnetocaloric regenerators have been performed (see the review of Nielsen et al., 2011), while other studies deal with the design and optimization of the permanent-magnet assemblies that are normally used in prototypes (Bjørk et al. 2010a; Roudaut et al., 2010; Tušek et al., 2010, 2011; Zimm et al., 2006; Okamura et al., 2006; Rowe, 2011). A very large number of studies is focused on the magnetic materials (e.g., Tishin and Spichkin,

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Nomenclature

Standard

B	magnetic flux density (T)
b	height of the wavy structure (m)
C	cost (Euro)
d	diameter (m)
COP	coefficient of performance (–)
H	magnetic field strength (A m^{-1})
h	length of one magnetocaloric element (m)
L	length (m)
$\dot{m}$	mass flow (kg s^{-1})
P	power (W), wetted perimeter (m)
p	pressure (Pa)
$\dot{Q}$	cooling power (W)
s	specific entropy (J K^{-1} kg^{-1})
T	temperature (K)
x	thickness of magnetocaloric material (m)
y	content of hydrogen (–)

Abbreviations

eth	ethanol

Indices

0	external, vacuum
ad	adiabatic
c	cooling, low-field region
ch	chiller
ci	chilled in
co	chilled out
compr	compressor chiller
pl	pressure loss
h	heating, high-field region, hydraulic
hg	heat gain from the environment
hys	hysteresis
ip	internal efficiency of pump
m	motor, motor drive
mc	magnetocaloric material
pump	pump

2003; Pecharsky and Gschneidner, 2006; Brück et al., 2008; Gutfleisch et al. 2010; Bjørk et al., 2010b). However, there have been few publications related to the economics of magnetic refrigeration. Most of such publications look at a cost evaluation of machines based on permanent magnets (Egolf et al., 2006; Russek and Zimm, 2006; Kitanovski et al., 2010a; Rowe, 2011; Bjørk et al., 2011).

This article deals with the application of rotary magnetic liquid chillers with permanent magnets and an assessment of their performance. For the purpose of the study, the permanent-magnet assemblies were numerically simulated and designed in order to provide magnetic flux densities of 1 T, 1.5 T and 2 T, respectively. After the basic design idea was drafted, numerous simulations were performed; first with the simple "freeware" numerical tool FEMM (2011), then its results were confirmed with the more sophisticated software ANSYS Multiphysics (see also Egolf et al., 2009a, 2010). After that, the thermodynamic and the fluid dynamic characteristics were calculated by using a simple, self-developed numerical tool. This tool is based mostly on explicit mathematical relations, and considers a quasi, steady-state, Brayton-like, regenerative, inverse thermodynamic cycle. The model is not presented here but may be found and downloaded from the website of the SFOE (see Egolf et al., 2006 and Kitanovski and Egolf, 2008, with the related links). The cost analysis was performed in order to compare the two rival technologies (the magnetic and compressor-based chiller, respectively) and to propose guidelines for potential further improvements and cost reductions.

Magnetic refrigeration technology is at an early stage of its development, where numerous technical issues are still unsolved and at the same time new discoveries in domains of materials, magnetics and technology fields are needed before the technology will be able to penetrate some consumer markets. Despite of that, the goal of this article is to demonstrate the potential of this technology (see also Kitanovski and Egolf, 2009), as well as to encourage industry and research institutes to enter this new, promising domain.

2. Rotary magnetic liquid chillers with wavy structures

2.1. Design and simulation of permanent-magnet assemblies

Fig. 1 shows the basic design concept for the magnet assembly. It comprises the outer and inner part. Between the two parts of the magnet assembly, the magnetocaloric material in a form of a coaxial porous structure rotates, while the inner and outer part of the magnet assembly is at rest. The outer part of the magnet assembly consists of soft iron and NdFeB magnets, whereas the inner part of the magnet assembly represents a guide for the magnetic flux, consisted of soft iron. Fig. 1 also shows the simulation results of magnetic field distributions resulting from the application of an approximate finite-element analysis using the simple numerical tool FEMM. The magnet assembly consists of more than 50% soft iron; the rest is NdFeB permanent magnets with an energy product of 32 MGOe. Three different magnet assemblies – with the same outer diameter, i.e., 40 cm – were designed (Fig. 1). It was found, after a discussion with magnet manufacturers, that a diameter larger than 40 cm would require too large, or too many permanent-magnet parts. As a result it was decided that an outer diameter of 40 cm is close to the upper limit for realistic applications. Since we were looking at a rotary type of magnetic chiller, the magnetic field should have at least two symmetric regions for the coaxial magnetocaloric regenerator (cylinder). Therefore, it was decided to further investigate the case with two symmetric regions. The dimensions of the coaxial magnetocaloric regenerator (magnet bore) are shown in Fig. 1. The magnetic flux distribution over the length of the magnet was almost