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Development of Safety Design Technologies for Sodium-Cooled Fast Reactor Coupled to Thermal Energy Storage System with Sodium-Molten Salt Heat Exchanger

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Abstract. Next-generation innovative reactors have a new value of their flexibility with variable renewable energy. A sodium-cooled fast reactor (SFR) can make flexibility by coupling a thermal energy storage (TES) system with molten salt. New challenges for the SFR coupled with TES are to develop a safety design approach and a heat exchanger (HX) between sodium and molten salt. On that account, since 2022, a three-year project has been performed to develop 1) a safety design approach and risk assessment methodology of the SFR with TES, 2) a performance evaluation technology of an HX between sodium and molten salt, and proposal of heat transfer improvement measures, and 3) an evaluation technology of chemical reaction characteristics between sodium and molten salt, and proposal of safety improvement measures. This paper describes the project overview and recent progress. For 1), this study investigated the record of operation and incidents or troubles of a TES system that uses molten salt as a heat storage medium for concentrating solar thermal power generation, which includes about 50 commercial facilities. These data could serve as a reliability database for risk assessment. For 2), this study selected a straight shell-and-tube type HX as a result of investigating several types of HXs. Using the intermediate HX of the experimental SFR in Japan as a reference, the heat transfer performance of the HX was evaluated by a simple method. This study developed the most promising HX type by improving the heat transfer performance with parameters of heat transfer tube diameter, heat transfer tube pitch ratio, heat transfer tube material change, primary side/secondary side replacement, and cross flow. For 3), this study preliminarily evaluated the chemical reaction characteristics using an equilibrium phase diagram with thermodynamic equilibrium calculation software. No database for the reaction of nitric acid molten salt and sodium was confirmed, so that a basic reaction experiment is necessary. This study prepared a glove box and reagents in 2022, and a thermal analysis-related equipment is also introduced in 2023.

Keywords. Sodium-cooled fast reactor, thermal energy storage, safety design, sodium, molten salt, heat exchanger

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1. Introduction

Next-generation innovative reactors have a new value of their flexibility with variable renewable energy, in addition to safety and economic competitiveness [1]. A sodium-cooled fast reactor (SFR) can make flexibility by coupling a thermal energy storage (TES) system with molten salt. In the United States, TerraPower has been developing an SFR with TES, named Natrium^{TM}, which can increase power generation output (500 MWe) when electricity demand is high due to the expansion of renewable energy introduction [2]. In France, CEA recently introduced new nuclear startups, one of which is named Hexana, comprising two small reactor units (400 MWth each) with TES to ensure the flexible production of electricity on demand [3]. In Japan, a new fast neutron irradiation field was recently proposed as a research and development infrastructure necessary for next-generation innovative reactors. Expectations are rising for its role as a regulating power source that complements renewable energy, in combination with a TES system [4]. This facility is under consideration in Japan Atomic Energy Agency [5].

In order to realize the power storage, there are various technologies such as TES and pumped water in addition to a direct power storage using batteries. The TES technology is advantageous to achieve a large-capacity energy storage, in terms of flexibility and cost [6]. In recent years, a sensible TES technology using nitric acid-based molten salt as a heat medium (temperature range around 500°C) is commercialized in solar thermal power generation business all over the world, and there is little room for technological development [7]. In Japan, Toshiba has been developing a high-temperature gas reactor with the TES system using nitric-acid molten salt [8].

A development element unique to the SFR with TES is the HX between sodium and molten salt. There is very limited information on Natrium^{TM} that is being developed, and in particular, there is no information regarding its HX. In addition, there is no guideline for safety design and evaluation for SFRs with TES. Furthermore, the safety design needs to take into account the risk of sodium-molten salt contact that could occur in a heat transfer tube failure in the HX. As far as the authors know, however, the chemical reaction characteristics have never been clarified. The lack of knowledge for quantitative evaluation of the safety of the TES system is a bottleneck in deploying the SFR with TES.

Therefore, new challenges for the SFR coupled with TES are to develop a safety design approach and a heat exchanger (HX) between sodium and molten salt. On that account, since 2022, this study is conducting a three-year project to develop 1) a safety design approach and risk assessment methodology of the SFR with TES, 2) a performance evaluation technology of an HX between sodium and molten salt, and proposal of heat transfer improvement measures, and 3) an evaluation technology of chemical reaction characteristics between sodium and molten salt, and proposal of safety improvement measures. This paper describes the overview of the three-year research project and the progress in the first year (2022).

2. Project Overview

This study is intended to develop a draft safety design guideline that complies with domestic regulatory standards, and a basic policy for constructing a reliability database necessary for risk assessment.

The HX performance evaluation aims to optimize the HX design considering heat transfer improvement through computational fluid dynamics (CFD) analyses. The objective of this evaluation is to significantly improve the heat transfer performance compared to replacing sodium with molten salt on one side in a reference sodium/sodium HX.

In the chemical reaction characteristic evaluation, as basic research, the objective is to understand the chemical reaction characteristics of liquid metal sodium and nitric-acid molten salt to ensure safety in the event of boundary failure in the HX, such as heat transfer tube failure. This study will develop a database of the reaction in a temperature range up to higher than 800°C of the upper limit of the reaction experiment, taking into account its uncertainty.

2.1. Safety Design Approach and Risk Assessment Methodology of the SFR with TES

In order to deploy the SFR with TES in Japan, it is necessary to develop the safety design guideline, for which this study examines the compliance with regulatory standards regarding the TES system. For this purpose, this study investigates accidents and troubles in molten salt TES systems and examines the effect of sodium-molten salt heat transfer tube failure. Based on the results, we propose the draft safety design guideline for the SFR with TES.

This study also develops the reliability database for risk assessment, which summarizes the number of HX tube failures and molten salt exposure time. Furthermore, issues necessary to comply with domestic regulations are identified.

2.2. Performance Evaluation Technology of a Heat Exchanger Between Sodium and Molten Salt, and Proposal of Heat Transfer Improvement Measures

To specify the evaluation conditions of heat transfer characteristics of HXs, the first task is to survey basic specifications for nitric-acid molten salts, nitric-acid molten-salt loop structural materials, TES systems, etc.

Although there are various types of HXs, the HX for liquid metal sodium and nitric-acid molten salt is conceptually designed in this study, on the basis of a simple evaluation of the heat transfer characteristics of various HX types.

For the most promising HX concept, a CFD analysis with a partial model is applied to the HX performance evaluation. This study needs to confirm applicability of the CFD analysis using sodium and nitric-acid molten salt, which have significantly different thermal conductivities and physical properties.

This study optimizes measures to improve heat transfer performance, and finally confirms the effectiveness of the most representative measure using the CFD analysis.

2.3. Evaluation Technology of Chemical Reaction Characteristic Between Sodium and Molten Salt, and Proposal of Safety Improvement Measures

To understand the basic behavior of the chemical reaction between liquid metal sodium and nitric-acid molten salt, basic reaction experiments are carried out under an inert-atmosphere environment, in which chemically active sodium can be handled. The experiments are performed using a thermal analysis device such as a differential scanning calorimetry (DSC) equipment, which is introduced into a new glove box environment maintained in an argon atmosphere. For fundamental information, reaction onset temperature and reaction heat are measured in a temperature range from approx. 500°C to higher than 800°C. The reaction products are also investigated by analyzing samples that have been produced during the experiment.

An expected reaction system and reaction products are evaluated using thermodynamic equilibrium calculation software with available databases, which finally compares the calculated results with the experimental ones.

This study comprehensively evaluates the reaction behavior between sodium and molten salt that may occur at the HX of the TES system, and proposes measures to improve the safety against the chemical reaction.

3. Progress in 2022

3.1. Safety Design Approach and Risk Assessment Methodology of the SFR with TES

The authors surveyed the record of operation and incidents or troubles of TES systems using molten salt (solar salt) as a TES medium for concentrating solar thermal power generation based on publicly available information around the world. There is a demonstration facility (power-tower type) in the United States: Solar Two, and approximately 50 commercial facilities in the United States, Spain, etc. [9] [10]. Regarding accidents and troubles, several cases were found in the molten salt system of the demonstration facility, such as in its light concentrating part and steam generator [11] [12]. Trouble cases of commercial facilities are also published with facility names anonymized. Available facilities with useful records are 9 power-tower type and 29 parabolic-trough type. The parts that experienced incidents or troubles include a light concentrating part, a steam generator, and a heat storage tank for the power-tower type facility, and a molten salt-oil HX and a heat storage tank for the parabolic-trough type.

To contribute to the development of a safety design guideline proposal for the SFR with a molten salt TES system, the authors investigated a safety design policy in a case connecting a new chemical plant called a hydrogen production facility to an existing nuclear reactor plant. This study also examined domestic regulatory compliance policies and indicated the direction of consideration toward developing regulatory compliance policies for a nuclear reactor plant equipped with a molten salt TES systems.

3.2. Performance Evaluation Technology of a Heat Exchanger Between Sodium and Molten Salt, and Proposal of Heat Transfer Improvement Measures

In this study, solar salt is selected as a representative nitric-acid molten salt because it is already commercialized. The most characteristic thermal physical properties of solar salt are the density, which is approximately twice that of sodium, and the thermal conductivity, which is two orders of magnitude lower than that of sodium [13][14]. Such properties are not suitable for HXs. In other aspects, the amount of corrosion of structural materials in molten salt is a practical level below 500°C, and stress corrosion cracking can be prevented [15]. The authors determined the conditions for evaluating HX performance based on the TES materials and operating temperature range, referring basic specifications of molten salt TES systems. After investigating multiple HX types, this study selected a straight shell-and-tube type HX as the main option.

The heat transfer performance of the HX was evaluated using a simple method using the intermediate HX, as a reference design, of the experimental SFR, Joyo, as listed in

Table 1 [16]. The heat transfer area for evaluation in this study is 329 m^2, because the effective heat transfer area includes a design margin and bypass flow.

Table 1 Specifications of Joyo intermediate heat exchanger [16].

Items		Specifications	
HX Type		straight shell-and-tube type	
Exchange heat (MWt/unit)		70	
Unit		2	
		Inlet	Outlet
Temperature (°C)	Primary side	500	350
	Secondary side	300	470
Flow rate (kg/h)	Primary side	1.3×10^6	
	Secondary side	1.2×10^6	
Heat transfer tube			
Number of tubes		2088	
Outer diameter (mm)		19.0	
Thickness (mm)		1.0	
Material		SS316 (316FR steel)	
Effective heat transfer area (m^2)		363	
Heat transfer area for evaluation (m^2)		329	

The simple calculation is assumed to fix the exchange heat, inlet/outlet temperatures in the HX primary (sodium) and secondary (molten salt) sides, and mass flow rate in the primary side. The mass flow rate in the secondary side can be determined by the density and specific heat of solar salt because of the fixed exchange heat and temperature conditions. The heat transfer area can be calculated under such conditions. First, the secondary sodium is replaced by the nitric-acid molten salt as a base-case calculation.

The sodium-side heat transfer coefficient is based on Lubarsky & Kaufman equation, which is expressed by the following equation [17].

$$\mathrm{Nu} = 0.625\mathrm{Pe}^{0.4} \tag{1}$$

where Nu is Nusselt number, and Pe is Peclet number.

The salt-side heat transfer coefficient is based on Dittus- Boelter equation, which is expressed by the following equation [17].

$$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \tag{2}$$

where Re is Reynolds number, and Pr is Prandtl number.

The salt-side cross-flow heat transfer coefficient is based on Zukauskas equation, which is expressed by the following equation [17].

$$\mathrm{Nu} = 0.35(\mathrm{Y}/\mathrm{X})^{0.2}\mathrm{Re}^{0.8}\mathrm{Pr}^{0.36}(\mathrm{Pr}/\mathrm{Prw})^{0.4} \tag{3}$$

where X and Y are heat transfer tube pitch, and Prw is Prandtl number at the wall temperature.

The simple evaluation results of heat transfer performance are listed in Table 2. In this table, the ratio represents the transfer area divided by that of the reference case (Case 0). The bracket value is calculated by the ratio of the heat transfer area of the base case (Case 1) divided by the heat transfer area.

This study developed the most promising HX type by improving the heat transfer performance with parameters of heat transfer tube diameter, heat transfer tube pitch ratio, heat transfer tube material change, primary side/secondary side replacement, and cross flow. This simple evaluation clarified the greatest influence of the primary side/secondary side replacement and cross flow on improving heat transfer, by which the HX performance is improved about three times. It should be noted that the pressure loss on the secondary side increases when the cross flow is adopted.

Table 2 Results of simple evaluation on heat transfer performance of various heat exchanger.

Case	No.	Conditions	Heat transfer area (m^2)	Ratio
Reference case (Joyo)	0	-	329	1.00
Replace sodium with molten salt for secondary coolant (Base case)	1	-	1801	5.47 (1.00)
Heat transfer tube size	2	Outer diameter: 15.9mm thickness: 0.89mm	1714	5.21 (1.05)
Tube pitch (2,522 tubes with velocity reduction)	3	1.25	2025	6.16 (0.89)
Tube pitch (1,518 tubes with velocity increase)	4	1.6	1518	4.61 (1.19)
Tube material	5	9Cr-1Mo	1773	5.39 (1.01)
Primary/secondary coolant replacement (increase in secondary channel)	6	-	2363	7.18 (0.76)
Primary/secondary coolant replacement and cross flow	7	Baffle plate interval: 300mm	563	1.71 (3.20)
	8	Baffle plate interval: 450mm	634	1.93 (2.83)

In 2023, the CFD analysis using a commercial code, STAR-CCM+, is conducted using a unit model simulating a part of the cross flow to confirm the validity of the heat transfer coefficient in the simple heat transfer evaluation. In 2024, using a partial model of the tube bundle, the next step is to investigate the effects of the bypass flow, uneven flow, pressure loss, etc.

3.3. Evaluation Technology of Chemical Reaction Characteristic Between Sodium and Molten Salt, and Proposal of Safety Improvement Measures

There is limited knowledge regarding the reaction characteristics between liquid sodium and nitric-acid molten salt [18]. As a result of literature survey, the authors found that this study should focus on the reaction characteristics of molten salt with sodium immediately after the salt is melted for the basic experiment to be conducted in 2024.

This study attempted to investigate the reaction mechanism and products between metallic sodium and nitric-acid molten salt based on an equilibrium phase diagram using the thermodynamic equilibrium calculation software with the available database. The authors confirmed that there was nothing related to this reaction and reaffirmed the need to confirm the reaction characteristics through basic reaction experiments of this study.

For preparation of the chemical reaction experiment, the glove box (Fig. 1) was introduced as a test environment. In addition, the reagents of nitric-acid molten salt were prepared for thermal analysis, and the authors considered the specifications for thermal analysis equipment and related devices to be introduced in 2023.

Figure 1. Glovebox for chemical reaction experiment.

4. Conclusions

This paper describes the overall outline of this research project and its progress in 2022. One of the main conclusions is to select the shell-and-tube type for a first sodium-salt HX concept based on simple evaluation. This study encompasses compliance with domestic regulations, which enables clarifying the path to the deployment of the SFR with TES in Japan. The results obtained in this study will be useful in the design of HXs using sodium and molten salt, of which heat transfer performance is analyzed using the CFD code in 2023. The present study will greatly contribute to the development of the SFR with TES, which is currently studied by SFR developing countries.

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