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The Analysis of Loss of Forced Flow Event on the HTGR Type Experimental Power Reactor

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***Abstract*— Since 2014, Indonesia's National Atomic Energy Agency (BATAN) has been launching a plan to construct a 10 MWt Experimental Power Reactor (*Reaktor Daya Eksperimental* / RDE). The RDE design is based on the small-sized pebble-bed high-temperature gas-cooled reactor (HTGR) technology with TRISO fuels. By concept, HTR-10 design, which was developed by the INET of China, is used as the reference design. During the development process, a safety analysis report (SAR) of RDE design has to be prepared to be evaluated by the Indonesia Nuclear Regulatory Agency (BAPETEN). The report contains, among others the description of the RDE accident sequences, which can be only provided by simulations using a certain code. This paper emphasizes the transient analysis, which is simulated using RELAP5/SCDAP/Mod3.4 , which is a thermal-hydraulic code specified for light water coolant systems. The simulated event is the loss of primary coolant mass flow, which is caused by the failure of the primary gas blower motor. The methodology of simulation is first by modelling the RDE nuclear steam supply system to verify steady-state operational parameter of the RDE design. The second step is to simulate the event of loss of flow, which is followed by the failure to shut down the reactor. The simulation results in the decrease of the fuel pebble temperature during the event due to the negative fuel temperature reactivity coefficient and the core heat removal by the cavity cooling. Overall, the RELAP5 code has a limitation in the RDE simulation to define two different non-condensable gases, which reduces the accuracy of the simulation results.**

***Keywords*— experimental power reactor; loss of flow; RELAP5; accident simulation.**

I. INTRODUCTION

In 2014, Indonesia's National Atomic Energy Agency (BATAN) announced a plan to construct a 10 MWt Experimental Power Reactor or Reaktor Daya Eksperimental (RDE), which will be the country's first indigenous small modular reactor. The plan is a part of the strategic milestone for the construction of large-scale nuclear power plants in Indonesia in the future [1]. The RDE design is based on the small-sized high-temperature gas-cooled reactor (HTGR) technology using pebble bed core with low enriched uranium-oxide TRISO fuel. Its basis design relies on the research and development progress of nuclear power technology, especially in China [2, 3]. The HTGR has been becoming a world trend not only for electricity production but also for industrial purposes, such as hydrogen production, water desalination, coal liquefaction, etc. Pebble bed reactors are also considered as the most advanced technology, especially by offering the advantages of emission-free operation, high energy efficiency, with a naturally safe (no meltdown) operation [4].

The pre-project phase began in 2015, in which BATAN worked in cooperation with Russian-Indonesian consortium RENUKO as a consultant for conceptual design. Based on the completed basic engineering design of RDE, BATAN received a siting license from the Indonesia Nuclear Regulatory Agency (BAPETEN) in 2017 at the Serpong site, where the biggest Indonesia research reactor of RSG-GAS is also located [5]. The next step is preparing a detailed engineering design (DED) of RDE, simultaneously with the safety analysis report (SAR), fulfilling the regulatory body's important requirement to obtain the design certification. The DED completion is aimed by the end of 2019 by involving a consortium of Indonesian universities and private companies.

By concept, HTR-10 design developed by the INET of China is used as a reference design in the RDE development [6]. The RDE core is similar to the HTR-10 design, as shown by the active core dimension (radius and height), generated thermal power of 10 MW, pebble diameter (6 cm), and UO_2 kernel material with 17 % enrichment of TRISO design. The core power is generated by 27,000 fuel pebbles with the multi-pass fuel loading scheme, in which 25 fresh fuel pebbles are loaded, while each fuel pebble will pass through the reactor core five times (on average) before they are discharged into the spent fuel cask [7]. The pebble bed is cooled by the helium gas and located inside a pressure vessel, in which the graphite and carbon bricks reflector surround the pebble bed as the thermal insulation. The heated helium gas is directed into the steam generator through the hot gas duct. The helium gas flows from the top downwards on the outer surfaces of tubes bundles of the steam generator, which has a helical-coiled arrangement. The heat of the helium gas is removed by the feed water, which flows inside tubes of the steam generator from the bottom upwards. The colder helium gas is then pumped by the single-stage blower through the cold gas duct back into the reactor pressure vessel.

The RDE safety analysis report (SAR) contains how the RDE operates safely according to the determined design criteria in the steady-state and accident condition. In the report, design basis accidents are listed, which need to be analyzed to show their conformity with safety limits. In the SAR draft, those events are grouped into nine main event types. One of the main event types is the primary heat transfer system malfunctions, which consist of 8 selected initiating events, in which the event of the loss of primary coolant mass flow is included. In the description of the event sequence, the loss of primary coolant mass flow is caused by the failure of the primary gas blower motor or inadvertent closure of the blower damper, which initiates the reactor protection system to respond the event. To complete the event sequences in the descriptions, an analysis of the event must be carried out by simulating the event using a particular code.

This paper emphasizes the transient analysis resulted from the simulation using the RELAP5/SCDAP/Mod3.4, which is a specific thermal-hydraulic code for the simulation of light water reactors. It is a highly generic code, which contains fluid properties ranged from a mixture of steam, water, non-condensable gases, and non-volatile solute [8]. The non-condensable gas of helium used as cooling in the HTGR and spherical heat structures as fuel model in the pebble bed core are also accommodated in the RELAP5 code. Therefore, in theory, the HTGR can be modeled and simulated using RELAP5. There are only limited published researches related to the application of RELAP5 code in the gas-cooled reactor. Among them, the thermal modeling of HTR-10 only on the core section has been conducted and analyzed [9].

II. Materials and Method

Modeling of the RDE is basically to describe the helium gas flow inside the reactor pressure vessel on the way to cool the pebble bed core. The primary system pressure is 3.5 MPa by design, in which the helium circulator moves the helium with 4.27 kg/sec of mass flow rate. After entering the reactor pressure vessel (RPV), the helium flow path is deflected downwards inside the annular space into the lower part of RPV. It changes the direction upwards to enter the cold helium channels inside the graphite block reflectors. The helium gas is then collected in the upper cold helium plenum inside the top reflector, from which mainstream helium flow goes downwards passing through the pebble bed core into the core outlet channels in the bottom reflector. The hot helium gas coming from outlet channels is mixed with the small part of hot helium gas from the lower plenum to obtain a heated helium gas with the temperature of 700 °C in average before flowing inside the hot gas duct into the steam generator. The heated helium gas from the RPV should transfer its energy through the helical tubes inside the steam generator, in which the temperature of helium drops to 250 °C before flowing inside the cold gas duct into the RPV. Fig 1 shows the main components of the RDE, and the path of helium flows inside the reactor and the steam generator.

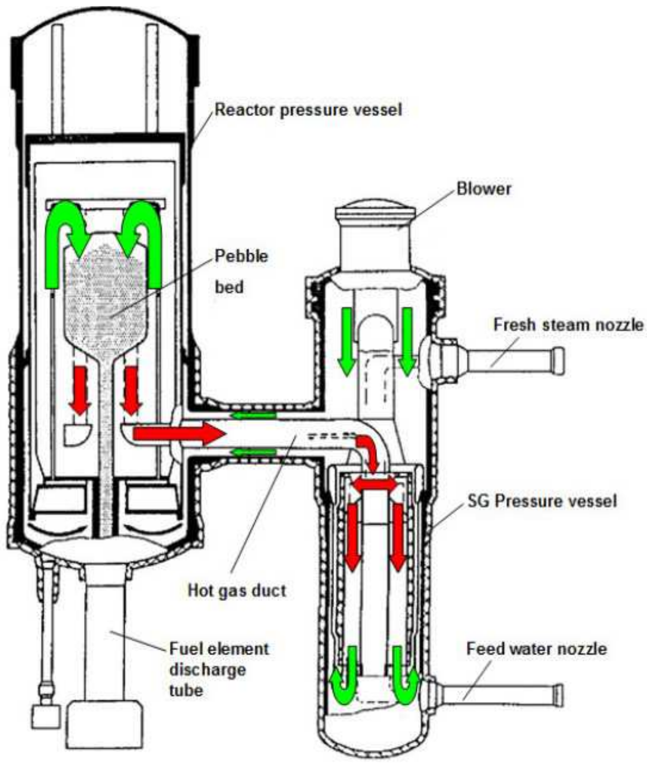

Fig. 1 Main components of the RDE and the helium flow path inside

Modelling of the RDE has been performed in two steps separately, which were the reactor part and the helical steam generator part. The purpose of the two steps modelling was to obtain a steady-state calculation of thermal parameter according to the basic design. In the separated modelling of the reactor part, the boundary condition, especially the inlet gas temperature, reactor pressure and helium mass flow rate, were easily determined to simulate the heat transfer from the pebble bed core into the helium gas. On that case, the purpose of the simulation was to calculate the core outlet helium temperature and the highest pebble bed temperature under 10 MW core thermal power [10]. In the helical steam generator part, thermal parameters to be validated were the core inlet helium temperature and the superheated steam temperature due to the heat transfer in the helical tubes from the helium gas into the feedwater flow under constant feed water temperature and mass flow rate.

A. *Core Modelling*

The RDE core modelling assumed a volume separation of helium flow inside the pebble gaps and the pebble bed. In the radial direction, there were six core zones, in which the helium and the pebble volume were defined by the averaged void fraction ε_b of 0.39. ε_b itself is defined as the average volume of the gaps between the pebbles (porosity) in a single volume inside the core. Fig. 1 shows the developed core model in the RDE reactor using the RELAP5/SCDAP/Mod3.4 code in the previous work. On each radial core channel, the number of pebbles were determined based on the 0.06 m pebble diameter, 1.8 m core diameter, 1.98 m core height, and averaged ε_b, which generated heat to the helium volume attached to them. The total number of the pebbles should be 27,000 on nearly similar channel division as defined by the spherical heat structures provided by RELAP5. The input data in the core channels are summarized in Table 1 shows the number of spherical heat structures, helium flow areas, calculated void fraction ε_b, and core channel (ring) outer diameter.

TABLE I
SUMMARY OF THE CORE CHANNEL MODELLING FOR THE RELAP5 INPUT DATA

Core channel	**Number of pebbles**	**Flow area, m^2**	**Void fraction, ε_b**	**Core channel (ring) diameter, m**
1	2000	0.0758	0.386	0.5
2	2600	0.0986	0.383	0.76
3	3600	0.1289	0.381	1.0
4	5600	0.2032	0.379	1.3
5	5800	0.2027	0.379	1.54
6	7400	0.2579	0.378	1.8

In the axial direction, each core channel was divided into ten segments with cross-flow on each segment starting from the middle core channel (1st channel) to the surrounding core channels up to the last core channel (6th channel) as showed in Fig. 2 (left figure). The flow inside the middle core channel entered the fuel discharge tube into the inner hot helium plenum. In other core channels, the heated flow from the pebble bed was directed by outlet channels into the outer hot helium plenum, where mixing of hot helium flow from the inner plenum took place before going out into the hot gas duct.

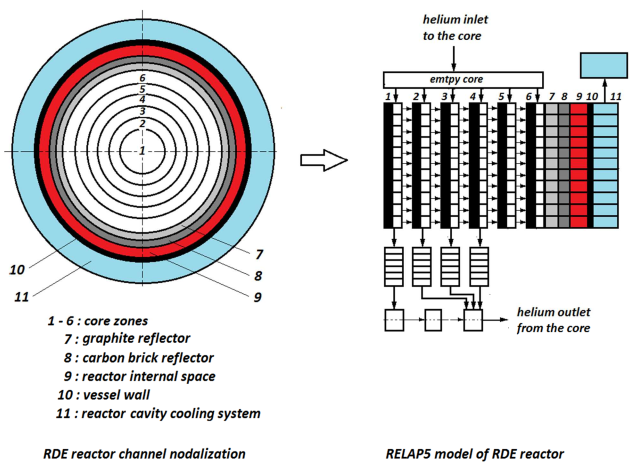

Fig. 2 Developed core model and core heat loss using RELAP5

In addition to the core section, the heat transfer into the graphite and carbon bricks reflector was also modelled as other heat structures with the thickness of 0.778 m and 0.432 m respectively as showed in Fig. 2 (right figure). Related material properties for those structures such as thermal conductivity and capacity are available in the IAEA document [11] as the function of temperature. Overall, the core heat loss will take place in the side reflectors, side helium gap inside RPV, vessel wall, and the air volume of the reactor cavity cooling system (RCCS).

The air inside RCCS acts as the ultimate heat sink, in which the core heat loss is directed to the outside environment. By design, the RCCS is engineered structures consisting of cooling water panel, air cooler, and evaporation tank to continuously remove the heat from the reactor vessel during the normal operation or the decay heat during a postulated loss of forced cooling accident into the environment by means of conduction, radiation, and convection [11]. In the RELAP5 model, the heat transfer inside the air cavity to the environment was simplified using the helium gas with a certain heat transfer coefficient. This method is taken to maintain the temperature inside the cavity around 60 °C or correspond with the 240-kW heat dissipation during normal operation [12].

The heat transfer mechanism inside the RDE is represented by the material thermal properties forming the reactor such as the helium, pebble fuel, graphite reflector and carbon bricks, and vessel wall. The RELAP5 code provides the thermal properties of helium gas such as the density, specific heat capacity, dynamic viscosity, and conductivity. The material properties for graphite reflector, carbon bricks, and vessel wall of the SA508 material are provided by the IAEA document [11], which are defined as heat conductivity and specific heat capacity. The most important material properties are related to the pebble component, which in this case assumes the heat conductivity of uniform pebble bed for input data. That heat conductivity (W/cmK) as a function of temperature (°C) combines the effect of different heat transfer mechanism of radiation, conduction, and convection [13, 14], which is defined by the following relation:

$$\lambda = 1.1538.10^{-6}.(T + 100)^{1.6622} \quad (1)$$

B. Core Power Definition

The RDE core power was defined as a point kinetic in RELAP5, which assumes that the reactor power can be separated into space and time functions. The point kinetic model allows the coupled simulation of core reactor kinetics and thermal-hydraulics by considering a lumped parameter approach for the kinetics [15, 16]. The core power must represent a certain power distribution axially and radially, which are determined by neutronic analysis. The RDE core neutronic was analyzed for two modes of pebbles circulation through the core, which is once-through-then-out (OTTO) and multi-pass mode. For this analysis, power density distributions for OTTO mode were used, which were calculated using GAVROSH code [10]. The radial power distribution was estimated for the six core sections to represent the radial power fractions, in which each of those 6 core sections followed the profile of the axial power fraction for the ten axial segments as the axial power distribution.

C. Helical Steam Generator

The helical steam generator of RDE was modelled by first assuming the multiple-layer of helical tubes as a straight tube with the flow area calculated from all 49 helical tubes. The feedwater flowing inside the helical tubes has a specific heat transfer mechanism, which is analytically higher than the straight tubes by 16 to 43 % [17]. The helical steam generator is designed to generate superheated steam at 520 °C temperature and 6 MPa pressure from the feed water at 145 °C temperature and 3.45 kg/sec mass flow rate flowing from the bottom upwards. The validation of the separated helical steam generator model resulted in the helium temperature moving back to the RDE of 236 °C and the generated superheated steam temperature of 525.45 °C, which were based on the constant helium temperature entering the steam generator at 700 °C and 3.5 MPa primary pressure.

D. Modelling of the Loss of Primary Flow Event

The event is started after the reactor simulation reaching the steady-state condition of 100 % core power. It is initiated by the failure of the helium blower, which stops the helium flow in the primary loop. That event will initiate the isolation of the primary system from the secondary water-cooling systems of the helical steam generator. In the RELAP5 input data, the blower part is modelled by a Pump component to define the RDE blower specifications such as rated flow, velocity, torque, density, and head parameter. During the input validation, the mass flow rate will change with the helium density, which causes the value of 4.27 kg/sec as the constant mass flow rate difficult to achieve. Therefore, the blower component is controlled to maintain the rated flow rate by automatically setting the pump velocity to achieve the steady-state condition. To analyze the effect of the event, a complete RDE model should be provided first, in which the reactor model and the helical steam generator model are integrated to form a nuclear steam supply system (NSSS) of the RDE. The simulation of NSSS should be performed first to achieve the steady-state condition before the initiation of the loss of primary flow event.

III. Results and Discussion

A. Steady-state Simulation

The loss of primary flow event to be simulated requires a steady-state calculation from a complete model of the RDE. Fig. 3 illustrates the result of integrating the reactor and helical steam generator of RDE by the co-axial cold and hot gas duct and the blower component. As described in the design, the hot gas duct (P-400) directs the hot gas helium from the reactor to the upper part of the helical steam generator before entering the outer surface of helical-coiled tubes (P-440), in which the heat transfer to the feed water inside the helical tubes (P-670) takes place. The cold gas helium is then deflected into the gap between the steam generator vessel and the shroud (P-460) before entering the suction part of the blower and discharged into the cold gas duct (P-300). The steady-state calculation is summarized in Table 2, showing the operational parameter of the RDE for the 10 MWt core power. One important parameter to be noticed is the maximum fuel center temperature, which should not exceed 1,230 °C as the margin temperature during full-power operation [12, 18]. As shown in the table, the average calculated helium temperature in the core inlet is 4.1 % smaller, and the outlet temperature is 1 % higher than the design values. The core inlet temperature is an averaged temperature, which is calculated from the helium temperature in the cold gas duct (P-360) and in the empty core volume (B-115) above the pebble bed. The resulted steam temperature is lower than the design value. Even it is already superheated under the calculated steam pressure as expected. The calculated highest pebble temperature in the whole core takes place in the middle core zones (P-116) in the lowest segment, which is below the limit value.

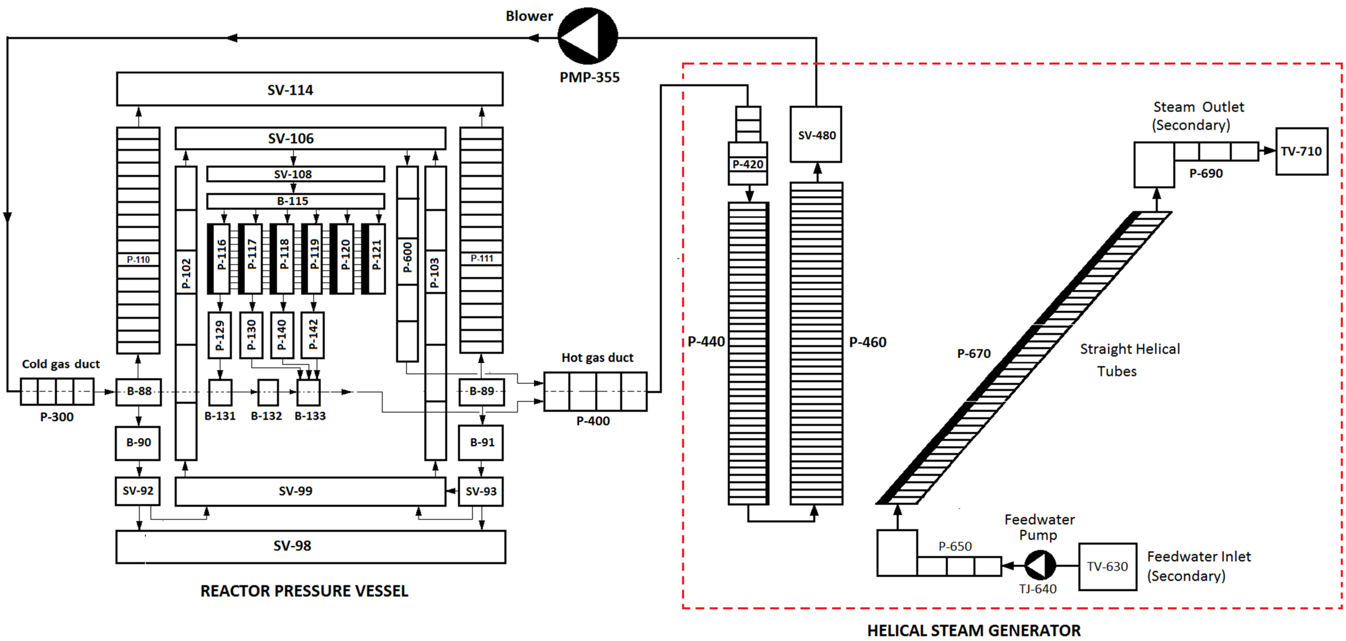

Fig. 3 The integrated model of RDE Nuclear Steam Supply System (NSSS) developed by RELAP5 code

TABLE II
STEADY-STATE CALCULATION OF THE RDE OPERATIONAL PARAMETER

Parameter	Value	
	Design [10]	RELAP5
Core power, MWt	10	10 *
Temperature of helium, °C - vessel inlet - vessel outlet	 243.0 700.0	 229.71 712.18
Mass flow rate of helium, kg/sec	4.27	4.27 *
Pressure of helium, MPa	3.5	3.5
Mass flow rate of steam, kg/sec	3.54	3.54 *
Pressure of superheated steam, MPa	6.2	6.24
Temperature of superheated steam,°C	525.0	475.12
Temperature of feed water, °C	145.0	143.49 *
Highest pebble temperature, °C	1,015.0	1,149.0

** set as input data*

B. Loss of the primary flow event

After the steady-state condition is achieved, the trip of the blower component is initiated to simulate the loss of primary flow event. There are two events to be simulated following the event, which are with and without activation of the reactor protection system to shut down the reactor. To respond the event, the reactor protection system (RPS) detects the changes in the operational parameter to initiate management actions, which are shut down the reactor by dropping the reflector rods and isolation of the secondary system. In the RELAP5 input data, the reactor shutdown is initiated by inserting the negative value reactivities for a certain time period. The RPS action is initiated after one of several specific limit values is exceeded, which in this case the increase of the cold gas helium temperature bigger than 290 °C is used in the simulation [18]. The results of the simulation presented here are only for the sequences without the reactor trip, since the core power will automatically decrease after the dropping of the reflector rods.

The sequences without the RPS activation will rely on the reactor responses capability to the increase of the fuel pebble temperature due to the loss of cooling. During that event, the fuel temperature reactivity coefficient (FTC) plays a significant role to ensure the safety of the reactor. The FTC value for the equilibrium core adopts the HTR-10 calculation, which is – (minus) 2.55 pcm / °C [18]. The value is then recalculated to provide several reactivities as a function of the fuel temperatures. The overall average score FTC is subdivided into the 6 core zones according to the power fraction.

The decrease of the primary flow will cause a decrease of core heat removal as shown later by the increase of the pebble temperature. Fig. 4 shows the transient of the primary flow for 50,000 seconds and the primary pressure in the cold gas duct (P-360) and above the pebble bed (B-115) after the blower trip. In the figure, the primary pressure increases steadily into a constant level, because the heat transfer on that volume is affected by the heat loss through the reflector and finally to the RCCS cavity, which requires particular modelling on the structures.

The increase of helium pressure in Fig. 4 corresponds with the increase of the helium temperature in the cavity above the pebble bed (B-115). Both parameters are affected by the residual core power, which still produces heat, as shown in Fig. 5.

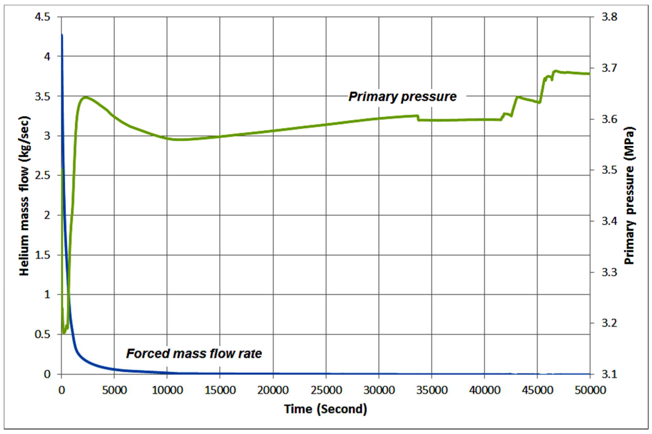

Fig. 4 Transients of the primary mass flow and helium temperature without a reactor trip

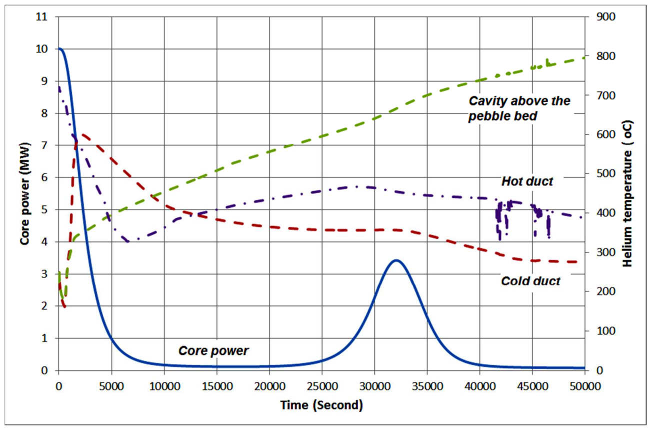

Fig. 5 Transients of the core power and helium temperature in the primary system

On that figure, the helium temperature above the pebble bed increases steadily, while in the cold and hot duct decrease, which affect the primary pressure as shown previously in Fig. 4. The effect of the negative FTC can be seen on the automatic decrease of the core power even the RPS was not activated. After some time, the core will become critical again, which is showed by the fission power oscillation. That negative FTC will respond to the increase of fuel pebble temperature after the loss of forced flow event, as shown in Fig. 6, which finally change the core power.

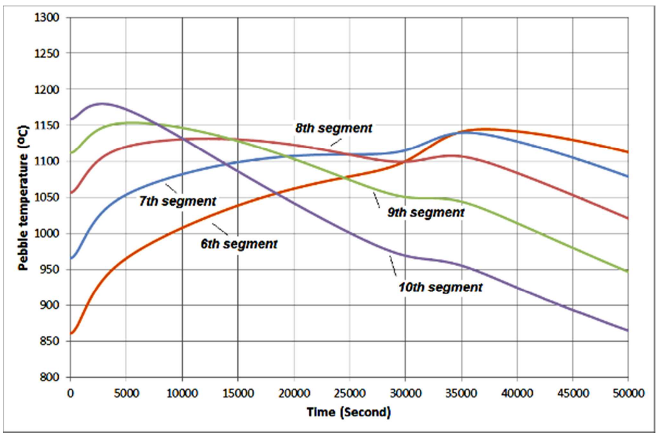

Fig. 6 Transient of pebble temperature (5 lowest segments) in the middle core following the event with the insertion of FTC

Overall, the temperatures in the fuel pebble, especially in the middle core channel (HS-116) with the highest radial power distribution, are below the limit of the 1,230 °C. Fig 7 shows the calculated pebble temperatures for the six core channels (HS-116 to HS-121) in the axial direction at the end of the simulation. The calculated temperatures in the middle of the graphite and carbon brick reflector, internal reactor space, vessel, and the air in the RCCS cavity are also summarized in that figure.

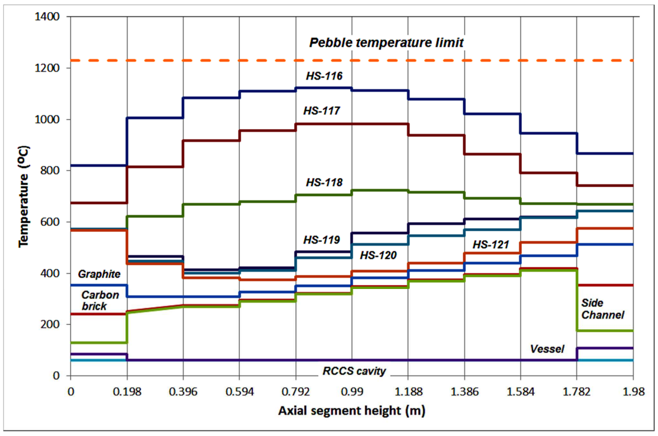

Fig. 7 The temperature of the pebble in the core, graphite and carbon brick reflector, reactor internal space, vessel, and air in the RCCS cavity

Based on the simulation, the role of the heat transfer modelling into the air of RCCS cavity is very significant to achieve a more realistic temperature change, especially inside the reactor vessel. The RELAP5 limitation to model two different non-condensable gases (air and helium) will affect the results of the simulation, which requires special treatment in the input data preparation.

IV. CONCLUSION

The loss of forced flow in the experimental power reactor (RDE) model has been simulated using the RELAP5 code specified for the simulation of coolant systems of the light water reactor. The spherical fuel option in the RELAP5 has been fully utilized to obtain the pebble bed core model. The steady-state calculation of nuclear steam supply system (NSSS) has resulted in an operational parameter, which is close to the RDE design data in the primary and secondary system. The following loss of forced flow can be stimulated by the RELAP5 blower component model, in which the reactor responses are analyzed. The scenarios of the event without reactor shutdown result in the safe decrease of the fuel pebble temperature during the simulation progress, which is more because of negative FTC and the core heat removal by the RCCS cavity cooling. The safe limit of pebble temperature of 1230 °C is not exceeded following the event. Overall, the RELAP5 code has a limitation, especially to define the two different non-condensable gases existed in the RDE system and because of the complexity of radiation model. Those factors contribute to reducing the accuracy of the simulation results. However, part of the simulation results can be used to contribute to the preparation of RDE safety analysis report.

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