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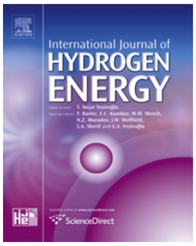

Performance predictions of a first stage magnetic hydrogen liquefier

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ABSTRACT

This work deals with the study of the first stage hydrogen magnetic liquefier operating through an active magnetic regenerator (AMR) cycle, over the temperature range: 298–233 K. For this purpose, an unsteady and one-dimensional numerical model has been developed for predicting the thermal performances of such a liquefier. The transient energy equations are considered to account for the heat transfer between magnetic refrigerant and hydrogen flowing throughout the regenerator bed. The gadolinium has been chosen as a constitute material for the regenerator bed. Simulation results including mainly the cooling capacity and the coefficient of performance (COP) of the AMR cycle as functions of the cycle frequency, the mass flow rate, and the applied magnetic field, are presented and discussed. The capability of the numerical model of predicting consistent results has been shown.

1. Introduction

Liquid hydrogen seems to be a promising medium for transporting and storing hydrogen economically. However, conventional gas liquefiers are considered, in general, inefficient and non-ecological systems; furthermore, they require high capital investment costs [1,2]. Therefore, the needs for developing more promising and environmental friendly gas liquefaction devices, especially for production of liquid hydrogen or liquefied natural gas, have prompted a renewed interest in the study of magnetic refrigeration (MR) technology [3–10]. Engineering and economic evaluations indicate that, in principle, MR with its promises of higher efficiencies and lower capital investment costs would create an immediate market niche and new opportunities. The concept of MR is based on the principle of the magnetocaloric effect (MCE) exhibited by some materials, when they are subjected to changes in external magnetic field (i.e. adiabatic magnetization/demagnetization processes of materials). The magnitude values of MCE are about 1–8 K per 1–2 T of magnetic field change for typical ferromagnets near their Curie temperature [11]. Hence large temperature-span magnetic systems (such as gas liquefaction devices) are based on regenerative thermodynamic cycles. Among the cycles that have been extensively studied and built in practical magnetic systems is the active magnetic regenerator (AMR) cycle [12,13].

In attempt to investigate and analyse the performance of AMR cycles, mainly two different classes of models and methodologies were suggested and published previously. The first ones are based on thermodynamic considerations (namely, second law analysis, exergy losses), as well as on design optimization and experimental considerations, for AMR cycles operating under steady-state conditions [10,14–18]. While, the seconds are based on transient energy conservation equations to account for heat transfer between

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Nomenclature

B	magnetic field, T
$B_J(\chi)$	Brillouin function
C	specific heat, J/kg K
COP	coefficient of performance
e	regenerator plate thickness, m
f	cycle frequency, Hz
g	Landé factor
h	coefficient of heat transfer, W/m^2 K
J	total angular momentum quantum number
k	thermal conductivity, W/m K
k_B	Boltzmann constant, 1.38×10^{-23} J/kg
L	regenerator length, m
l	fluid passage height, m
MCE	magnetocaloric effect, K
M_R	regenerator mass, kg
m_f	mass flow rate, kg/s
N	number of spin per unit mass, kg^{-1}
N_{cy}	number of cycle
n	number of atoms per unit mass, kg^{-1}
p	pressure, N/m^2
Q	heat rate, W
T	temperature, K
t	time, s
V	fluid velocity, m/s
x	spatial coordinate, m
W	work, W
w	regenerator wide, m

Greek letters

M	specific magnetization, J/T kg
μ_B	Bohr magneton, 9.27×10^{-24} J/T
γ	Sommerfeld constant, J/kg K^2
ρ	density, kg/m^3
τ	time duration of either cold or hot blow, s
θ_C	Curie temperature, K
θ_D	Debye temperature, K

Subscripts

cy	cycle
e	electronic
f	fluid
H	high-temperature reservoir
dmg	demagnetization
m	magnetic
mg	magnetization
L	low-temperature reservoir
l	lattice
R	regenerator

regenerator bed and circulating fluid, in order to perform the simulation of AMR cycle operating under typical unsteady conditions [12,19–23]. These latter appear thus to be the more convenient models, since they allow to handle most of practical design and physical parameters, and consequently predicting more accurately performances. However, such models still require considerable computation time, therefore they are one-dimensional analyses, furthermore, in certain others, some simplifications have been made, such as, neglecting axial thermal conductivity, assuming constant properties of the magnetic regenerator and heat transfer fluid (e.g. heat capacities, fluid density).

In this paper, we propose a numerical model belongs to the second class, but it takes into account most of the physical problems for AMR cycles; namely, the axial thermal conduction, the viscous dissipation effects of the fluid flow, the temperature dependence of the fluid properties, as well as the temperature and magnetic field dependence of the regenerator properties. The governing equations of the model have been derived for a typical reciprocating AMR design, with parallel flat plates as a geometrical configuration of the regenerator bed. The transient energy equations are considered to account for the heat transfer between the magnetic refrigerant and the flowing fluid throughout the bed. To solve the resulting mathematical model, a computer program based on the implicit finite difference method [24] has been developed.

This work is focused on thermal analysis of a first stage hydrogen AMR liquefier operating over the temperature range: 298–233 K. The gadolinium has been chosen as a constitute material for the regenerator bed. The required magnetic and thermal properties of regenerator have been determined using the molecular field theory, as well as the Debye and Sommerfeld models [25]. Simulation results including mainly the cooling capacity and the coefficient of performance (COP) of the AMR cycle as functions of the cycle frequency, the mass flow rate, and the applied magnetic field, are presented and discussed. The capability of the numerical model of predicting consistent results has been shown.

2. Description of the first stage hydrogen AMR liquefier cycle

Practical hydrogen liquefiers operate on large temperature-span (i.e. typically from 300 K to 20 K, at atmospheric pressure), thereby, from practical point of view, a number of cascade cycles are required. That is to have the liquefaction process in stages (i.e. to use two or more AMR cycles that operate in series). This work deals with the study of the first stage of the hydrogen AMR liquefier cycle. The principle of operation of such an AMR cycle is thus described here.

Fig. 1 shows a schematic of the first stage hydrogen AMR liquefier, which is constituted primarily of (i) an AMR bed (i.e. solid magnetic material which can act as refrigerant and regenerator media), (ii) a circulating fluid (i.e. in this study, gas to be liquefied, hydrogen), and (iii) a blower to force the flow throughout the regenerator at a convenient velocity. Unlike conventional mechanical-cycles, AMR cycle involves complex thermodynamic interactions between the fluid and the magnetic regenerator. The AMR cycle consists of four processes, namely, magnetization and demagnetization steps, by application and removal of a magnetic field (through adiabatic or isothermal steps; in this study, only adiabatic steps are considered), as well as cold and hot blows (i.e. cooling and heating the circulating fluid). During the adiabatic