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Investigation of bypass fluid flow in an active magnetic regenerative liquefier

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ABSTRACT

Active magnetic regenerators (AMR) with second order magnetocaloric materials operating below the Curie temperature have a unique property where the magnetized specific heat is lower than the demagnetized specific heat. The associated thermal mass imbalance allows a fraction of heat transfer fluid in the cold heat exchanger to bypass the magnetized regenerator. This cold bypassed fluid can precool a process stream as it returns to the hot side, thereby increasing the efficiency of liquefaction and reducing the cost of liquid cryogens. In the present work, the net cooling power of an active magnetic regenerative liquefier is investigated as a function of the bypass flow fraction. Experiments are performed at a fixed temperature span yielding a 30% improvement in net cooling power, affirming the potential of bypass flow in active magnetic regenerative liquefiers.

1. Introduction

Liquid cryogens are an excellent method of storage, transport, and delivery of industrial gases and cryofuels such as LNG and LH2. Existing gas-cycle liquefaction plants with metric tons per day capacity for LNG are primarily based on the mixed refrigerant or reverse turbo-Brayton cycles. Similarly, existing LH2 plants are primarily based on the LN2 precooled Claude cycle. These plants have efficiency figures of merit (FOM) in the range of 20–35% [1,2]. A number of systems have recently been proposed with simulated exergetic efficiencies exceeding 50% [3–6], however these have not been demonstrated to date. The energy consumption of present liquefaction plants is a significant cost component in the price of cryogens, and techniques such as active magnetic regenerative liquefaction with the potential to increase FOMs to much higher values, e.g., 60% [7], are of great interest.

In an active magnetic regenerative liquefier (AMRL) [8], one or more ferromagnetic refrigerants with sequentially lower Curie temperatures below room temperature are layered into compact, porous, high-performance regenerators. When these regenerators are cycled through high to low applied magnetic fields with a sequence of reversing heat transfer fluid, the different magnetic layers execute cascaded magnetic Brayton cycles producing temperature spans several times the adiabatic temperature change (ΔT_{ad}) of each refrigerant. In addition, features such as the use of environmentally benign solid refrigerants rather than gaseous refrigerants, use of superconducting (SC) magnets to change refrigerant entropy instead of gas compressors and use of highly effective thermal regenerators combine to offer efficient, compact and environmentally friendly designs. For cryogenic liquefiers with external process streams that must be cooled and eventually liquefied, an AMRL has a unique thermodynamic feature of bypass fluid flow that has the potential to improve the FOM over conventional gas-cycle liquefiers.

The concept of bypass fluid flow in an AMRL originates from a ferromagnetic refrigerants thermomagnetic properties below its Curie temperature [9–12]. Fig. 1 shows the heat capacity of gadolinium as a function of temperature and applied magnetic induction near its Curie temperature of 293 K. Over the 30–40 K span below the Curie temperature, the magnetic heat capacity is approximately 10% larger when demagnetized than when magnetized to 6 T. If the symmetry (σ) of a thermal regenerator is defined as the ratio of low to high field specific heat:

$$\sigma = \frac{c_s(T,B_L)}{c_s(T+\Delta T_{ad},B_H)} \tag{1}$$

the symmetry changes from $\sigma > 1$ to $\sigma < 1$ at the Curie temperature. This has important implications for the selection of operating

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Nomenclature

Roman

B	magnetic flux density [T]
c	specific heat [J kg^{-1} K^{-1}]
h	enthalpy [J kg^{-1}]
HTF	heat transfer fluid subsystem
m	mass [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
$\dot{Q}$	cooling capacity [W]
P	pressure [Pa]
T	temperature [K]

Greek

β_{bypass}	bypass flow fraction [–]
Φ	utilization [–]
σ	regenerator symmetry [–]
τ_{blow}	period of regenerative blow [s]

Subscripts and superscripts

ad	adiabatic
bypass	bypass stream
C	cold reservoir or cold side
d	displaced
f	fluid
H	hot reservoir or high field
L	low field
p	constant pressure
s	solid
span	regenerator temperature span

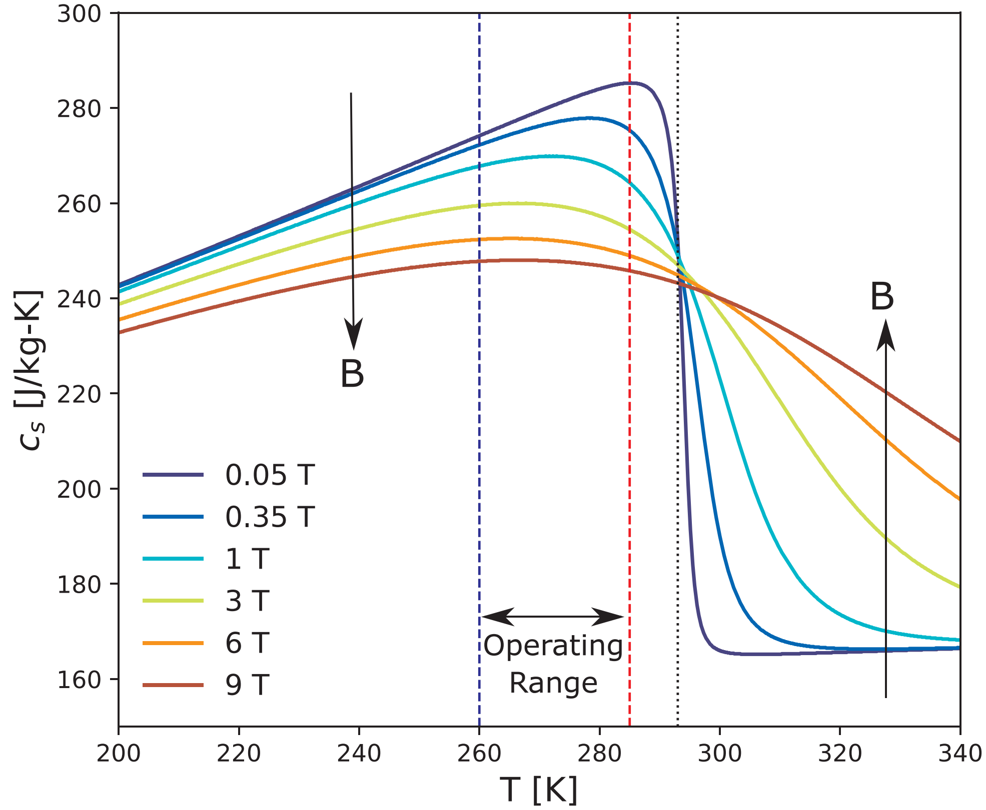

Fig. 1. Specific heat of gadolinium as a function of temperature and applied field, generated with molecular mean field theory (MFT). Similar behaviour is observed in cryogenic refrigerants [9,11].

temperatures for an AMRL stage or layer.

An AMRL stage or layer operating below the magnetic ordering temperature (e.g. $T_H = 285$ K and $T_C = 260$ K for a Curie temperature of 293 K as indicated in Fig. 1) can exploit this feature as the low field thermal mass (mc) is greater than the high field thermal mass ($\sigma > 1$). Consider the utilization (Φ), defined as the ratio of fluid to solid thermal mass:

$$\Phi = \frac{m_d c_p}{m_s c_s(T,B)} \tag{2}$$

where m_d is the displaced fluid mass in a regenerative blow and c_s is a function of temperature and field. This difference in solid thermal mass allows more heat transfer fluid to be displaced in the low-field blow (hot-to-cold) than the high-field blow (cold-to-hot). The resulting flow imbalance allows several percent of the cold heat transfer fluid to bypass the magnetized regenerator. With a perfect heat exchanger, this bypassed fluid can cool a process stream initially at T_H to the cold temperature of the stage before returning to the heat transfer fluid subsystem, illustrated in Fig. 2. This minimizes the large irreversible entropy production from heat transfer across excessive temperature approaches in discrete process HEXs [13] found in most conventional gas-cycle liquefiers.

DeGregoria et al. [15,16] first recognized thermal mass differences in magnetic refrigerants could improve AMRL efficiency by creating a bypass stream of cold heat transfer gas. The authors analyzed and designed an AMRL operating between 77 K (LN2) and 20 K (LH2). The design consisted of two reciprocating superconducting magnets around dual, stationary regenerators and had an estimated combined FOM of