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Optimization and sensitivity analysis of the nitrogen Brayton cycle as a power conversion system for a sodium-cooled fast reactor

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ABSTRACT

The sodium-cooled fast reactor (SFR) is a promising next generation reactor type. Existing prototype generation IV nuclear reactors use a steam Rankine cycle for power conversion. However, the reaction between sodium and water presents a major safety issue in the development of SFR. In this aspect, the nitrogen Brayton cycle can be a suitable alternative to the conventional steam Rankine cycle for SFR. Compared to the steam Rankine cycle, the nitrogen Brayton cycle is relatively simple; further, nitrogen does not react with sodium due to its chemically inert feature. Therefore, a nitrogen Brayton cycle coupled with SFR can be a good combination. In this work, the nitrogen Brayton cycle for KALIMER-600 has been studied. In addition, sensitivity analysis, optimization of the cycle, and the preliminary design of components were performed. Mathematical models for conducting sensitivity analysis of the cycles were developed using FORTRAN. Sensitivity studies were carried out by varying the cycle maximum temperature, turbine inlet pressure, and pressure ratio. The optimized results showed that the cycle efficiency is 38.26%. The preliminary design of components was performed to assess the viability of the proposed system. In order to improve cycle thermal efficiency, sensitivity studies of heat exchanger was performed to understand the effects of printed circuit heat exchanger (PCHE) channel shape. The analysis results show that a significant improvement in cycle efficiency (improve 1.3%) was obtained by changing the PCHE channel shape.

1. Introduction

Generation IV nuclear reactors (Gen IV reactors) are being actively studied to achieve higher thermal efficiency and improve safety, and consequently. The design objectives for a Gen-IV reactor are sustainability, enhanced safety, competitive economics, and proliferation resistance [Hahn et al., 2007]. Among the Gen IV reactors, the sodium-cooled fast reactor (SFR) is a promising future reactor design. The SFR is advantageous in that it is a long cycle fast reactor that requires lower capital/operation costs, has a low proliferation risk, and can reuse the spent fuel from past reactors [Kim and Taiwo, 2010; Kim et al., 2012].

Initially, SFRs used the steam Rankine cycle as a power conversion system (PCS). However, the vigorous sodium-water reactions (SWR) has led to safety and design concerns. The SWR forms corrosive sodium hydroxide (NaOH) and explosive hydrogen gas (H_2) while generating substantial amount of reaction heat in high chemical reaction rate and this can potentially threaten the system safety and economy substantially [Jung et al., 2017]. Therefore, in order to ensure safety, safety features related system is important in order to use steam Rankine cycle as a power conversion system. Several studies have focused on SWR detection and mitigation; however, SWR still remains a major safety issue [Ahn et al., 2016; Deguchi et al., 2017]. Therefore, to overcome the limitation and safety hazards posed by SWR, researchers have studied newer power conversion systems [Dostal et al., 2004; Zhao and Peterson, 2008].

Various gas Brayton cycles, such as supercritical CO_2 (S-CO_2) Brayton cycle, helium Brayton cycle, and nitrogen Brayton cycle, were proposed as alternative power conversion systems. The S-CO_2 Brayton

Abbreviations: ASTRID, advanced sodium technological reactor for industrial demonstration; CEA, commissariat à l'énergie atomique et aux énergies alternatives ; Gen, generation; HELP, very high temperature helium experimental loop; HTGR, high temperature gas-cooled reactor; HPC, high-pressure compressor; KAERI, Korea Atomic Energy Research Institute; KALIMER, Korea advanced liquid metal reactor; LPC, low-pressure compressor ; Min, minimum; NIST, National Institute of Standards and Technology ; PCHE, printed circuit heat exchanger; PCS, power conversion system; POSTECH, Pohang university of science and technology; SFR, sodium-cooled fast reactor; SWR, sodium-water reaction; S-CO_2, supercritical carbon dioxide; SM-SFR, small modular sodium-cooled fast reactor; SGHX, sodium to gas heat exchanger ; SG, steam generator; SCIEL, Supercritical CO_2 integral experiments loop; TOP, turbine outlet pressure; TTD, terminal temperature difference

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