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THERMAL HYDRAULICS ANALYSIS OF THE FLUORIDE-SALT-COOLED, HIGH-TEMPERATURE REACTOR

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ABSTRACT

Fluoride-salt-cooled, high-temperature reactor (FHR) technology combines the robust coated particle fuel of high-temperature, gas-cooled reactors with the single phase, high volumetric heat capacity coolant of molten salt reactors and the low-pressure pool-type reactor configuration of sodium fast reactors. This paper discusses one key technology area required to further define and develop the FHR: the thermal hydraulic performance of the core, primary system and second loop. Shanghai Institute of Applied Physics (SINAP) is leading the China Academy of Science (CAS) FHR program. A TMSR-SF1 reactor with a fluoride cooled pebble bed design has been suggested by SINAP, and the design is currently in progress. For this preliminary thermal hydraulic assessment, a TMSR-SF1 system model was developed using RELAP5. The RELAP5 model was used to help define and size systems such as the intermediate coolant salt selecting. A loss of flow transient was also simulated to evaluate the performance of the reactor during an anticipated transient event. A steady-state calculation was carried out and the calculated initial conditions show the influence of different salt. The loss of forced flow (LOFF) transient simulation results show that the passive residual heat removal system can effectively remove all decay heat from the primary loop under this extreme accident scenario. Some initial recommendations for modifying system component designs, such as heat exchanger with different salt and install place of pump, are also discussed.

1. INTRODUCTION

Fluoride salt-cooled High-temperature Reactors(FHR) are an emerging reactor class that combines attractive attributes from previously developed reactor classes. The FHR is a high-temperature reactor that uses coated-particle graphite-matrix fuels (TRISO) and a molten-fluoride-salt coolant. The fuel is the same as that used in high-temperature gas-cooled reactors (HTR). Design limits placed on this fuel are typically in the range of ~1600ºC during accidents. The proposed mixture of fluoride salts has a freezing point of ~400ºC and a boiling point of ~1400ºC at atmospheric pressure. The reactor operates at near-atmospheric pressure. At operating conditions, molten-salt heat-transfer properties are similar to those of water. Heat is transferred from the reactor core by the primary molten salt coolant to an intermediate heat-transfer loop, which uses a secondary molten salt coolant to move the heat to the turbine hall. In the turbine hall, the heat is transferred to a multi-reheat nitrogen or helium Brayton cycle power conversion system. For hydrogen production, heat is also transferred to a thermochemical hydrogen production facility, which converts water and high-temperature heat to hydrogen and oxygen [1].

Several studies of fluoride-salt cooled, high temperature reactors delineate the potential for attractive economic performance while meeting high standards for reactor safety and security by Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL) and the University of California at Berkeley (UCB) [2] . In China, CAS has initiated a large FHR development program to develop and refine future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts. SINAP is leading CAS FHR program. Within the scope of this project, SINAP will develop Thorium-based Molten Salt Reactor nuclear energy system (TMSR), and plans to construct a test reactor. A TMSR test reactor (TMSR-SF1) with fluoride cooled ordered pebble bed design has been suggested [3], and the design is currently in progress. The General objective of TMSR-SF1 are listed as follows: 1) the integration capabilities and operation technology for the TMSR systems; 2) achieving molten salt cooling technology; 3) studying and achieving the usage of thorium resources; 4) verifying the behavior of fuel pebbles in reactor environment

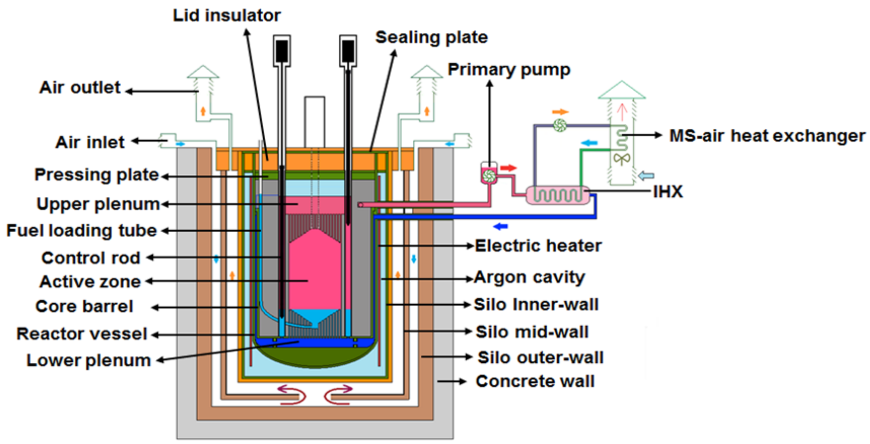

Fig 1. Schematic of TMSR-SF1 reactor system

5) verifying the behavior of structural materials in the reactor environment. The final application goal of this project is large-scale commercial reactor. Therefore on one hand the basic conceptual design and technology should be achieved; on the other hand it should be aimed at application goal of large commercial reactor, to reserve technical as much as possible. Therefore this small experimental reactor will test various technology with high priority and the overall structure of the reactor under the premise of safety as much as possible; In addition, we need to try to improve the program of commissioning, operation and experiment, to obtain a variety of technical parameters through all kinds of commissioning, operation, and experimental design.

In the current design, the TMSR-SF1 is 10MW test reactor simulating the thorium reactor. In order to try fairly large molten salt pump, the temperature rise of the coolant salt as it passes through the core is 50℃. Considering the slat and structure material temperature limits and future power conversion system, the average temperature is 625℃. Figure 1 show the schematic design of the reactor system, and key parameters are described in table 1. The coolant in primary loop is a binary molten salt system of the 66.6%^{7}LiF-33.3%BeF_2 (mol) (FLiBe) originally used in the molten salt reactor[4], the coolant in intermediate loop is salt and the coolant in third loop is air. The primary reactor system consists of the reactor vessel, the heat exchanger, the circulating pump, and the interconnecting piping. The reactor secondary system consists of the coolant pump, a radiator in which heat is transferred from salt to air, and the piping between the pump, the radiator, and the fuel heat exchanger. The reactor is a graphite-moderated thermal reactor composed of the core and reflector, respectively consisting of fuel spheres and high-density graphite. The active region of TMSR is comprised of fuel spheres. Cold salt enters the reactor cavity through cold leg, then flows downward in the annular gap between the core barrel and the reactor vessel. TMSR has a cylinder core through which the coolant flows upward. The coolant pumps and primary heat exchanger are located above the reactor core; thus, the reactor cannot lose its coolant except by failure of the primary vessel. For decay heat removal, the TMSR-SF1 uses a passive residual heat removal system. As shown in Figure 1, the passive residual heat removal system decay heat is 1) transferred from the reactor core to the reactor vessel by force circulation of the molten salt, 2) conducted through the reactor vessel 3) transferred across an argon protection by radiation to the air heat exchanger, 4) removed from outside of the guard vessel by natural circulation of ambient air.

Table 1 Key TMSR-SF1 parameters

Parameter	Value	Units
Core thermal power	10	MW
Fuel sphere diameter	6	cm
Core height	2.5	m
Core diameter	1.3	m
Number of fuel sphere	8317	
Primary coolant salt	LiF-BeF_2	
Average reactor outlet temperature	650	℃
Primary coolant return temperature	600	℃
Primary coolant flow rate	84	kg/s

This paper discusses one key technology area required to further define and develop the TMSR: the thermal hydraulic performance of the primary system and intermediate system. Up to this point, only scoping analysis has been performed to assist in the other supporting TMSR design activities. Although these calculations represent only the initial phases of thermal hydraulic analysis for this reactor, they will be used to provide feedback to other design features needed as this design advances.

For this preliminary thermal hydraulic assessment, a TMSR-SF1 system model was developed using RELAP5. The

RELAP5 model includes all of the primary components, second loop and passive residual heat removal system: the core, lower plenum, hot legs, cold legs, pumps, the primary heat exchangers, the gas-salt heat exchanger etc. The RELAP5 model was used to help define and size systems such as the primary heat exchangers and the passive residual heat removal system. A loss of force flow transient was also simulated to evaluate the performance of the reactor during an anticipated transient event.

2. RELAP5 MODELING

This section documents the development of a RELAP5 system model for the TMSR-SF1, including the core, lower plenum, hot legs, pumps, heat exchangers etc.

RELAP5 is a generic transient analysis code for thermal-hydraulic systems using a fluid that may be a mixture of steam, water, noncondensables, and a nonvolatile solute. Due to its success performance in analysis of light water reactor accidents and the complete codes available, RELAP5 is expected to be the basis analyzer in transient analysis of TMSR by necessary modification. RELAP/SCDAPSIM/MOD4.0 is the latest versions among RELAP5 family, developed by Innovative system software [5].

To model TMSR reactor, thermodynamic properties, such as FLiBe, FLiNaK and air, and a simple heat transfer correlation for forced convection through pebble beds are implemented into RELAP/SCDAPSIM/MOD4.0. The thermal hydraulics correlations for pebble bed are obtained by considering the bed as a porous media with a given porosity.

The development of the TMSR-SF1 design is at the conceptual stage. An initial candidate mechanical design of the reactor system was produced in 2015. The thermal hydraulic analysis of the TMSR reactor is performed by the RELAP5 code for hot full power reactor operating condition at the beginning of life. The components of a nuclear reactor are represented with a user-defined nodalization that contains hydrodynamic control volumes and junctions that represent flow paths between control volumes and heat structures. Nodlization The RELAP5 TMSR-SF1 model is shown in figure 2. The major RELAP5 components are discussed and described below.

2.1REACTOR VESSEL AND INTERNAL COMPONENTS

The reactor vessel is cylindrical, as shown in figure 1. The vessel wall and the core barrel is made of Hastelloy N. The downcomer is the gap between the reactor vessel and the core reflect. The core reflect is cylindrical with a height of ~ 3.0m and an outside diameter of ~ 2.8m.

The core active area is a random pebble bed composed of fuel sphere. To simulate core activity hot spot temperature, the core active area is divided into several channels in RELAP5 model. Assuming the peak temperature of the fuel pebble in the central channel is hot spot temperature, power and flow is the same as the design value in modeling. In present study, the core is divided in two parallel channels and thirteen axial layers, one is the cooling channel and another is the hot channel. And a portion of the power is allocated to each layer during the steady state conditions. During the transients, the power causes a temperature variation in the layers with introduces a reactivity disturbance. The net reactivity is then fed back into the point reactor kinetics model. It is important to notice that the axial power profile has been chosen to be fixed and has been determined once from the reference core. The radial and axial power peaking factors are respectively 1.21 and 1.27.

Considering the pebble bed core, RELAP5 model hydraulics control volume of activity area is defined as the coolant of core activity area, and the equivalent method is presented as follows: 1) the same coolant volume, 2) the same height of activity area, 3) the same pressure drop. Heat structure of activity area is defined as the fuel sphere elements. The equivalent method is presented as follows: 1) sphere fuel element, 2) homogeneous fuel area 3) the same porosity 4) modified wakao formula [6] is used to calculate heat transfer for coolant through pebble bed and the formula is as follows:

$$Nu = 2 + 1.1 \times (\mathrm{Re}_d \times 0.4)^{0.6} \times \mathrm{Pr}^{1/3} \quad (1)$$

Where Re_d is Reynolds number based on superficial velocity, and 0.4 is porosity of porous medium.

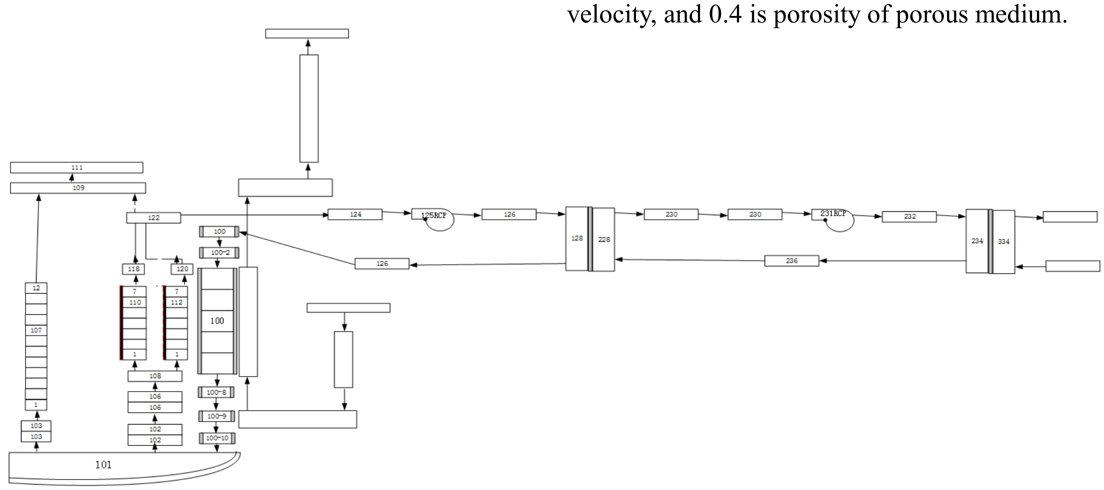

Figure 2 Nodalization of TMSR-SF1 System

For the core reflect section, RELAP5 does not allow an outer surface to have mixed boundary conditions [7]. This brings a significant inadequacy when modelling the reflector region with the coolant channels. In order to tackle the reflector with the coolant channels, two heat structures have been defined, one on each side of the coolant channels (molten salt channel shown in Fig.2). Heat can then be transferred from the hotter to the colder heat structure, but solely by convection of the molten salt.

2.2 COOLANT SYSTEM

This section described the major component of coolant system, including the intermediate heat exchanger (IHX), the pump, the pipe and the molten salt-air heat exchanger. The intermediate loop uses molten salt-air heat exchanger to transfer heat to the final heat sink. In the coolant system design, the first decision is selected salt for the intermediate loop. In general, there are a few factors in determining the intermediate salt (e.g. salt properties, corrosion, major component design, operating parameters, etc.) Comparing the major salt properties (melt point, viscosity, heat capacity, etc.), LiF-BeF_2 KF-ZrF_4 and FLiNaK salts are selected as second loop coolant candidate. The coolant thermal properties are given in Table 2.

Table 2 Coolant thermal properties [8]

	Primary loop	Intermediate loop		
Coolant salt	LiF-BeF_2	KF-ZrF_4	FLiNaK	LiF-BeF_2
Density(kg/m3)	1950	2850	2064	1950
Viscosity(Pa s)	0.00609	0.00522	0.00390	0.00609
Conductivity(W/mk)	1.1	0.42	0.89	1.1
Specific heat capacity (j/kg K)	2416	1051	2010	2416
Pr	13.32	12.95	8.85	13.32

The IHX is a tube-and–shell design. The radiator is a tube design. For simplicity, the IHX and the radiator are using same equivalence method in RELAP5 model. The equivalence method for coolant flows along the tube side modeling, is presented as follows: 1) flow area is the area sum of all heat exchange tubes; 2) same hydraulics diameter; 3) same flow length; 4) same pressure drop. Channels of coolant is complicated on shell side and the equivalence method is presented as follows: 1) same coolant volume; 2)same channel length; 3) hydraulics diameter by default; 4) same pressure drop. The equivalence method for heat structure of heat exchanger is presented as follows: 1) cylindrical heat structure; 2) same heat exchange area; 3) same heat transfer hydraulic diameter; 3) tube and shell side adopts the generalized DB heat transfer formula, and keeping heat transfer capacity the same as design value.

The overall layout of pipe keeps the same as total length, elevation and pressure drop, by using general hydraulics control volume and heat structure.

Molten salt pump is a vertical cantilever fluid centrifugal pump. There are blanket gas and an overflow port in pump bowl. The overflow port is used to control molten salt level. When molten salt liquid level exceeds the overflow port position, molten salt of pump bowl flows into overflow tank through overflow port. Default pump model of code can't simulate blanket gas and overflow port effect.

In RELAP5 TMSR-SF1 model molten salt pump function is divide into two parts pressure regulating function gained through blanket gas and pressure driven by pump. To simulating the pressure regulating function gained through cover gas of pump bowl, a pressurizer is added in pump inlet. To simulate the pressure driven, a pump component is chosen and the equivalence is presented as follows: 1) the same volume 2) the same volume flow 3) the same elevation and pressure head 4) built-in Westinghouse pump 5) adjusting the ration of initial pump velocity to rated pump velocity according to the design value 6) minimum moment of inertia simulates pump without moment of inertia.

2.3 PASSIVE RESIDUAL HEAT REMOVAL SYSTEM

The passive residual heat removal system is mainly composed of the reactor cooling system and direct discharging system for silo gas. Working processes of the system are as follows.

Residual heat will be transferred from the reactor core to argon chamber through the graphite reflector, core barrel, pressure vessel downcomer and the reactor vessel, and then passed to the cylinder tank inner wall and its insulation layer by radiation and convection. The tank inner wall insulation layer then transfers the residual heat to the cylinder tank and finally most of heat is discharged to the atmosphere by air natural circulation in the tank and a small part of the residual heat is transferred to the atmosphere by concrete wall outside of the tank.

Material properties of graphite reflector, core barrel and reactor vessel are added to RELAP5 for simulation, and the gas outside of the reactor vessel is equivalent to a constant temperature boundary. So it can avoid uncertainty of calculation on simulation of the air heat exchanger located in reactor room and concrete wall cooling system.

3 SIMULATE

Calculations of steady state and a loss of forced flow (LOFF) transient were carried out with the RELAP5 TMSR-SF1 model. The steady-state simulation was performed to obtain initial conditions for the transient simulation. For future TMSR design, LiF-BeF2 KF-ZrF4 and FLiNaK were all performed for steady-state simulation. A loss of flow transient was simulated to evaluate the performance of the passive residual heat removal system during an anticipated tarnsient. In the LOFF transient, only using FLiNaK as the intermediate in RELAP5 model, all the primary coolant pumps are assumed to fail at the beginning of transient without any pump coastdown.

3.1 STEADY-STATE

Table 3 summarize of the calculated steady-state of the three slat design options examined based on the same IHX and MS-air design. Option 1 use LiF-BeF_2, option 2 use FLiNaK, option 3 use KF-ZrF_4. It shows that option 1 and option 2 is much the same comparing with option 3. Considering the component design, the coolant system can use same design for the LiF-BeF_2 and FLiNaK salts.

Table 3 Steady-state of design option

	Option 1	Option 2	Option 3
Intermediate salt	LiF-BeF_2	FLiNaK	KF-ZrF_4
Reactor outlet temperature (℃)	601.19	599.27	600.00
Primary coolant return temperature (℃)	650.73	648.85	628.00
Primary coolant flow rate (kg/s)	84.02	84.02	121.85
IHX inlet temperature (℃)	519.77	517.45	500.00
IHX outlet temperature (℃)	547.10	549.30	545.00
Coolant flow rate (kg/s)	152.58	166.00	211.44

3.2 LOSS OF FORCED FLOW

The LOFF transient was simulated to compare the intermediate salt performance. The protection for loss of coolant flow accident is provided by under voltage or under frequency signal or low coolant loop flow. According to the perceptual design report of SINAP, TMSR-SF1 reactor is operating at 10.0MW with only one main pump without moment of inertia in the coolant circuit. The reactor trip on low primary coolant loop flow is provided to protect against loss of flow conditions. When electric power is lost, the reactor control system is activated with assuming max delay equals to 2.0 s and the control rods drop to the core with 6.0 s.

When the transient occurs, the primary coolant pumps is shut down at time 2 s, resulting in an immediate reduction of core flow, and the reactor is shut down immediately, as well. Within a few seconds, the passive residual heat removal system open, the core begins to cool down. At the beginning of the transient, the reactor outlet temperature increase at fist then decrease, because the residual heat removal system power is small than the decay heat. At about 7000 s in the transient, the coolant temperature reaches the maximum value 675℃ at the exit of the core as presented in Figure 3. After that, the coolant begins to gradually cool down as the decay heat decreases.

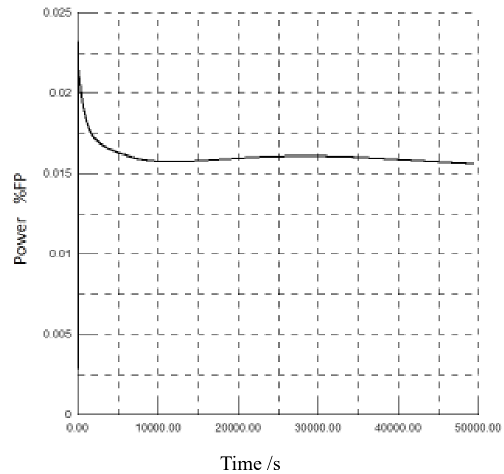

Figure 2 Passive residual heat removal system power

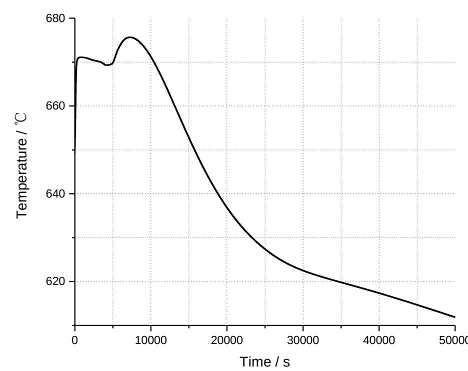

Figure 3 Reactor outlet temperature

4 CONCLUSIONS

This paper aims at the modeling and thermal hydraulic analysis of TMSR. A RELAP5 system model has been developed to analyze the safety performance of the TMSR-SF1. The RELAP5 model is a detailed representation of the TMSR-SF1 plant system, including the reactor core, three primary loops, intermediate loops and passive residual heat removal system.

A steady-state calculation was carried out and the coolant system can use same design for the LiF-BeF2 and FLiNaK salts. A loss of forced flow transient was simulated, and the results show that the passive residual heat removal system can effectively remove all decay heat from the primary loop under this extreme accident scenario.

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