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

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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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sink temperature was investigated for power conversion system of SFRs [11]. The S-CO_2-based mixture Brayton cycle were investigated to use as a power conversion system of SFRs [12]. The reactor outlet temperature and the effects of the critical temperature of different CO_2-based gas mixtures on cycle efficiency are studied and optimized [13].

To investigate advanced Brayton cycles that use a supercritical fluid, the Sandia National Laboratory has built a carbon dioxide experimental loop [14]. The Korea research team conducted experimental investigation and established a transient model for the S-CO_2 cycle, and used experimental data to conduct transient analysis of the S-CO_2 Brayton cycle [15]. Also, many studies have been performed to assess the S-CO_2 Brayton cycle for solar applications. The S-CO_2 Brayton cycle was coupled with a concentration solar power (CSP) as a power conversion system [16–25]. To investigate the effects of transient nature of solar energy on S-CO_2 cycle efficiency, transient model for S-CO_2 cycle was developed using experimental data [19,25]. The authors compared different S-CO_2 Brayton cycles integrated with a solar power tower, and concluded that the recompression cycle reached the highest thermal efficiency and the highest net power output at peak hours [20]. A thermodynamic assessment of the S-CO_2 cycle for the CSP has been performed [20–24].

Various studies of the S-CO_2 Brayton cycle have been conducted with various heat sources. An S-CO_2 bottoming power cycle in conjunction with a topping cycle of landfill gas with nine different cycles was compared; to increase the thermal efficiency and the net produced work, the recuperation process is much more important than the intercooling process in the S-CO_2 cycle design [26]. Thermodynamic analysis of a high-efficiency coal-fired power plant with CO_2 capture using S-CO_2 Brayton cycle and realistic industrial modeling were conducted [27,28]. The trans-critical CO_2 (tCO_2) power cycle was also studied [29]. Thermodynamic analysis of a 600 MW_{th} power cycle with Brayton recompression cycle layout used two simulation tools to model the recompression system studied [30]. A combined cogeneration cycle in which the waste heat from a recompression S-CO_2 Brayton cycle is recovered by a tCO_2 cycle generating electricity was investigated by using exergy based cycle analysis [31–33].

Previous researchers have worked on various applications of the S-CO_2 Brayton cycle. Numerous S-CO_2 cycle layouts have been proposed and compared to attain improvement of cycle efficiency with the optimal layout for SFRs, fusion reactors, CSPs [9,34,35]. The recompression cycle was the most efficient [9]. The recompression with main compression intercooling (MCIC) for solar central receivers had the best thermal and exergetic efficiency among all the studied cycle layouts [36,37]. Several cycle layouts were analyzed and a 'combined' cycle composed of recompression, reheating and intercooling was the efficient cycle, to develop operational strategies for S-CO_2 Brayton cycle to adapt to fluctuations in solar energy [38]. Thermodynamic analysis and optimization of a molten salt solar power tower integrated with an S-CO_2 Brayton recompression cycle was performed based on integrated modeling [39]. Previous research demonstrated that three plant layouts are the most promising for power conversion system: the recompression cycle, recompression partial cooling, and recompression with MCIC; their ability to achieve high efficiency was demonstrated.

Currently, the recompression cycle layout is widely-used in S-CO_2 Brayton cycle because it has a high thermal efficiency and simple layout. The S-CO_2 Brayton recompression cycle is expected to be promising layout among the various cycle layout due to its simplicity, high efficiency and cost. Therefore, in this paper the recompression cycle was selected as a layout of S-CO_2 Brayton cycle.

In spite of that several previous research have been already considered the use of S-CO_2 Brayton cycle as a power conversion system and its optimization have been already conducted, this paper is proposing an optimization of the S-CO_2 Brayton recompression cycle for the power conversion system of three types of 300-MWth SMR systems; a pressurized water reactor (PWR), a sodium-cooled fast reactor (SFR), and a high-temperature gas-cooled reactor (HTGR). Temperature conditions were adopted to couple the S-CO_2 Brayton cycle with the PWR with turbine inlet temperature (TIT) = 583.15 K, the SFR with TIT = 823.15 K, and the HTGR with TIT = 923.15 K. To conduct the optimization and sensitivity analysis of the cycle, a thermodynamic model was developed in FORTRAN. Sensitivity analyses were conducted to optimize pressure ratio (PR) and flow split fraction (FSF) for the three turbine inlet conditions. The cycle and design of heat exchanger and turbomachinery were optimized to assess the viability of the proposed system. Moreover, due to characteristics of supercritical fluid, difficulties on S-CO_2 Brayton cycle turbomachinery design and manufacturing is exist. Therefore, attaining of high efficiency of the turbomachinery is difficult and these difficult affected to cycle thermal efficiency on S-CO_2 Brayton cycle. Thus, the impact of efficiencies of components on cycle thermal efficiency also will be addressed. The pressure drop of heat exchanger is different according to channel shape of heat exchangers. These difference can be affected to cycle thermal efficiency. Thus, the investigations of the effect of the type of printed-circuit heat exchanger (PCHE) channel on the cycle thermal efficiency were conducted.

2. Mathematical analysis model of S-CO_2 Brayton recompression cycle

The recompression cycle (Figs. 1 and 2) is composed of a main compressor, a recompression compressor, a turbine, a low-temperature recuperator (LTR), a high-temperature recuperator (HTR), and a precooler; thermodynamic processes occur at state points in the cycle.

Two recuperators minimize the heat that is wasted after the turbine stage. The precooler is set to achieve thermodynamic conditions of the main compressor inlet. This cycle uses a flow split in front of the precooler to allow some of the CO_2 to bypass the cooling process and to be recompressed. The FSF affects the efficiency of the system.

A thermodynamic analysis model, Recompression Cycle Analysis Model (RCAM) (Fig. 3) was developed in FORTRAN, and the thermodynamic properties of CO_2 were obtained directly using NIST REFPROP [40]. RCAM is composed of five subroutines: RECOMP, COMPRESSOR, TURBINE, HXcal, and PROPERTY. Each subroutine calculates an outlet condition of temperature, pressure, enthalpy, entropy and density. RECOMP is the main subroutine. Based on input data, the pressure of the cycle is calculated. We assumed the isentropic efficiency of turbomachinery for design point cycle analysis. To conduct cycle analysis, a turbomachinery-specific design was not defined—only the isentropic efficiency of the turbomachinery was defined.

$$\eta_{\text{comp}} = \frac{W_{comp,s}}{W_{comp}} = \frac{h_{in} - h_{out,\,s}}{h_{in} - h_{out}}. \tag{1}$$

$$\eta_{\text{turb}} = \frac{W_{turb}}{W_{turb,s}} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}}. \tag{2}$$

Thus, the calculation process for the turbomachinery was simplified. Therefore, we use isentropic efficiency to calculate the real expansion and compression process. Subroutines COMPRESSOR and TURBINE use calculation of non-isentropic efficiency process to calculate the turbomachinery outlet condition as