Applied Energy 100 (2012) 229–237

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Quantitative feasibility study of magnetocaloric energy conversion utilizing industrial waste heat

D. Vuarnoz [*,1], A. Kitanovski [2], C. Gonin, Y. Borgeaud, M. Delessert, M. Meinen, P.W. Egolf

University of Applied Sciences of Western Switzerland, Avenue des Sports 20, CH 1401 Yverdon-les-Bains, Switzerland

HIGHLIGHTS

- We model magnetic energy conversion machine for the use of industrial waste heat.
- Efficiencies and masses of the system are evaluated by a numerical model.
- Excellent potential of profitability is expected with large low-exergy heat sources.

ARTICLE INFO

Article history:
Received 4 October 2011
Received in revised form 28 February 2012
Accepted 30 April 2012
Available online 21 July 2012

Keywords:
Magnetocaloric energy conversion
Waste heat
Exergy
Thermodynamic efficiency

ABSTRACT

The main objective of this theoretical study was to investigate under which conditions a magnetic energy conversion device (MECD) – utilizing industrial waste heat – is economically feasible. Furthermore, it was evaluated if magnetic energy conversion (MCE) has the potential of being a serious concurrent to already existing conventional energy conversion technologies. Up-today the availability of magnetocaloric materials with a high Curie temperature and a high magnetocaloric effect is rather limited. Therefore, this study was mainly focused on applications with heat sources of low to medium temperature levels. Magnetic energy conversion machines, containing permanent magnets, are numerically investigated for operation conditions with different temperature levels, defined by industrial waste heat sources and environmental heat sinks, different magnetic field intensities and different frequencies of operation (number of thermodynamic cycles per unit of time).

Theoretical modeling and numerical simulations were performed in order to determine thermodynamic efficiencies and the exergy efficiencies as function of different operation conditions. From extracted data of our numerical results, approximate values of the total mass and total volume of magnetic energy conversion machines could be determined. These important results are presented dependent on the produced electric power. An economic feasibility study supplements the scientific study. It shows an excellent potential of profitability for certain machines. The most important result of this article is that the magnetic energy conversion technology can be economically and technically competitive to or even beat conventional energy conversion technologies. This is true especially in those cases when large, low-exergy heat sources are at one's disposal.

1. Introduction

The society learns more and more about the finiteness of energy and material sources on the planet Earth, as well as of the human harmful impact on the environment. An efficient energy use and improvements of technologies positively reduce the exploitation of sources, and thus reduce harmful impacts on the environment (see e.g. Ref. [1]). The optimization of energy utilization can be efficiently performed by the application of exergy concepts and related exergy analyses [2–4]. The latter represents a perfect tool to determine reductions of irreversibility's and the introduction of improvements in different kinds and at different levels of processes. Most important is the choice of an appropriate energy source and to efficiently operate the chosen process. It must be further evaluated if users with different kinds of energy and exergy demands can be combined in a single process. For instance, besides of power generation, the use of waste heat can be efficiently integrated into district heating networks [5] or into different industrial processes [6], including the cooling by sorption technologies [7,8].

* Corresponding author. Tel.: +41 24 557 76 00; fax: +41 24 557 76 01.
E-mail addresses: peter.egolf@heig-vd.ch, km@unprinted.ch (D. Vuarnoz).
[1] Present address: Dept. of Mech. Eng., Kobe Univesity, 1–1 Rokkodai-chos, Nada-ku, Kobe 657–8501, Japan.
[2] Present address: Faculty of Mech. Eng., Ljubljana University, Askerceva 6, 1000 Ljubljana, Slovenia.

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.04.051

Nomenclature

Standard

f	frequency ($Hz = s^{-1}$)
H	magnetic field strength ($A\,m^{-1}$)
M	magnetization ($A\,m^{-1}$)
n	real number (–)
P	power, power loss (W)
Q	heat (J)
$\dot{q}$	specific heat flux ($W\,kg^{-1}$)
$\dot{Q}$	heat flux (W)
s	specific entropy ($J\,kg^{-1}\,K^{-1}$)
T	temperature (K, °C)
U	internal energy (J)
V	volume (m^3)
w	specific work (J/kg)
W	work (J, N m)
ZT	thermoelectric figure of merit

Greek

μ	magnetic permeability ($A^{-1}\,m^{-1}$)
η	efficiency

Indices

ad	adiabatic
admax	maximal adiabatic
ass	magnets assembly
C	cold sink
Carnot	Carnot
Curie	Curie
Eddy	eddy currents
el	electric
ext	real temperature difference
Gen	general, heat losses
Gap	fluid gap
H	hot, source
hot	hot
hyd	hydraulic for one stage
Hyd	hydraulic for *n* stages
Hyst	hysteresis
mag	magnets
max	maximal
mcm	magnetocaloric material
Mot	motor
multi	multistage
n	number of stages
Sc	superconducting
source	source
stage	stage
sup	superconductivity
tot	total, overall
th	thermodynamic
thmulti	thermodynamic multistage
0	external, vacuum
II	exergy

Furthermore, all the processes must be optimized and the losses minimized [9]. In newer applications an increasing number of energy conversion processes are involved to gain back energies with higher exergy potentials [10]. Most of ancient power generation technologies that utilize waste heat, are based on the Water Steam Rankine Cycle. In the last five decades, numerous new technologies became available on the systems market. For utilizing heat sources with a low exergy potential, the Organic Rankine Cycle (ORC) [11–14], and the Kalina cycle [15–17] were successfully applied. Another interesting alternative is the thermoelectric energy conversion method. This technology is interesting because of its simplicity and the lack of any moving parts. However, because of the very low efficiency, large efforts are undertaken to increase it. This is especially the case in bulk thermoelectric materials [18–22]. The thermoelectric efficiency of these devices is characterized by the Figure of Merit (*ZT*). Whereas the best bulk materials show *ZT* values slightly above one, in super lattices these can reach values of up to $ZT = 3$ (see also in Fig. 9 which efficiencies can be achieved by different *ZT*'s). Another well known technology is the Stirling power conversion technology. This technology may be further divided into the mechanical and the thermoacoustic part. Stirling engines are mostly applied in micro-cogeneration [23,24].

The production cost and operation efficiency of the above described existing technologies are well known. On the other hand – to the authors' best knowledge – up-today there is no existing commercially driven magnetocaloric engine (in the literature named also thermomagnetic engine). Power plants, based on the magnetic or magnetocaloric principle, are serious candidates for more efficient and economic energy conversion in the near future. Takahashi [25] and Solomon [26] have investigated magnetic systems to recreate exergy from low-level industrial waste heat processes. Takahashi dealt with a hot source of a liquid of 95 °C. An experimental tri-pole wheel machine was investigated and the main results have been published. Solomon [26] made a relevant study of a "static machine" and evaluations of the coefficient of performance for industrial machines (20 MW of net power) with a hot source temperature up to 225 °C. A recent study, performed for the Swiss Federal Office of Energy (SFOE) [27], summarizes the present state of the conventional energy conversion technologies and makes first proposals for magnetic, respectively magnetocaloric energy conversion systems. In this study the potential of this technology is estimated, and its limits are outlined. This article mainly presents results of the study, however, it shows a focus on the utilization of industrial waste heat. Therefore, detailed information on magnetocaloric energy conversion for industrial applications is presented. The analysis performed is based on a very simple model. The reason for this kind of approach was to develop a simple and fast tool, and by avoiding too complex configurations and geometries to avoid the demand for very sophisticated models.

2. Magnetocaloric energy conversion machines

Magnetic energy conversion can actually be driven with every material showing a temperature dependent magnetization curve. A magnetic material in the alternating magnetic field shows a force that depends on the magnetization of the material. If now from an entrance to an outlet of a magnetic field region, a magnetic material is moved and its temperature is increased by heat absorption, then the force field at the entrance and the one at outlet are different. This results in a torque, which can move a slab or rotate a wheel. If such a moving object is connected to an electric generator, by simply using heat from a heat source, electricity can be gained (see e.g. [28–33]). Studying magneto-thermodynamics in general [28] and with more focus on the temperature-entropy diagram, it immediately becomes evident that the magnetocaloric effect increases the efficiency of a thermodynamic cycle of a magnetocaloric energy conversion machine. The reason is the reversibility of the processes of magnetization and demagnetiza-