Energy 160 (2018) 520–535

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimization and thermodynamic analysis of supercritical CO_2 Brayton recompression cycle for various small modular reactors

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A R T I C L E I N F O

Article history:
Received 4 February 2018
Received in revised form
21 June 2018
Accepted 23 June 2018
Available online 26 June 2018

Keywords:
Supercritical carbon dioxide (S-CO_2)
Brayton cycle
Cycle optimization
Small modular reactor (SMR)
Printed circuit heat exchanger (PCHE)
Turbomachinery

A B S T R A C T

This paper presents optimization of a supercritical carbon dioxide Brayton cycle for three types of 300-MWth small modular reactors (SMRs); a pressurized water reactor (PWR), a sodium-cooled fast reactor (SFR) and a high-temperature gas-cooled reactor (HTGR). The parameters of the pressure ratio and the flow split fraction were examined for sensitivity analysis and optimization of cycle. The optimized cycle efficiencies of PWR, SFR, and HTGR were 30.6%, 46.38%, and 50.04%, respectively. Key components, i.e. turbomachinery and heat exchangers for the SMRs were designed to develop the optimized cycles. The cycle thermal efficiency was improved by using investigating the effects of the channel shape (zigzag, s-shape, airfoil fin) of the printed circuit heat exchangers (PCHEs) on the pressure drop. The study indicated that using airfoil fin type PCHE may increase the cycle thermal efficiency by about 1.0% in comparison with zigzag type PCHE. The effect of turbomachinery efficiencies on the cycle thermal efficiency were investigated.

1. Introduction

The supercritical carbon dioxide (S-CO_2) Brayton cycle has high thermal efficiency, simple cycle layout, compactness of component and wide operation range [1]. These advantages are the results of the high density and low compressibility of CO_2 near its critical point (304.13 K, 7.38 MPa) due to wide and rapid variation in the thermodynamic properties [1]. Because of these advantages, the S-CO_2 Brayton cycle has been evaluated as a power conversion system for numerous applications, including nuclear, geo-thermal, solar, and thermal power plants. Also, based on advantages, the S-CO_2 Brayton cycle can achieve higher thermal efficiency and smaller cycle layout than the conventional steam Rankine cycle. Therefore, S-CO_2 Brayton cycle can be a good alternative to steam Rankine cycle.

Research effort to find alternative methods of generating electricity has been discussed during the 60's. In 1967, simple regenerative cycle layout was proposed by Feher, during find the application of the supercritical fluid cycle [2]. Several cycle layouts can be proposed and one of the most detailed investigation on that topic have been conducted by Angelino in 1968 [3]. Angelino thus stated that the recompression cycle is suitable for high temperature nuclear heat sources [3]. Also, Dostal et al. evaluated the S-CO_2 Brayton cycle for advanced nuclear reactors for power generation application using the basic thermodynamic approach [1].

Recently, the S-CO_2 Brayton cycle is being studied for various applications; such as nuclear power plants, solar concentration plants, waste heat recovery systems, coal-fired plants and so on. Many studies have been conducted to apply the S-CO_2 Brayton cycle to nuclear reactors, such as Sodium cooled Fast Reactors (SFRs), fusion reactors, and Small Modular Reactors (SMRs). A comparison between steam, helium and CO_2 cycles for prototype fusion power reactors has been conducted, and the S-CO_2 Brayton cycle is recommended because of its efficiency and small size [4]. Also, energetic and exergetic analyses have been conducted for a recompression S-CO_2 Brayton cycle to optimize the effect of various operating and design parameters on the cycle's efficiency in nuclear applications [5]. The S-CO_2 Brayton cycle for SMRs with recompression cycle have been studied [6]. Previous research concluded that S-CO_2 Brayton cycles are a viable alternative option [7]. The S-CO_2 Brayton cycle has become one of the most promising thermodynamic cycle for SFRs [8]. Cycle optimization of the S-CO_2 system was conducted for SFRs [9,10]. The study of the off-design behaviour of the S-CO_2 recompression cycle in increasing heat

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https://doi.org/10.1016/j.energy.2018.06.155
0360-5442/