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Research articles

Passive force balancing of an active magnetic regenerative liquefier

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ABSTRACT

Active magnetic regenerators (AMR) have the potential for high efficiency cryogen liquefaction. One active magnetic regenerative liquefier (AMRL) configuration consists of dual magnetocaloric regenerators that reciprocate in a persistent-mode superconducting solenoid. Issues with this configuration are the spatial and temporal magnetization gradients that induce large magnetic forces and winding currents. To solve the coupled problem, we present a force minimization approach using passive magnetic material to balance a dual-regenerator AMR. A magnetostatic model is developed and simulated force waveforms are compared with experimental measurements. A genetic algorithm identifies force-minimizing passive structures with virtually ideal balancing characteristics. Implementation details are investigated which affirm the potential of the proposed methodology.

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1. Introduction

Although hydrogen (H^2) has a gravimetric energy density several times greater than common fossil fuels such as gasoline or diesel, the low volumetric energy density of gaseous hydrogen has motivated research efforts on liquid hydrogen [1] and liquefaction technologies [2]. The low process efficiency of state-of-the-art liquefiers coupled with the added expense of long-distance transport in cryogenic tankers significantly raise the cost of liquid hydrogen at distributed refueling stations.

The active magnetic regenerator (AMR) uses a magnetocaloric material (MCM) as the matrix media in a thermal regenerator [3], and shows promise for high efficiency distributed cryogen liquefaction [4]. In an AMR, each differential regenerator section undergoes an independent Brayton refrigeration cycle consisting of: (1) adiabatic magnetization, (2) isofield heat rejection, (3) adiabatic demagnetization and (4) isofield heat absorption. In operation, warm fluid is pumped to the hot end at T_H where heat is released and cold fluid is pumped to the cold end at T_C where heat is absorbed.

Room temperature AMR devices using permanent magnets have demonstrated commercially relevant cooling powers [5], efficiencies [6] and temperature spans [7]; however, costs must be reduced for market penetration [8,9]. While room temperature AMR devices are an active area of research, active magnetic regenerative liquefiers (AMRL's) are less mature and only a small number of cryogenic devices using superconducting magnets (SC) have been reported. Zimm et al. (1996) [10] measured a 35 K temperature span while rejecting heat to liquid nitrogen (LN2). Rowe and Tura (2006) [11] measured a 50 K temperature span from room temperature using a three material regenerator, and the device was later modified for cryogenic testing [12]. The layered experiments were investigated in subsequent analytic and numerical works [13–15]. Kim et al. (2013) [16] presented a no-load cold temperature of 24 K while rejecting heat to LN2 using 83 grams of magnetocaloric material. The AMRL was recently retrofitted with a GdBCO high temperature superconducting solenoid [17]. The device was numerically investigated and an optimized layering composition was proposed [18]. While the temperature spans reported by Kim et al. [16] approached the domain of a hydrogen liquefier, larger devices are required to provide commercially relevant capacities.

Barclay et al. (2016) [19] and Holladay et al. (2017) [20] described a large-scale AMRL with an ultimate goal of hydrogen liquefaction from room temperature. While a temperature span of 100 K was reported with 2.1 kg of a single magnetocaloric material, the varying permeability in the solenoid core induced an electromotive force across the copper superconducting stabilizer. This ultimately heated the superconducting winding towards

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Nomenclature

Roman

A	area [m^2]
B	magnetic flux density [T]
F	force [N]
H	magnetic field strength [$A\,m^{-1}$]
I	solenoid winding current [A]
j	current density [$A\,m^{-2}$]
M	magnetization [$A\,m^{-1}$]
$\dot{Q}$	heat transfer [W]
r	radius [m]
t	time [s]
$\overleftrightarrow{T}$	Maxwell electromagnetic stress tensor [$N\,m^{-2}$]
T	temperature [K]
V	volume [m^3]
z	spatial coordinate along solenoidal axis

Greek

δ_{ij}	Kronecker delta [–]
Γ	geometric factor [–]
μ_0	Permeability of free space [H/m]
ρ	density [$kg\,m^{-3}$]
ρ_e	electrical resistivity [Ωm]
σ	specific magnetization [$A\,m^2\,kg^{-1}$]

Subscripts and superscripts

C	cold reservoir or cold side
coil	superconducting magnet winding
Curie	magnetic ordering temperature
Eddy	Eddy current
H	hot reservoir or hot side
m	middle passive structure
magnet	position of AMR relative to magnet
o	outer passive structure

the critical temperature, limiting the applied field strength to 3.3 T. The magnet heating was found to increase with regenerator mass, applied field strength and operating frequency.

Improved cooling capacities require increased regenerator mass which, to avoid a magnet quench, decreases the magnetic field strength and consequentially the cooling capacity; a challenge with reciprocating AMRL configurations. The magnetic field from the coupled regenerator-solenoid system must be explored to reduce spatial and temporal magnetization gradients. Barclay et al. (1986) [21] simulated force waveforms for reciprocating and rotary configurations. Rowe and Barclay (2002) [22] used the centerline field of a static, air-bored solenoid simulation to evaluate magnetization and magnetic forces. An optimization routine found a flywheel configuration minimizing the cycle RMS torque accounting for magnetic, pumping and inertial loads. While forces were balanced at the drive input, a flywheel does not resolve the magnetization gradients and coupled magnet heating problem.

Peksoy and Rowe (2005) [23] later performed magnetostatic field simulations to investigate the variation of magnetization in a single and two-material AMR. Rowe and Tura (2008) [24] continued this work by investigating ferromagnetic shims to concentrate magnetic field lines in the regenerator, demonstrating that the influence of magnetic material on the magnetic field distribution can be both the detrimental and beneficial. Recently, Mira et al. (2017) [25] solved the magnetostatics problem to investigate demagnetization in gadolinium (Gd) regenerators.

Arnold et al. (2011) [26] reported experimental measurements of the mechanical, eddy and magnetic work in a reciprocating AMR device. Although large forces were present, it was found that the thermodynamic cycle work was on the order of the experimental uncertainty. This emphasized that while *regenerator* efficiencies can be high, *device* efficiencies may be heavily penalized without force balancing.

While Peksoy and Rowe (2005) [23] and Mira et al. (2017) [25] solved the magnetostatics problem, several works have investigated magnetic forces with a simplified treatment of the magnetic field distribution (i.e. $\vec{B} = \mu_0\vec{H}$). Kamiya et al. (2006) [27] analyzed the force waveform of a reciprocating AMR with two gadolinium doped dysprosium aluminum garnet regenerators using a similar methodology as Rowe and Barclay (2002) [22]. The authors reported a 60 % force reduction using magnetic material between regenerators. Allab et al. (2006) [28] simulated the magnetic force on a Gd sample as a function of the local magnetic field strength, and presented force waveforms for a magnetized and demagnetized regenerator. Balli et al. (2011) [29] and Gama et al. (2016) [30] compared experiments and simulations of the force on magnetic material using a similar formulation.

In the present work, a 2-D, axisymmetric magnetostatic model is developed to study the interaction of a multilayered AMR and superconducting magnetic field generator. Magnetic forces are analyzed and compared with experiments on the AMR device described by Barclay et al. (2016) [19] and Holladay et al. (2017) [20]. A passive, soft ferromagnetic structure is proposed to balance both spatial and temporal magnetization gradients in an effort to simultaneously address the force balancing and magnet heating problems impeding AMRL development. An optimization is formulated to find passive geometries minimizing the force waveform of a dual regenerator assembly. The optimized force waveform is discussed and implementation details such as solution sensitivity and field distribution are investigated.

2. Methodology

2.1. AMR configuration

Passive force balancing is investigated on the AMR configuration shown in Fig. 1 [19,20]. A persistent-mode, conduction-cooled NbTi Cryomagnetics 70–650-010CF superconducting solenoid is used to generate the magnetic field for two regenerators mounted axially opposite to each other onto a common cold heat exchanger (CHEX). The solenoid consists of two composite windings with the properties listed in Table 1.

Each regenerator contains eight layers of magnetocaloric material which are summarized in Table 2 and shown in Fig. 3. The layers consist of rare-earth gadolinium and gadolinium alloys with yttrium, terbium, erbium, dysprosium and holmium with compositions selected for a respective Curie temperature spacing of 20 K per layer. Spherical particles of each refrigerant are prepared by AMES using a rotating disk apparatus [20] and packed into monolithic regenerators with an approximate porosity of 0.36 and mean particle size of 225 μm.

A linear actuator drives the regenerator assembly with constant velocity, as shown in Fig. 1, and a second actuator drives a double-acting piston displacing 2520 cm_3 of pressurized Helium. The two