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Technical note

Adoption of nitrogen power conversion system for small scale ultra-long cycle fast reactor eliminating intermediate sodium loop

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ABSTRACT

As one of SFRs, the ultra-long cycle fast reactor with a power rating of 100 MW_e (UCFR-100) was introduced for a 60-year operation. As an alternative to the traditional steam Rankine cycle for the power conversion system, gas based Brayton cycle has been considered for UCFR-100. Among Supercritical CO_2 (S-CO_2), Helium (He), Nitrogen (N_2) as candidates for the power conversion system for UCFR-100, an N_2 power conversion system was chosen considering both safety and thermal performance aspects. The elimination of the intermediate sodium loop could be achieved due to the safety and stable characteristics of nitrogen working fluid. In this paper, sensitivity studies with respect to several controlled parameters on N_2 power conversion system were performed to optimize the system. Furthermore, the elimination of the intermediate loop was evaluated with respect to its impact on the thermodynamic performance and other aspects.

1. Introduction

Among Gen IV nuclear reactors, a sodium fast reactor (SFR) is the most promising type of reactor. The long cycle fast reactor is one of the SFR designs, which is operated in a long cycle without refueling. The initial concept of long cycle fast reactor was introduced in the 1950s while it is being highlighted for its significant advantages of uranium utilization and nuclear proliferation issues. The operational mechanism of the long cycle fast reactor is once-through fuel cycle through the breed and burn system. The main characteristics are constant neutron flux and power density for the operating period in a reactor core while their position moves along with an axial direction of fuel rod every moment at a constant speed for 60 years. The benefits of the long cycle fast reactor include capital/operation cost reductions, low proliferation risk, and the interim storage of light water reactor (LWR) spent fuel (Kim and Taiwo, 2010; Kim et al., 2012). For the development of the long cycle reactor, various strategies have been adopted. CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) which is proposed by Hiroshi Sekimoto, adopts a breed-and-burn strategy in the axial direction enabling the core life to be extended by increasing the axial length. It operates in such a long cycle without any reactivity control by an operator (Sekimoto et al., 2001). Another ultra-long life core strategy named traveling wave reactor (TWR) was proposed by TerraPower Inc. (Weaver et al., 2010; Ahlfeld et al., 2011). TWR core has different features from CANDLE that allows fuel shuffling rather than the movement of a depletion zone along the active core.

As one of the long cycle fast reactors, the Ultra-long Cycle Fast Reactor with a power rating of 1000 MW_e (UCFR-1000) was proposed for the purpose of a 60-year operation (Tak et al., 2013). UCFR-1000 utilizes low enrichment uranium (LEU) as an igniter in the lower part of the fuel region and natural uranium (NU) as a blanket material on top of the LEU region based on the breed-and-burn concept in the axial direction. Then the active core region moves upward from the bottom over the 60-year operation. However preliminary safety analysis of UCFR-1000 evaluated that the fuel and cladding temperatures as well as neutron fluence exceed the design limits due to its high reactor power density including high axial peaking (Seo et al., 2012). To secure enough safety margin, modified core design of small-sized UCFR with the power rating of 100 MW_e (UCFR-100) was developed by decreasing the load of power for each rod (Tak and Lee, 2012). As a result, the active core height was decreased from 3.6 m to 1.2 m and the axial power peaking factor was also decreased from 6.6 to 2.2. The safety evaluation of the thermal–hydraulic design criteria of the newly designed core, UCFR-100, confirmed that thermal–hydraulic parameters such as fuel, cladding and coolant temperatures meet the safety limit of general SFR design criteria for the whole operation period of the UCFR-100 (Seo et al., 2014).

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Nomenclature

c	heat capacity [kJ/kg °C]
h	enthalpy [kJ/kg]
m	mass flow rate [kg/s]
q	heat input [kW]
T	temperature [°C]
w	work [kW]
Greek symbols	
ε	effectiveness of heat exchanger
η	efficiency
Subscripts	
cycle	overall power cycle
gas	working fluid in energy conversion system
hpc	high-pressure compressor
IHX	intermediate heat exchanger
lpc	low-pressure compressor
Na	sodium in primary loop
Na_2	sodium in intermediate loop
PHX	primary heat exchanger
rcp	recuperator
t	turbine

Simultaneously with the development of advanced reactors, a new power conversion system has been considered. Initially SFRs have considered a Rankine steam cycle for the power conversion system. Most of current prototypes and demonstration of sodium fast reactors (i.e., Phenix, SuperPhenix, BN-600, etc.) used a sub-critical Rankine cycle. However the Rankine steam cycle for SFRs has serious safety issues related to the sodium–water reaction and the secondary sodium fire. Potential sodium–water reaction results in the generation of combustible hydrogen gas and exothermic energy release that threatens the integrity of the reactor. Although some SFR designs employed safety systems for the protection and mitigation of the sodium–water reaction such as detectors and double wall steam generator, those couldn't ensure the security of the reactor from the potential sodium–water reaction (Hahn et al., 2007; Yamaguchi et al., 2007; Miyata et al., 2013). Thus, many researchers have proposed alternative techniques for the power conversion system to eliminate related safety issues. Among those techniques, gas based Brayton cycle is a promising alternative for the power conversion system. Compared to steam cycles, the gas based Brayton cycle is simple, compact and less expensive, and has shorter construction periods.

Many inactive gases have been selected as a working fluid in Brayton power cycle, mainly Supercritical CO_2 (S-CO_2), Helium (He), Nitrogen (N_2). In 1960s, Angelino and Feher evaluated the supercritical power cycle using several working fluids and suggested a S-CO_2 power cycle for the nuclear reactor (Angelino, 1967; Feher, 1968). Dostal et al. stressed thermodynamic advantages such as low critical temperature and high critical pressure, and evaluated economic analysis for a balance of plant (BOP) as well as turbomachinery aspect (Dostal et al., 2004). The evaluation showed 45.3% thermal efficiency for a simple Brayton cycle reducing the cost of the power plant by 18% compared to a conventional Rankine steam cycle. Cha et al. proposed the S-CO_2 Brayton cycle coupled with KALIMER-600 sodium-cooled fast reactor (Cha et al., 2009). The author evaluated the cycle efficiency and the plant net efficiency at 42.8% and 40.3%, respectively in the single recompression layout. In addition, CFD analysis of the S-CO_2 turbomachinery was performed to optimize design parameters for each component. S-CO_2 power cycle was evaluated even for the high temperature gas-cooled reactor employed (Harvego and McKellar, 2011). However, S-CO_2 still has potential for reaction with sodium. CO_2–sodium reaction produces a solid product, which has the possibility to have an auto ignition reaction around 600 °C (Eoh et al., 2011). Helium cycle has been mainly considered for high temperature gas-cooled reactor because of its inert and stable characteristics in high temperature operating condition. The initial application of the helium cycle for sodium-cooled reactor was proposed by Peterson et al. which has multiple reheat molten coolant gas cycle (MCFC) concepts (Peterson, 2003). Then Zhao et al. evaluated thermodynamic analysis of the helium power cycle achieving a maximum of 47% of thermal efficiency with reactor outlet temperature in the range of 510–650 °C (Zhao and Peterson, 2008). Recently, Perez-Pichel et al. evaluated the helium based Brayton cycle combined with super-critical organic fluid Rankine cycle, while the thermal efficiency of the power cycle was around 35% which is lower than the super-critical Rankine cycle (Perez-Pichel et al., 2011). Nitrogen cycle is another alternative technique that enables to eliminate the sodium reaction. CEA in France has developed the nitrogen power cycle for ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration). Saez et al. performed thermodynamic analysis for the gas based Brayton conversion cycle using several working fluids including nitrogen and showed the potential of the nitrogen Brayton cycle for ASTRID SFR prototype (Saez et al., 2008). Then Alpy et al. compared the nitrogen cycle to S-CO_2 cycle in terms of thermodynamic performance (Alpy et al., 2011). Although the thermal efficiency of the nitrogen cycle was 6% lower than that of S-CO_2 cycle, the author considered the nitrogen cycle as short-term technology for ASTRID prototype. In addition, Cachon et al. designed heat exchangers for the nitrogen cycle for better thermal-hydraulic and thermal-mechanic performance using CFD evaluation (Cachon et al., 2012).

Previous studies have focused mainly on S-CO_2 power conversion system for SFRs because of its high thermodynamic performance and economic advantage. However, UCFR-100 requires certain safety prior to thermodynamic performance due to its long-cycle operation without refueling. In this study, therefore, a nitrogen Brayton cycle was chosen considering its inactive and stable state and analyzed in thermodynamic aspect for an optimized power conversion system coupled with UCFR-100. Finally, the elimination of the intermediate sodium loop was evaluated to the improvement of N_2 power conversion system for UCFR-100.

2. Design considerations for power conversion system

2.1. Working fluid evaluation

UCFR-100 is a small scale sodium-cooled reactor for a 60-year operation without refueling. These two features of UCFR-100 require the deliberate choice of the working fluid for the power conversion system. Based on previous studies, three candidates that are S-CO_2, He and N_2 were considered as the working fluid in the Brayton cycle coupled with UCFR-100.

Fig. 1 showed thermal efficiencies of S-CO_2, He, N_2 Brayton cycles for different turbine inlet temperatures from previous studies (Dostal et al., 2004; Alpy et al., 2011; Wang et al., 2002). The thermal efficiency of the S-CO_2 cycle was evaluated based on the