Conceptual study of Fast-Spectrum Molten Salt Reactor combined with Energy Storage System.

Jaejin Choi[a] , Seongmin Lee[a], Yong Hoon Jeong[a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology,291, Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[*]*Corresponding author: jeongyh@kaist.ac.kr*

1. Introduction

According to the "Net Zero by 2050-A Roadmap for the Global Energy Sector" from the International Energy Agency (IEA), almost all fossil energy is expected to be replaced by renewable energy such as solar power, wind power and bioenergy[1]. However, renewable energy sources have not been dispatchable generation because it was affected by time and the natural environment. The base load electricity needed for the providing energy consistently. Therefore, nuclear power combined with energy storage system were suggested.

The reactor type, passive safety system, and energy storage system were considered for the nuclear power plant combined with an energy storage system. The size of reactor units has 100 MWt power of Small Modular Reactor (SMR), and the reactor type is a fast-spectrum molten salt reactor (FS-MSR). The reactor has a high inherent safety due to the melted core and the atmospheric operating pressure. Also, Reactor Vessel Auxiliary Cooling System (RVACS) was adopted as the concept of a passive safety system which air-cooled by natural circulation.

In addition, energy storage applications that are less limited by space than pumped-storage hydroelectricity (PSH) are needed. Also, the energy storage system needs high capacity than a battery that has a kWh unit. Liquefied air energy storage (LAES) was selected because of high capacity and less space limitation. LAES is a technology that uses surplus power and heat to store the cooled and liquefied air in a vacuum insulation tank. When the power is needed, a liquefied air was pressurizes, vaporizes, and expands to converts it back into power. In 2018, a LAES demonstration plant with a capacity of 5 MW/15 MWh was established near Manchester, the United Kingdom, and the performance test was conducted in combination with the gas power plant [2]. LAES is also expected to be available in connection with nuclear reactors.

In this study, the reactor core and ESS were conceptual studied and proposed to establish FS-MSR combined with ESS. In addition, the feasibility of RVACS was evaluated.

2. Methods and Results

This section describes the modeling methods and results for the conceptual development of the FS-MSR combined with ESS systems.

2.1 Reactor Core

The purpose of the reactor under development is a power supply system with high safety. FS-MSR was chosen considering the following three advantages. First, in terms of inherent safety, the molten salt reactor has the advantage that core melting accidents are excluded because nuclear fuel is already melted. Second, core power can be controlled by adjusting the molten salt temperature and concentration without the control rod. Therefore, it can exclude rod ejection accidents. Third, operating pressure of molten salt reactor is atmosphere due to high boiling temperature. Low operating pressure prevent depressurization accidents and loss of coolant accidents.

Table1. Reactor core parameters

Parameter	Value
Reactor type	FS-MSR
Fuel Salt	46KCl-54UCl$_3$
Cl enrichment	99 a/o
U235 enrichment	19.75 w/o
Reactor power	100 MWt
Reactor life-time	50 years
Core temperature	650 °C
Core diameter/height	218 cm
Initial heavy metal	35,576 kg

Online refueling is one of the advantages of a molten salt reactor. However, it has technical and economic problems. Therefore, the fast spectrum reactor chosen due to high economic efficiency. The fast reactor has a long lifetime of about 50 years without online refueling. Also, the fast reactor use generally fluoride-based salt and chloride-based salt. The chloride-based salt has a lower viscosity than fluoride-based salt by one-fifth, allowing smaller pumps and higher power density. Also, the fluoride-based salt has a significant deceleration effect, which adversely affects the reactor's breeding ratio. Therefore, FS-MSR used chloride-based salt with a small deceleration effect. When the using Cl-35 for the molten salt, it produce Cl-36 and beta decay into Ar-36 with a long lifetime and emission of 709 keV of beta ray. The problem was solved by using Cl-37 instead of Cl-35. Detailed parameters of reactor core were summarized in Table 1.

In addition, helical type internal heat exchanger was also used, and installed an off gas system to capture non-soluble gaseous fission products. The noble metal is also collected and removed through helium bubbling, which injects inert gas into the bottom of the core.

2.2 Energy Storage System(ESS)

A supercritical CO_2 power converwsion system is applied for SF-MSR. By using sCO_2 as a fluid in the high-temperature Brayton cycle, efficiency increases about 5 % compared to rankine cycle. The high efficiency of the sCO_2 cycle results in the reduction of greenhouse gas, and it can also capture carbon dioxide due to the operating mechanism. The relatively high density of sCO_2 makes the turbine smaller and simpler. The FS-MSR combined with ESS system generates 30 MWe considering thermal efficiency. According to Sandia National Laboratories (SNL) study, the propse system's in this study optimum turbomachinery speed is 10,000 RPM, and its size is 40 cm. Also, the turbine type is a radial multi-stage[3].

Liquid air energy storage (LAES) is an energy storage system (ESS) that uses extra power to compress air and store it in the form of liquefied air. When power demand is reduced and surplus power is left, LAES is charged by surplus power activating the compressor. Conversely, when additional power generation is needed due to increased demand for power, LAES is in a discharge process in which the stored liquid air evaporates and expands. The capacity of LAES needed was simply calculated. The power consumption is the biggest difference over time in July, 2020. The power consumption is 34.7 % higher at noon to midnight than midnight to noon. Our system LAES should have a capacity to store at least 14.8 % of power generation, which means a 4.44 MW/53.28 MWh capacity energy storage system is needed.

This system also has a Thermal Energy Storage (TES) to store heat transferred without decreasing temperature. TES contains a hot insulated tank and a cold insulated tank. Figure1 shows simple schematic for a sCO_2 power conversion, LAES, and TES combined system.

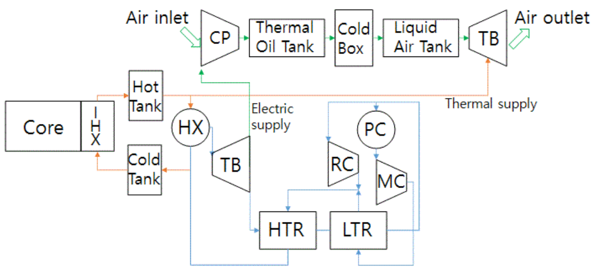

Fig 1. Schematic diagram of a system combined LAES, TES, and sCO_2 power conversion.

2.3 RVACS

The RVACS is a passive safety system that heat is removed by natural circulation. The RVACS uses natural circulation to keep the reactor temperature below the design limit by removing decay heat from the reactor module. RVACS improves safety by ensuring the availability of decay heat removal after shutdown regardless of power availability. The heat removal capability was calculated to figure out the RVACS feasibility for the FS-MSR.

Configulation of RVACS on the FS-MSR is similar to RVACS applied to PRISM reactor[4]. MATLAB code was used to evaluate heat removal capability. The assumptions for the calculating are steady-state analysis, air separator was insulated board, and containment vessel height is 3m, and RVACS height is 6m. The emissivity of the containment vessel is 0.7. Also, temperature of inlet air is 50℃, and atmospheric pressure. When the heat removal rate is hard to keep the molten salt level below the overflow liner, another molten salt flow path connecting the hot pool and the cold pool is established. However, the overflow was not considered in this evaluation. RVACS heat transfer was calculated by changing the containment vessel temperature (Tcv). In RVACS, if the buoyancy force is bigger than the total pressure drop (geometric pressure drop and friction pressure drop), then natural circulation occurs. The chracteristics of air changed through y-axis due to the heat convection and radiation. The inlet mass flow rate is 1 kg/s when the natural circulation occurs. Table 2 shows the total heat transfer change according to the containment vessel temperature. The criteria for evaluating feasibility were set at 1.5 MWt that 1.5 % of heat generation after the reactor shutdown. This result show RVACS is not enough to remove heat alone and needs an additional heat removal system. For more accurate information, transient analysis will be conducted with fewer assumptions.

Table2. Reactor core parameters

Tcv	Heat Transfer(kW)
550℃	229.11
600℃	254.57
650℃	280.03

3. Conclusions

A clean energy system for netzero that is available 24hours a day without pollutants has been proposed.

The reactor core and ESS were determined through this conceptual studies. The main features are fast reactor and MSR, which chloride-based salt. Also, the power conversion using sCO_2, and combined with LAES, TES.

The feasibility of RVACS was also evaluated. As the result, when the containment vessel temperature is 600℃, the RVACS heat transfer is 254.57 kW. The result is not enough to decay heat removal after the 100MWt reactor shutdown. Therefore, this reactor needs an additional heat removal method using water evaporation when the initial state of the reactor shutdown. Also, the RVACS needs to be reevaluated for the transient state, and considered temperature of outer separator and concrete silo.

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