PRELIMINARY STEADY STATE AND TRANSIENT ANALYSIS OF A MOLTEN SALT BASED REACTOR USING RELAP/SCDAPSIM/MOD4.0

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ABSTRACT

As a Molten Salt Reactor (MSR) has the advantages of economy, safety, sustainability and nuclear nonproliferation, research on the MSR has been widely conducted. One of the most important tasks for the design and assessment of MSR performance is to develop system analysis codes. A modified version of RELAP/SCDAPSIM/MOD4.0 was used to perform a steady and transient analysis of the proposed MSR being developed at Shanghai Institute of Applied Physics (SINAP). SINAP proposed a Solid Fuel Thorium Molten Salt Reactor (TMSR-SF1) system with 10MW thermal power. It uses coated particles, and pebble bed fuel designs. The reactor coolants are the Fluoride-based molten salts. This paper describes the extensions of fluid properties and correlations in the RELAP/SCDAPSIM/MOD4.0 code and applications of the modified code for the TMSR-SF1. This work uses three Heat Transfer Correlations (HTCs) on the pebble bed and tests for the steady state analysis of the TMSR-SF1 system. A selected prototypical Design Basis Accident (DBA), Station Blackout (SBO) with scram transient also being analyzed. The steady state analysis results are roughly same for all of the three HTCs and the same with the design values. Results from transient calculations show that the maximum temperature of fuel element is 1040K, and the maximum temperature of the molten salt is 972.20 K, which far below the safety limit temperatures 1873.15K and 1123.15 K. Analysis shows that the Passive Residual Heat Removal system (PRHRs) has the ability to insure the reactor safety.

KEYWORDS: TMSR-SF1, Molten Salt, SBO, RELAP5/MOD4.0, PRHR

1. INTRODUCTION

The Shanghai Institute of Applied Physics, Chinese Academy of Science, is currently involved in the design and development of a Solid Fuel Thorium Molten Salt Reactor (TMSR-SF1). The TMSR-SF1 is a 10MWth solid fuel, molten salt coolant reactor [1]. Figure 1 shows the TMSR-SF1 system. This TMSR-SF1 concept is an innovative reactor design that uses the conventional TRISO coated particle fuel, with a low-pressure liquid fluoride salt coolant. Its design has the advantages of economy, safety, sustainability and nuclear nonproliferation.

There are four coolant circuits in this design. The first loop is the primary loop, where FLiBe molten salt as the coolant flows through the reactor core. It extracts heat from the pebble bed and transfers energy to the secondary loop, which uses the molten salt FLiNaK as the coolant fluid. The third loop is the heat sink using air as the coolant. The fourth loop is a passive residual heat removal system, using air as the coolant. The purpose of this kind of design is to insure that the residual heat can be removed through the heat exchanger between the insulation layer and the thermal barrier by conduction, natural circulation and radiation under accident conditions. The designed heat removal capability is 200 KW.

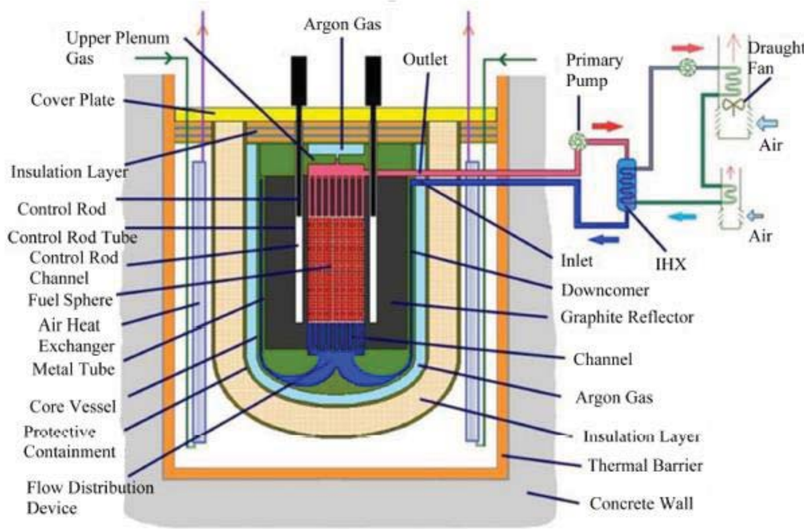


Figure 1. Schematic of TMSR-SF1 System

The current work involves thermal hydraulic calculation of TMSR-SF1. It uses the RELAP portion of RELAP/SCDAPSIM/MOD4.0. The current version of RELAP5 lacks the properties of FLiNaK molten salt, which is the coolant of secondary loop in TMSR-SF1. Thermodynamic and transport properties of the FLiNaK and three pebble bed heat transfer coefficients have been incorporated into the code.

The purpose of current assessment includes the analysis of the TMSR-SF1 to check the applicability of the RELAP5/SCDAPSIM/MOD4.0 code to compute FLiBe and FLiNaK thermodynamic/transport properties and heat transfer under steady state, Table 1 summarizes the operational parameters of TMSR-SF1. Moreover, the heat remove capability of the PRHR in the TMSR-SF1 system under a SBO with scram accident transient being analyzed preliminarily. The TRISO particles in the pebble bed have a failure temperature is 1600℃. This work did not consider the heat loss of the pipe. For high temperature primary loop components, Alloy 800H clad with Hastelloy N is used to provide corrosion resistance. The maximum acceptable temperature of the material is 850℃ (means that the outlet temperature should be lower than 850℃). This temperature is significantly less than the FLiBe boiling temperature (1400℃), so the structure material temperature limit of 850℃ is the main constrain of TMSR-SF1.

Table 1. Design and Steady State Calculated Results of TMSR-SF1

Description	Design data	RELAP5 Calculate Value
Thermal power (MWth)	10.0	10.0
Primary Loop Inlet Temperature (℃)	672.00	673.04
Primary Loop Outlet Temperature (℃)	700.00	700.66
Primary loop mass flow rate (kg/s)	150.00	149.66
Secondary loop mass flow rate (kg/s)	160.00	161.68
Pebble Diameter (m)	0.06	0.06
Pebble Number	15000	15000

2. MODIFICATION OF RELAP5/MOD4.0 FOR MOLTEN SALT REACTOR (TMSR-SF1)

RELAP5 [2] is a system code that has been successfully used to model different types of light water reactors. It was initially designed specifically for liquid and steam two phase flow system, but it also supports single phase flow problems. RELAP5/SCDAPSIM/MOD4.0 is the latest version that can handle different coolants for different reactor systems. RELAP5/SCDAPSIM/MOD4.0 version was used for the transient analysis of SINAP's TMSR-SF1 baseline design with some source code modifications being made.

2.1 Thermodynamic and Transport Properties Incorporated in the Code

The numerical schemes in RELAP5 [3] require the thermodynamic and transport properties of the molten salt over a range of temperature and pressure to solve the thermal hydraulic model. Thermodynamic and transport properties of the FLiNaK (Incorporated into RELAP/SCDAPSIM/MOD4.0) are listed in Table2. The FLiNaK molten salt thermal properties have been implemented into RELAP5/SCDAPSIM/MOD4.0 version. The code verification was done by using the US-NRC's Regulatory Guide 1.203 (Rg 1.203, 2005) [4]. Testing results show that the modified code inapplicable under non-condensable gas contact with flowing molten salt condition and when molten salt freezing and boiling occur.

Table 2. Correlations for thermodynamic and transport properties of FLiNaK.

Parameter	Correlation	Reference
Density (molten state) [kg/m3]	$\rho = -0.73(T - 273.15) + 2530$	From Powers et al. (1963) [5].
Vapor pressure [Pa]	$p = 133.32 * 10^{(9.04 - 10500/T)}$	Cantor et al. (1968) [6]
Specific volume [m3/kg]	$\gamma = 1/[-0.73 * (T - 273.15) + 2530]$	From Powers et al. (1963) [5]
Specific heat [J/kg-K]	1884	From Powers et al. (1963) [5]
Thermal expansion coefficient [1/K]	$\beta = 0.73/[-0.73(T - 273.15) + 2530]$	From Powers et al. (1963) [5]
Isothermal compressibility [1/Pa]	$k = (2.3 * 10^{-11} * e^{0.001 * T})$	From Cantor et al. (1968) [4]
Dynamic viscosity [Pa]	$\mu = 4.0 * 10^{-5} * e^{4170/T}$	From Powers (1963) [5]
Surface Tension [N/m]	$\sigma = -1.2 * 10^{-4} * (T - 273.15) + 0.26$	Cantor et al. (1968) [6]

2.2 Molten Salt Heat Transfer Correlations

Molten salts are a specific class of coolants. Their basic advantage is their high thermal conductivity and high Prandtl (Pr>10), which can enhance the heat transfer ability. New heat transfer correlations have been incorporated in RELAP/SCDAPSIM/MOD4.0 and the molten salt heat transfer correlations can be used whenever molten salt cooled pebble bed is modeled. Three empirical relations of dimensionless quantities Nu, Re and Pr have been selected from the literature [7]-[9]. These quantities are applicable for molten salt in a pebble bed under forced convection. They are listed in terms of Re and Pr numbers in Table 3.

Wakao proposed the first HTC, the experiment validate work have been done with liquid water, CO2 and H2 gas. This correlation can be used for a very narrow range of Pr and applicable for 10<Re<10000. Gnielinski proposed the second correlation for, 30<Re<10000, this correlation supported by various experiments with various gases. The third correlation is proposed by German regulatory commission, for gas cooled reactor, 100<Re<100000. The TMSR-SF1 normal operating Re is about 8460, 420 for the SBO transient, so these correlations can be used for the TMSR-SF1 pebble bed both steady state and typical operating conditions during SBO transient.

Table 3. Heat Transfer correlations recommended for Pebble Bed

Correlation [Nu]	Applicability	Developer
$Nu_{wak} = \frac{hd}{k} = 2 + 1.1 Re_d^{0.6} Pr^{1/3}$	10<Re<10000	Wakao [7]
$Nu_{gn} = 3.8 + 1.5 Re_d^{1/2} Pr^{1/3}$	30<Re<10000	Gnielinski [8]
$Nu_{KTA} = 1.27 \frac{Pr^{1/3}}{\varepsilon^{1.18}} Re^{0.36} + 0.033 \frac{Pr^{1/2}}{\varepsilon^{1.07}} Re^{0.86}$	100<Re<100000	Kaviany [9]

2.3 Pebble Bed Pressure Loss Correlations

Pressure loss correlations for a packed pebble bed are obtained by considering the bed as a porous media with a given porosity ε. Most of pressure loss correlations for porous media are extensions from Darcy's law. Empirical extensions of Darcy's law were first proposed by Ergun [10]. According to Ergun's law, the friction factor is given by equation (1):

$$\mathrm{f} = \frac{1-\varepsilon}{\varepsilon}\left(a\frac{1-\varepsilon}{Re_d} + b\right) \quad \text{with} \quad Re_d = \frac{\dot{m} d_p}{\mu A_c} \tag{1}$$

Re_d : the Reynolds number based on the pebble diameter
A_c : total area of the core [m^2]
μ : molten salt dynamic viscosity [Pa.s]
$\dot{m}$: Mass flow rate [kg/s]

A broad number of references give possible values for the two parameters, a and b, which depending on the precise geometry of the porous media and the roughness of solid/liquid boundary. According to a review [11], the recommended values for a smooth particles bed are a=180 and b=1.8.

According to RELAP5 manual [2], it is possible to input pressure losses coefficients at a given junction between two volumes as a known function of Re_d, where d is the hydraulic diameter of the junction. The possible functional expression is:

$$\mathrm{f}(Re) = \mathrm{b} + \mathrm{a}Re^{-c} \tag{2}$$

Ergun equation has a compatible expression with equation (2).

3. MODELING AND NODALIZATION OF TMSR-SF1

Figure 2 shows a RELAP nodalization of the TMSR-SF1. The reactor core has been modeled as pipe component 100 with a length 1.8m including 12 control volumes and 12 heat structures. The heat is transferred by FLiBe to the secondary side containing FLiNaK by a molten salt heat exchanger. The heat exchanger is modeled as pipe component 108 and pipe 200 in primary and secondary side respectively. The pressurizer is modeled as time dependent volume 403 with pipe 401. The third loop has been modeled using a sink for the air flow rate of 45kg/s at atmospheric pressure. The PRHR system has been modeled as a loop with pipe components 602 and 604. This system is connected to the reactor vessel. The reactor vessel has been modeled in detail using pipe components 115 and 116. The two pipe components are connected with cross flow junctions between them, to mimic the natural circulation effect.

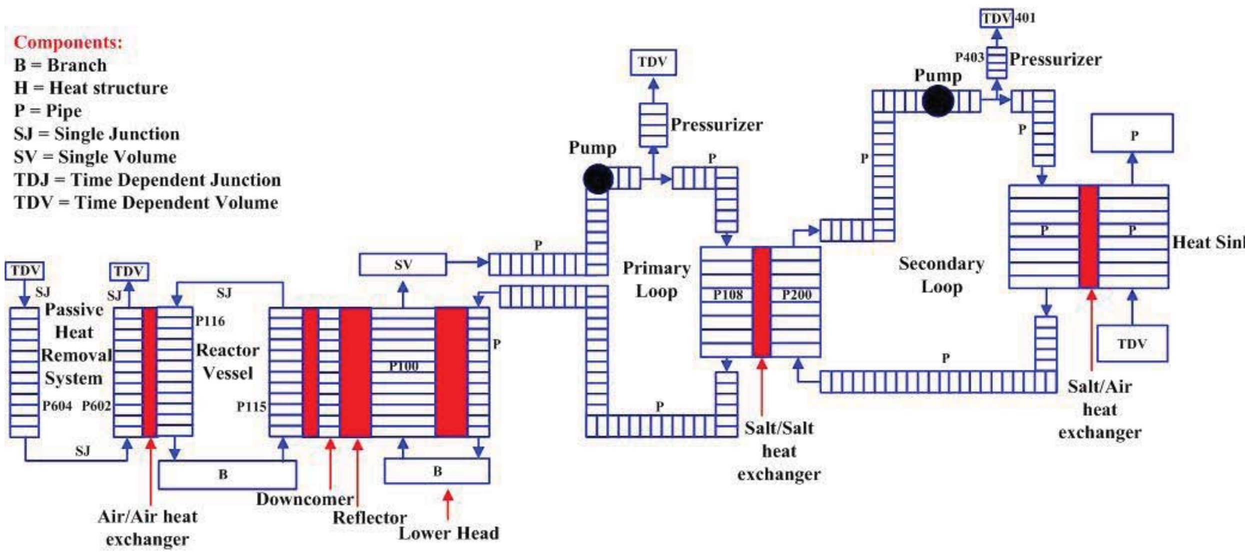


Figure 2. RELAP5/MOD4.0 Nodalization of TMSR-SF1 System

4. RESULTS AND DISCUSSION

The aim of this study is to check the applicability of the modified RELAP/SCDAPSIM/MOD4.0 code with FLiBe and FLiNaK properties for the TMSR-SF1 system and to verify that the three heat transfer correlations proposed for the pebble bed and PRHR system are reasonable under a SBO accident transient.

4.1 Steady State Results

This section discuss the steady state results using RELAP/SCDAPSIM/MOD4.0. They are reported in Table 1 and compared with the design data. All the operating variables (temperature, flow rate) of the system values match the design data.

4.1.1 Pebble bed inlet and outlet temperature

Steady state temperatures at the inlet and outlet of the pebble bed are presented in Figure.3. The inlet and outlet temperatures are 946.19K and 973.81K, which are close to the design values reported in Table 1. The temperatures with all three conditions overlap. Heat of 10Mw is deposited on pebble bed which is then removed by the secondary side and transferred to the heat sink.

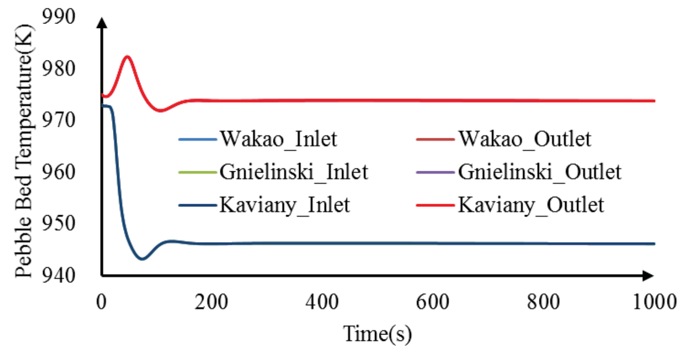


Figure 3. Molten Salt Temperature at Pebble Bed Inlet/Outlet

4.1.2 Mass flow rates

The calculated mass flow rate is 149.66 kg/s for the primary loop coolant and 161.68 kg/s for the secondary loop coolant as shown in Figure 4. The heat sink mass flow rate is 45.00 kg/s. These flow rates for molten salt and air are the same as the design values of 150.00 kg/s, 160.00 kg/s and 45.00 kg/s reported in Table 1. All of the three correlations overlap.

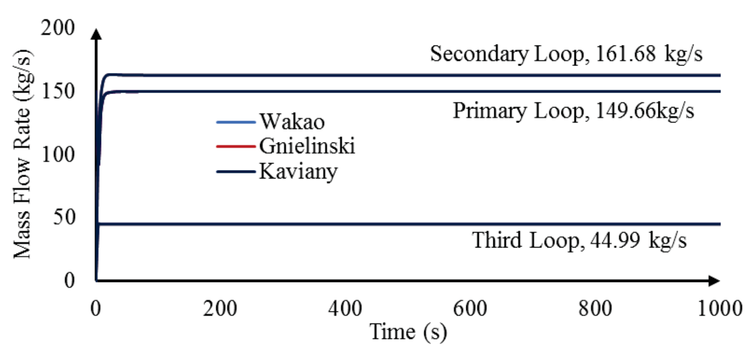


Figure 4. Mass Flow Rate of the System at Steady State

4.1.3 Pebble bed pressure drop

The designed pressure drop for the pebble bed is 50kPa. The pressure drop presented in Figure 5 is 48.37KPa and matches the design values. The calculated results indicate that the Ergun equation is valid in this kind of design.

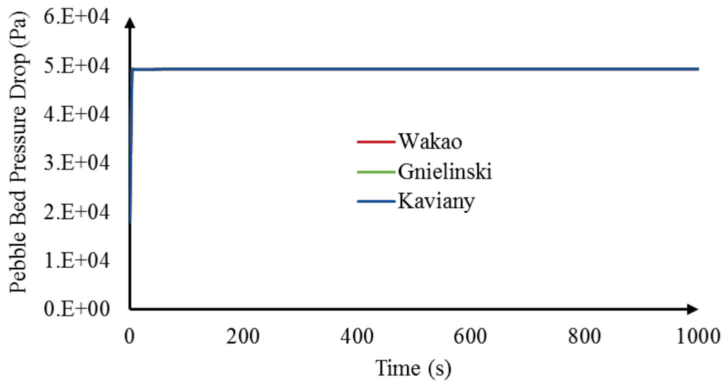


Figure 5. Pebble Bed Pressure Drop at Steady State

4.1.4 Heat transfer coefficient of pebble bed

Figure 6 shows the heat transfer coefficients for the pebble bed at the inlet and outlet. The heat transfer coefficients are important for calculating the correct amount of heat transferred from the reactor core. The heat transfer coefficients are 963.11/987.73 W/m^{2}K at the inlet/outlet and are the same for all the three correlations.

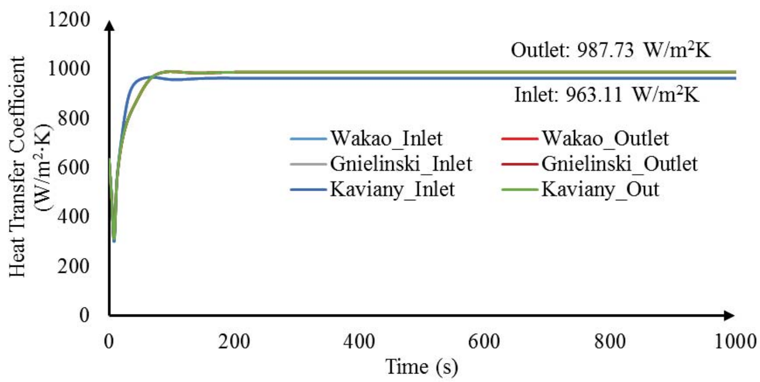


Figure 6. Heat transfer coefficient of the Pebble Beds

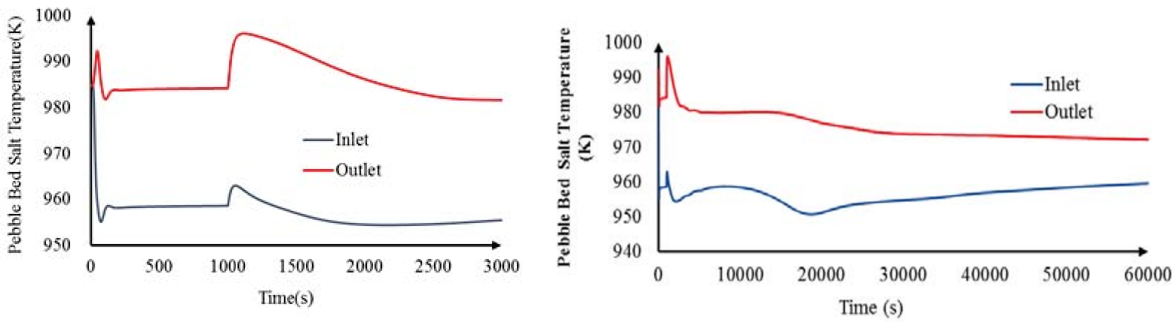
4.2 Transient Results

This section describes the SBO with scram for the transient study. The objective of the transient study is to obtain the maximum temperature attained in the pebble bed for a SBO transient. Based on the steady state analysis results, the three HTCs overlap each other. Therefore, the Wakao correlation is used for transient analysis. The SBO has been simulated for an interval of 59000s from 1000s to 60000s. The initial condition of the transient is the same as for the steady state condition.

Accident sequence assumption: a) Station Black Out occurred at 1000s with the primary pump, secondary pump and the air cooler fan of heat sink losing power followed by the reactor losing all of the active flow; b) at 1002s, emergency shut down of the reactor occurs and the reactor power drops to 2 % , then gradually falls to 0.3% of the total power; c) the passive residual heat removal system comes into use; and d) it is assumed that the container and pipe are adiabatic.

4.2.1 Inlet and outlet temperature of the pebble bed

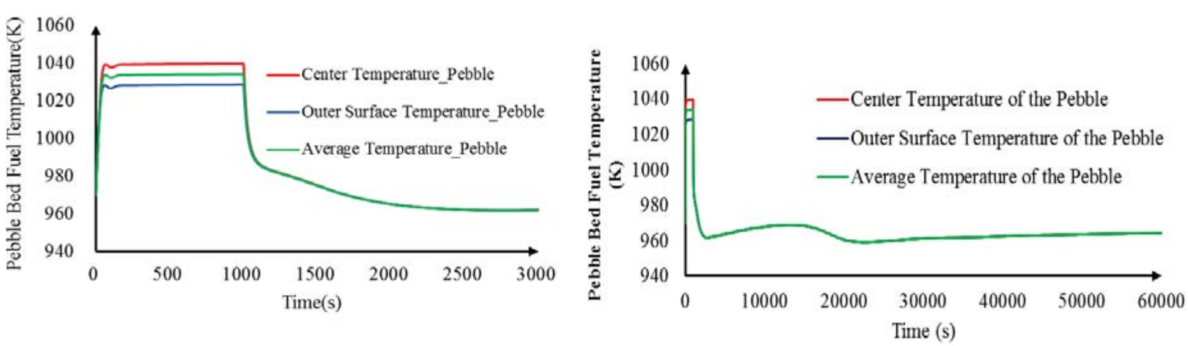
Both short term and long term temperature profiles of the inlet and outlet fluid of the pebble bed for the accident transient are presented in Figure 8. The outlet temperature increases to the maximum value of 982.45K at 1040.0s which is well below the boiling temperature of the FLiBe (1400K). The inlet/outlet temperatures reach 959.58/972.20 K at the inlet/outlet by 60000s.



a---Short term; b---Long term
Figure 7. Pebble Bed Inlet/Outlet Temperature at SBO Transient

4.2.2 Temperature of the pebble bed fuel

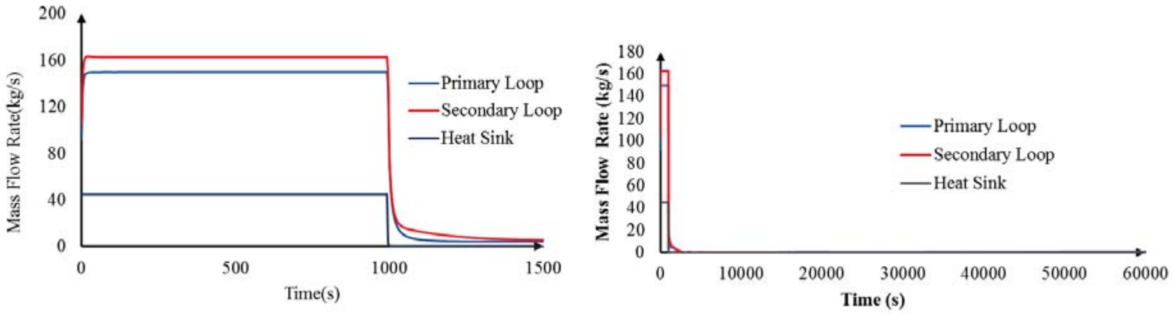
Both short term and long term temperature profiles for the fuel component are given in Figure 8. The fuel temperatures decrease rapidly in the first 50 s due to the emergency shut down of the reactor core. The maximum temperature of the fuel is 1040K, which is much lower than the failure temperature (1870K). After reactor shutdown, the maximum, the minimum, and the average temperature are almost the same due to the lower power condition.



a---Short term; b---Long term
Figure 8. Pebble Bed Fuel Element Temperature

4.2.3 Mass flow rate of the system

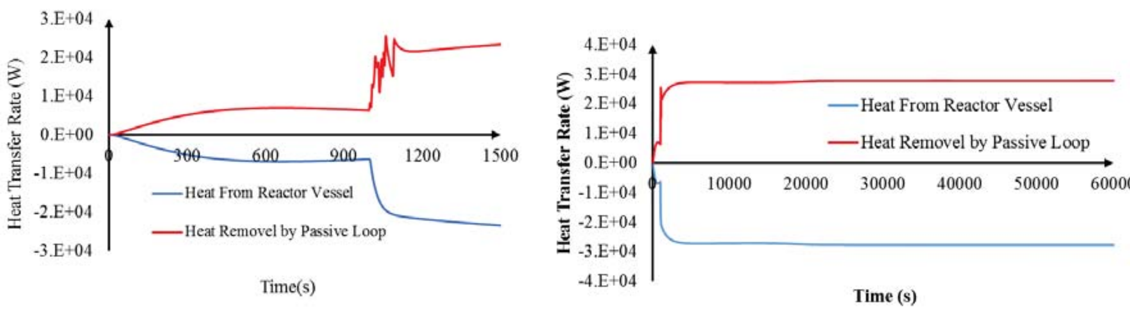
Figure 9 presents the transient behavior of short term and long term molten salt and air mass flow rates. At 1001s, the air flow rate has been reduced to zero from the operating value of 45.0 kg/s. At 2772s, the molten salt flow rate was reduced from the normal operating value of 150 kg/s to 0.82 kg/s, because of the inertia of the pump.



a---Short term; b---Long term
Figure 9. Mass Flow Rate of the System

4.2.4 Heat transfer rate of the passive residual heat removal system

The total heat removed by the air in the reactor vessel and by the passive residual heat removal system presented in Figure 10. The heat removed is 27.742 kW. The two values are fairly consistent during the transient process and do not change after 20000 s.



a---Short term; b---Long term
Figure 10. Heat Transfer Rate at SBO Transient

4.2.5 Natural circulation flow rate of the air in the reactor vessel

Figure 11 presents the natural circulation flow rate of the air in the reactor vessel. At the beginning of the transient, the flow rate is 0.714 m/s. It decreased to 0.6 m/s at 19050s, due to the shutdown of the reactor and the decrease in the temperature of the reactor vessel.

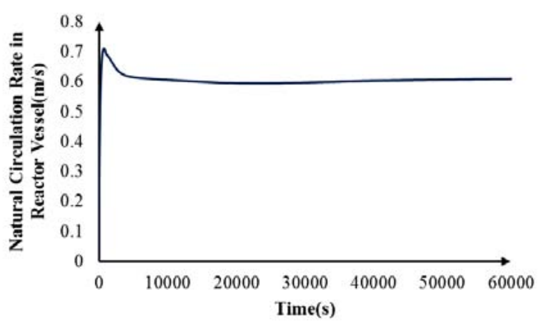


Figure 11. Natural Circulation Rate in the Reactor Vessel

5 CONCLUSIONS

The steady state results from the RELAP5/SCDAPSIM/MOD4.0 simulation match well to the design values. The three HTCs predict similar behavior for the TMSR-SF1 system, and the simulated results are roughly the same. The thermal response of the pebble bed is not highly sensitive to the convective heat transfer coefficients at the operating range. Any one of the HTCs can be used for analysis of the pebble bed of TMSR-SF1 reactor. Therefore the modified version of RELAP5/SCDAPSIM/MOD4.0 code is capable of solving the SBO transient at higher temperatures using the new resistance factor, heat transfer correlations, and properties for molten salt. The maximum temperature of molten salt is 972.20K. However, the predicted peak fuel temperature is 1040K during SBO transient, which are far below the failure temperature of the Alloy H and Pebble fuel. The preliminarily analysis results show that the modified RELAP5/SCDAPSIM/MOD4.0 is reasonable to model the TMSR-SF1, and the PRHR system of the reactor. This paper gives an insight into the application of the modified code to the molten salt reactor system.

The modified RELAP/SCDAPSIM/MOD4.0 is far from comprehensive, which need to do further extensions. The detailed homologous curves for molten salt pump will be inserted in the code. Fluid interactions of Molten Salt and air need to be incorporated in RELAP5 for studying LOCA and heat exchanger tube burst accident in postulated initiated events. Preliminary validation work of RELAP respect to FHR is done by SINAP based on the FLiNaK high temperature molten salt experimental facility. Data has been obtained and results will be published in new future.

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