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Thermal analysis of a multistage active magnetic regenerator cycle for hydrogen liquefaction

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ABSTRACT

The present paper deals with thermal analysis of cascade Active Magnetic Regenerator (AMR) cycle for the liquefaction of hydrogen starting from room temperature. For this purpose, the energy equations for fluid and solid within the regenerator bed of the AMR cycle have been considered. To solve the resulting mathematical model implicit finite difference method has been used. Thermal energy and mass balances are performed for several liquefaction systems composed of different number of cascade cycles. A simulation method using Hysys simulation commercial code has been presented. The multistage system operates with an ideal magnetic material as refrigerant and hydrogen gaseous as carrier fluid. First, the coefficient of performance (COP) of the AMR cycle and the required volume of magnetic material as functions of the number of cascades have been investigated. Then, the required volume is optimized by using the relationship between the COP and the volume. It has been found that a number of 6 AMR cycles operating in series is the optimal number of cascades required to liquefy 1 kg/h of hydrogen supplied at 25 °C. The system can operate between two volumes of magnetic material; namely, the minimum required volume (2.96 L) and the most efficient volume (7.44 L), corresponding to COP values of 1.23 and 4.7 respectively.

Introduction

In energy transition context, hydrogen is considered as one of the most important alternatives to fossil fuels and the best solution of depletion problems of resources and emissions of greenhouse gases. Hydrogen can also be, in the current situation, able to replace oil and natural gas, thanks to its various applications (fuel cells, engine fuel, boiler fuel gas, etc.) and its combustion qualities (non-toxic and generate only water vapor) [1]. Hydrogen can be produced from a diverse array of potential feed stocks including water, fossil fuels and organic matter [2]. In addition to its easiness of transmission and distribution under similar conditions to that of natural gas, hydrogen can be stored in tanks under pressure or in liquid form. Liquid hydrogen contains more energy per unit volume and thus provides a greater autonomy, while hydrogen gas must be stored at very high pressures in stainless steel tanks [3].

In conventional systems, liquefaction of hydrogen at 20.3 K can be obtained by the combined effect of cooling and adiabatic expansion of gas after it has been previously compressed. This liquefaction requires the use of large amounts of

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Nomenclature

A_P	Heat transfer area per volume unit (m^{-1})
B	Magnetic field (T)
$B_J(\chi)$	Brillouin function
COP	Coefficient of performance
C_P	Specific heat (J/kg.K)
D	Diameter (m)
G	Landé factor
h_{cv}	Heat transfer coefficient (W/m^2K)
J	Total angular momentum quantum number
K	Boltzmann constant (J/kg)
M	Specific magnetization (J/T.kg))
MCE	Magnetocaloric effect (K)
N	Number of spins per unit mass (kg^{-1})
Q	Heat rate (W)
T	Temperature (K)
T	Time (s)
S	Specific entropy (J/kg.K)
U	Average velocity at the inlet of bed (m/s)
V_AMR	Volume of magnetic material (liter or m^3)
W	Work rate (W)
X	Space variable (m)

Greek letters

ρ	Density (kg/m^3)
λ	Thermal conductivity (W/m.K)
ε	Bed porosity
μ_B	Bohr magneton (J/T)
γ	Sommerfeld constant ($J/kg.K^2$)
τ	Time period of fluid flow (s)
θ_C	Curie temperature (K)
θ_D	Debye temperature (K)

Subscripts

C	Cold-temperature reservoir
CB	Cold blow
Dem	Demagnetization
E	Electronic
Rej	Rejected
F	Fluid
H	High-temperature reservoir
HB	Hot blow
L	Lattice
Liq	Liquefaction
M	Magnetic
Mag	Magnetization
P	particul
S	Solid
St i	Stage i

energy through cooling loops and at the pre-compression of the gas [4] and [5]. The use of new refrigeration technology, more efficient and operating at low pressure like magnetic refrigeration, becomes necessary to reduce costs and risks associated with its handling [6].

The liquefaction of hydrogen by magnetic refrigeration is based on the magnetocaloric effect (MCE) which occurs in some materials when they are subjected to external magnetic field changes. The MCE is defined as the change of material temperature when applying or removing the magnetic field (magnetization/demagnetization process) [7]. In fact, if a magnetic material is placed in a magnetic field, there is usually an increase in its temperature. Conversely, demagnetization process has a cooling effect on it, as for the compression and expansion of gas [8]. Liquefaction could be carried out by cooling the gas through a thermomagnetic cycle, known as AMR cycle.

Indeed, the research interest on magnetic refrigeration as a new cooling technology began in 1976, when Brown [8] demonstrated the possible use of the magnetocaloric effect material to produce a noticeable cooling effect near room temperature. Later, the research works on magnetic refrigeration were increased substantially because of its potential of fulfilling cooling needs more efficiently than conventional systems without any negative side effect on the environment [9]. Primarily, the research interest has been focused on three areas: (i) thermal and thermodynamic analysis of magnetic refrigeration devices (namely AMR systems based cycles and development of experimental demonstrators, e.g. Ref. [10–15]), (ii) development of new magnetic working materials (e.g. Ref. [16–20]), and (iii) performance predictions and analysis of magnetic hydrogen liquefiers (e.g. Ref. [21–31]).

In order to show some explanation of magnetic refrigerator behaviors and how to predict their performance under various conditions, here some works related to thermodynamic analysis and thermal consideration are presented and discussed. From thermodynamic point of view, the ideal magnetocaloric effect behavior of AMR has been investigated by Smaili and Chahine [10]. Based on adiabatic magnetization temperature changes (magnetocaloric effect) and specific heat data of given magnetic materials, the authors proposed numerical approach to determine the optimum compositions of the resulting AMR. Zimm et al. [11] reported in their work experimental study on a rotary magnetic refrigerator designed and built by Astronautics Corporation of America. The device uses spherical particles of Gd and operates with a permanent magnet of 1.5 T. The authors presented and discussed performance of the device, based on experimental tests. Starting from the required AMR performance parameters, namely; cooling power and temperature profile, Bouchekara et al. [12] presented a study on the prediction and optimization processes of geometrical properties of the regenerator bed in an AMR cycle. Bouchard et al. [13] presented a transient three-dimensional model of a porous regenerator operating at room temperature. The model takes into consideration the porous character of the regenerator used for magnetic refrigeration and the coupled effects of the temperature and velocity fields. On the basis of experimental isofield heat capacities of working materials operating an Ericsson cycle, Diguet et al. [14] showed that the COP of composite refrigerant is almost equal to the COP of equivalent Carnot cycle, showing the interest for magnetic composite materials used as the working substance in a refrigeration cycle. Gomez et al. [15] presented a reciprocating magnetic refrigeration prototype using permanent magnets for operation at room temperature. The prototype can provide some test results with heat load applied on the cold heat exchanger and without thermal load.

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