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Thermodynamic optimization of reverse Brayton cycles of different configurations for cryogenic applications

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ABSTRACT

The thermodynamic optimization of differing Reverse Brayton Refrigeration (RBR) cycle configurations is presented in this study. These cycle configurations include: Conventional 1-stage compression cycle; Conventional 2-stage compression cycle; 1-stage compression Modified cycle with intermediate cooling of the recuperator using an auxiliary cooler; and an Integrated 2-stage expansion RBR cycle. For high pressure ratio applications, multi-stage compressors with intercooling are considered. Analytical solutions for the conventional cycles are developed including thermal and fluid flow irreversibilities of the recuperators and all heat exchangers in addition to the compression and expansion processes. Exergy analysis is performed and the exergy destruction of different components of the RBR cycles for different configurations is presented and the effects of important system parameters on performance are investigated. Thermodynamic optimization of the cycles with intermediate cooling of the recuperator is included. Effects of the 2nd law/exergy efficiency of the auxiliary cooler on the total system efficiencies are presented.

Optimisation thermodynamique des cycles de Brayton inversés de plusieurs configurations pour les applications cryogéniques

Mots clés : cycle frigorifique de Brayton inversé ; cryorefroidisseur ; refroidissement auxiliaire ; analyse selon le deuxième principe ; exergie

1. Introduction

RBR cycles offer several advantages over alternative cycle configurations for cryogenic application, including simplicity, a control on vibrations due to few moving parts and through specialized compressors and expanders, and the potential to partially recover the shaft power expended by the gas turbo-expander to increase cycle efficiency. RBR cooling systems for space applications are generally low power, through-put and compression cycles that rely on cooling load discharge to space through radiators. Potential terrestrial applications for RBR cycles include liquefaction of natural gas (LNG) for off-

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Nomenclature

A	Heat transfer area, m^2
$\dot{C}$	Heat capacity flow rate, WK^{-1}
COP	Coefficient of Performance
C_p	Specific heat, $Jgmol^{-1} K^{-1}$
$\dot{E}$	Exergy rate, W
$\dot{m}$	Molar/Mass flow rate, $gmol\ sec^{-1}$
NTU	Number of heat transfer units
p	Pressure, Pa
$\dot{Q}$	Heat transfer rate, W
T	Temperature, °C, K
U	Heat transfer coefficient, $Wm^{-2} K^{-1}$
$\dot{W}$	Shaft power, W
y	Stream split fraction
Z	Equipment Fractional Pressure Loss

Greek symbols

γ	Specific heat capacity ratio
Δ	Difference
ε	Heat exchanger effectiveness
η	Efficiency
λ	Heat exchanger ineffectiveness
σ	Compressor/Expander pressure ratio

Subscripts

AC	aftercooler
amb	Ambient
AUX	Auxiliary cooler
C,C1,C2	Compressor (stages)
CB	Cold box
cycle	RBR cycle
E	Expander
ex	Exergy
fuel	Fuel (input) exergy
IE	Intermediate expander
IC	Intercooler
n	Normalized
NET	Considering expander recovery
product	Product exergy
R,R1,R2	Recuperator(s)
RC	Recuperator cold side
RW	Recuperator warm side
SYS	Modified RBR system
TR	Expander recovery
WF	Working fluid

and on-shore operations, high-temperature superconductivity (HTS), medical procedures, chemical processing and hydrogen liquefaction for vehicle fuels and fuel cell technologies. Terrestrial cryogenic applications require higher system capacities, allow use of higher system operating pressures, higher compression ratios and multi-stage compression to improve system performance and efficiency, and have access to several ambient options for discharge of the heat of compression and cooling load power.

Recent articles describe the theoretical, laboratory and practical investigations completed and presently underway associated with RBR systems. The primary emphasis for these cycles has focused on small-scale applications for space (Kirkconnell et al., 2006; Nieuwkoop et al., 2009; Swift et al., 2002; Swift et al., 2003; Zagarola et al., 2003; Zagarola and McCormick, 2006), HTS (Gromoll, 2004; Hou et al., 2006; Park et al., 2005; Radebaugh, 2004; Hirai et al., 2009; Yoshida et al., 2010), and LNG (Skjeggedal et al., 2010) applications. Variants to the conventional RBR cycle have been proposed utilizing two/split recuperators, intermediate cooling and two integrated expanders for space and HTS applications (Swift et al., 2002; Zagarola et al., 2003; Yoshida et al., 2010). Modified RBR cycle configurations utilizing an auxiliary cooler or pre-cooler between two/split recuperators comprising a "cascade"-like system have also been described (Hou et al., 2006; Hirai et al., 2009; Nieczkoski, 2003; Nieczkoski and Mohling, 2004).

The purpose of this paper is to mathematically model and evaluate thermodynamic (2nd law) and exergetic performance of RBR cycle configurations for cryogenic cooling applications. Exergy and 2nd law analyses are well-established methods for evaluating the performance of refrigeration systems (Bejan et al., 1996). Recent exergy efficiency/optimization analyses of ideal gas RBR cycles have been presented previously by Chen and Su (2005), Tu, et al. (2006a), and Tu et al. (2006b). Non-isentropic compression and expansion were typically the only non-ideal cycle parameters considered in these analyses. RBR cycle modeling within this study incorporate 'real-world' inefficiencies that contribute to reduced 2nd law and exergetic performance, including the effectiveness of the intercooler, aftercooler, auxiliary cooler, recuperator(s) and cold box heat exchangers, and pressure losses of the working fluid through cycle equipment. Two-stage compression with intercooling and partial recovery of the induced gas turbo-expander shaft power have also been considered as mechanisms to improving cycle 2nd law and exergetic efficiency.

2. Analytical solutions

The RBR cycles and associated generalized temperature – entropy (T-s) diagrams investigated in this paper are shown in Figs. 1–4. The conventional 1-stage compression RBR cycle configuration depicted in Fig. 1(a) is relatively simple, relying on a balanced counter-flow recuperator heat exchanger. The thermodynamic and exergetic performance of the conventional RBR cycle can be enhanced for the same available cold box cooling power by replacing the single-stage compressor with two or more stages, and discharging the heat of compression between the stages to the ambient environment (T_{amb}) as depicted in Fig. 2. Multiple-stage compression with effective inter-stage cooling offers the opportunity to reduce the overall post-compression cooling load demand and decrease the associated irreversibilities, thus improving cycle efficiencies when compared to the conventional 1-stage compression RBR cycle.