Tri Dasa Mega Vol. 21 No. 2 (2019) 51–58

Jurnal Teknologi Reaktor Nuklir

Tri Dasa Mega

Journal homepage: jurnal.batan.go.id/index.php/tridam

Development of Experimental Power Reactor (EPR) Model For Safety Analysis Using RELAP5

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ARTICLE INFO

Article history:

Received: 28 May 2019
Received in revised form: 18 June 2019
Accepted: 20 June 2019

Keywords:

experimental power reactor
development
RELAP5
Steady-state

A B S T R A C T

Pebble bed reactor design, classified as the high temperature gas-cooled reactor (HTGR), is currently being part of BATAN main program to promote nuclear energy by starting the Experimental Power Reactor (EPR) program since 2015. Starting from 2018, the detail design document has to be submitted into nuclear regulatory body for further assessment. Therefore results of design analysis have to be supplemented by performing a design evaluation, which can be achieved by developing the model of the EPR. The development is performed using RELAP5/SCDAP/Mod.3.4 as the thermal-hydraulic analysis code validated for the light-water reactor having module for the pebble fuel element and non-condensable helium gas. Methodology of model development consists of defining the helium flow path inside the reactor pressure vessel, modelling of pebble bed core including its power distribution, and modelling of reflector components to be simulated under 100 % core power. The developed EPR model results in design parameters, which confirm the main thermal data of the EPR, including the pebble and reflector temperatures. The peak pebble temperature is calculated to be 1,375 °C, which requires further investigations in the model accuracy, since the reference values are around 1,015 °C, even it is below the pebble temperature limit. For safety analysis, the EPR model can be used under nominal core flow condition, which produces more conservative results by paying attention on the RELAP5 specific modules for the pebble bed-gas cooled system.

1. INTRODUCTION

The High Temperature Gas Cooled Reactor (HTGR) is a high temperature reactor type having nuclear fuels formed by small particles containing uranium in the core. There are two HTGR types looking at the core design, which are prismatic core HTGR, also defined as Prismatic Modular Reactor (PMR), and pebble bed core HTGR or Pebble Bed Reactor (PBR) [1, 2]. Both HTGR designs utilize the helium gas, which flows as a coolant to remove generated heat in the core. Pebble bed reactors are considered as the most advanced technology especially to power the future hydrogen economy by offering the advantages of emission free operation, high energy efficiency, and naturally safe or physically no fuel meltdown is possible [3]. The PBR also drew attention in Indonesia to be part of the one of national program to support the National Medium Term Development Plant in year 2015 – 2019 by starting the Reaktor Daya Eksperimental (RDE) or Experimental Power Reactor (EPR) program in 2015, conducted by the Indonesia National Nuclear Energy Agency

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DOI: 10.17146/tdm.2019.21.2.5449

(BATAN). The main goal of EPR program is to develop national capability of BATAN in the nuclear reactor technology by mastering the design, construction project management, commissioning and operation of a experimental power reactor [4]. The EPR program was inspired by the China R&D program for the HTGR began in the mid-1970s, which accomplished the construction of the HTR-10 test reactor in the 1990s [5]. One important step of the EPR program was the completion of EPR basic engineering design developed internally by BATAN in 2017, almost simultaneously with the approval of the EPR Site Licensing from the National Nuclear Regulatory Body (BAPETEN) in January 2017. The next step of the program is the detail design and safety analysis report of EPR to be completed in 2018.

One important part of the safety analysis report is the demonstration of the EPR plant to operate safely according to the determined design criteria. Those design criteria are normally presented in form of steady-state condition, in which several operational parameters should be in conformance with the design criteria, obtained from calculation using certain calculation program or code. That confirmation of the EPR design is important before conducting the safety analysis simulation to demonstrate the safety level of the EPR against specific safety criteria. One particular code owned by BATAN is the RELAP5/SCDAP/Mod3.4, which is originally developed for the thermal hydraulic transient simulation of light water reactor coolant systems. The use of RELAP5 with other version and other similar code in modeling the PBR can be found in the research article related to the thermal modeling of HTR-10 design [6, 7]. The purposes of this research is to develop a model of the EPR design using the RELAP5/SCDAP/Mod3.4 in order to study the RELAP5 capability in determining the most representative model for further safety analysis. The focus of the modeling is the pressure vessel and core section of the EPR design to obtain a general view of the modeling approach and its result on the steady-state parameter. One challenge to be found is modeling the pebble bed in the EPR core using model properties provided by RELAP5 and their additional input data such as defining the core zone, mapping helium flow inside reactor structures, and displaying specific heat transfer characteristic. As a source of model development, the EPR basic design document provided by BATAN as also several references related to the HTR-10 design were used.

2. DESCRIPTION OF REACTOR PRESSURE VESSEL OF EPR DESIGN

The basic concept of the EPR is that its pressure boundary consists of the reactor pressure vessel (RPV), the steam generator pressure vessel and hot gas duct connecting both main components. The EPR is designed to generate heat of 10 MWt from the spherical fuels forming the core inside the RPV. It uses helium gas as a coolant, that enters the lower portion of the vessel through the nozzle of cold gas duct into the vessel internals. The helium gas is then directed upward through cold gas columns in the side reflector made of ceramic internals into a upper plenum. From there, it flows downward into the reactor core to leave the RPV through the hot gas duct, which is coaxial with the cold gas duct. Fig. 1 shows the general illustration of the RPV, which also houses other components such as control rods, fuel inlet pipe, and metallic supports and other columns.

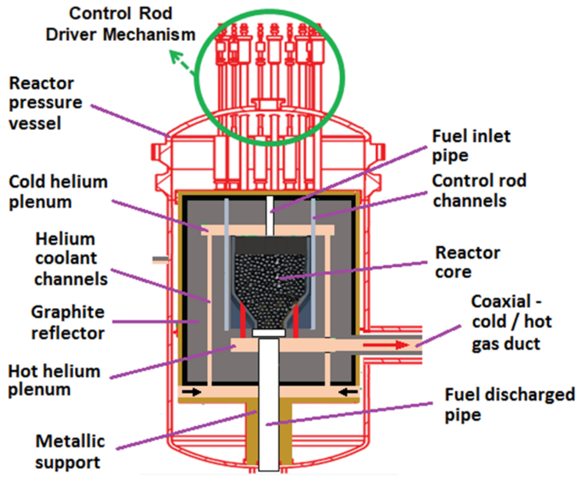

Fig. 1. General scheme of internal components of EPR's Reactor Pressure Vessel (RPV) [4]

The reactor core has a cylindrical geometry in the upper part and cone-shaped in the lower part formed by ceramics made of stacked graphit blocks. The core is filled with around 27,000 Uranium spherical fuel elements (TRISO pebbles) of 6 cm diameter to form a pebble bed, in which each pebble goes down through a fuel inlet pipe and is discharged through a discharging tube, alternately. The geometries of the RPV internals adopt the RPV descriptions of HTR-10, since the generated heat and the number of pebbles are identical [8]. Table 1 summarizes some geometrical data of the EPR internal structures inside RPV, in which helium gas flows inside.

Table 1. Geometrical data of the RPV internal structures of EPR [8]

RPV internals	Number	Size (cm)
Cold helium channels	20	Ø 8
Control rod channels	10	Ø 13
Cold helium plenum	-	Ø 50
Holes connecting upper plenum to the core	460	Ø 2.5
Core equivalent	-	Ø 180
Core active height	-	198
Height of empty cavity above pebble bed	-	40
Holes connecting core to the hot helium plenum	640	Ø 1.6
Equivalent outer / inner size of hot helium plenum		Ø 170 / 100
Fuel discharging tube		50

Each pebble or spherical ball consists of two parts, which are graphite shell with a thickness of 5 mm as the outer layer and graphite matrix with a diameter of 50 mm as the inner part containing homogenously dispersed coated fuel particles or kernels. The UO2 kernel has a diameter of 0.5 mm with initial enrichment of 17 %. The pebble bed is formed by the pebbles with the volumetric filling ratio of 0.61. The helium gas entering the pebble bed will be heated under designed pressure and mass flow rate provided by a gas circulator. The main thermal parameters generated from the EPR pebble bed are shown in Table 2.

Table 2. Main thermal parameters of the EPR [9]

Parameter	Value
Core thermal power	10 MW
Primary helium pressure	3.5 MPa
Helium temperature at reactor inlet	250 °C
Helium temperature at outlet	700 °C
Helium mass flow rate at full power	4.27 kg/sec

The data described in Table 1 and fuel element data will be used for modeling the EPR using RELAP5/SCDAP/Mod3.4. The aim of the modeling is to obtain the main thermal parameter as shown in Table 2.

3. MODELING OF EPR USING RELAP5 CODE

The RELAP5 code owned by BATAN is a version with the capability of severe accident calculations developed for thermal hydraulic transient simulation of light water reactor coolant systems. It is a highly generic code contains fluid properties ranged from mixture of steam, water, non-condensable gases, and non-volatile solute [10]. As a non-condensable gas, helium in the gas cooled reactor is also accomodated in RELAP5 code. Application of RELAP5 in the gas cooled reactor can be found in the thermal modeling of HTR-10, which is focused only on the core section [6]. The present model of EPR is not only limited to the core section but also extended to the helium flows inside the reactor internal structures, especially inside the reflector. In the core section, extensive study has been done to model pebble bed and helium flows among pebbles in the core to calculate pressure drop in the core [11].

The developed model of EPR using RELAP5 is illustrated in Fig. 2. In the model, two boundary volumes (TV-350 and TV-450) are determined to represent the cold helium gas as the starting system and hot helium gas as the end system. To define helium mass flow rate, a pump model (PMP-335) provided by RELAP5 is placed before the cold gas duct, which also acts as helium circulator in the primary system. After that, a number of pipes (denoted as P) and single volumes (denoted as SV) connected with junctions are modelled to represent helium gas flow inside the reactor internals. It starts with cold helium pipe (P-360), which is co-axialed placed surrounding the hot helium duct (P-400) to direct the helium gas into the side annulus inside the vessel wall, which is divided into left and right parts. The side annulus consists of the top side annulus (P-110 and P-111) and bottom side annulus (SV-92 and SV-93) to be united in the lower cold helium plenum (SV-99). From there, the cold helium gas enters the cold helium channels (P-102 and P-103) inside the graphite reflector into the upper helium plenum (SV-106) before directed in to the core. Part of the helium flow entering the core, is directed into a bypass volume (P-600) to simulate the leaked helium flow in the reflector gaps to be united in the hot gas duct. The calculated helium flow entering the core should be around 87 % of the nominal helium mass flow rate of 4.27 kg/sec [8]. The core chamber itself is formed by an empty part (B-115) modelled as the branch component and pebble bed, which is divided into 6 radial core sections. Those core sections are the P-116 as the middle or the 1st core section, P-117, P-118, P-119, P-120, P-121 as the 2nd to 6th core ring, respectively, in which all core sections are divided into 10 axial segments.

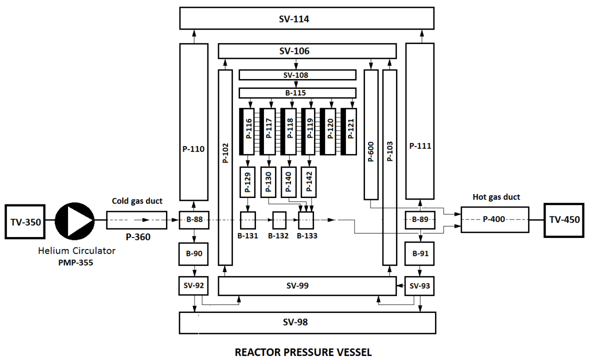

Fig. 2. Nodalization of helium flows inside the EPR reactor vessel using RELAP5

Among core sections, cross flow junctions are defined to allow radial helium flows inside the pebbles. Each core section defines the heat structures simulating the pebble fuel elements and voids representing the helium gas among the pebbles. From the 2nd up to the 4th core section, the helium gas flows through the holes (P-130, P-140, P-142) into the outer hot helium plenum (B-133) before entering the hot gas duct (P-400). Small part of the helium gas in the core also enters the fuel discharging tube (P-129) to be collected in the middle hot helium plenum (B-131) before directed into the outer hot helium plenum with big flow resistances.The heat structures representing the pebble fuel elements are characterized by material properties as input data in the RELAP5. Those properties are the thermal conductivity and heat capacity of the fuel element, which refer to the IAEA technical document [8].

Simulation of the model is performed based on the nominal EPR operational condition as summarized in the Table 1. To achieve that condition, the boundary condition in TV-350 is determined with the helium pressure and temperature at the reactor inlet of 3.5 MPa and 250 C and in the helium circulator of PMP-335 with 4.27 kg/sec of mass flow rate. The boundary condition in TV-450, especially the temperature is set similar with the reactor inlet, even there will be an increase of the helium gas temperature right after the core outlet to be anticipated. The core power of 10 MWt is defined in the heat structures of the core sections by calculating the number of the pebble fuel elements and the helium flow areas.

4. RESULTS AND DISCUSSION

The core model represented by the 6 core sections contains parametric values of helium flow area and the number of pebbles for generating core heat based on the determined void fraction. To estimate the helium gas flow area inside the pebbles, one parameter to be determined is the average porosity of the pebbles, ε_b, which is estimated by following equation [12]:

$$\varepsilon_b = \frac{0.78}{(D/d_p)^2} + 0.375 \qquad (1)$$

ε_b or the void fraction is defined as the average volume of the gaps between the pebbles in a single volume of the bed. D is the bed diameter according to the core section and dp is the pebble diameter, which in this case is 60 mm. By knowing the bed volume, void fraction for each pebble diameter, and the bed height, which is 1.98 m for all core sections, the void flow area can be calculated. Table 3 summarizes the calculated parametric values of each core section to be used in the RELAP5 input data.

Table 3. Summary of parametric values for the core zones.

	Core sections					
	1	2	3	4	5	6
A	0.5	0.572	0.655	0.826	0.825	0.931
B	0.386	0.383	0.381	0.379	0.379	0.378
C	0.075	0.098	0.128	0.203	0.202	0.257
D	0.613	0.616	0.618	0.620	0.620	0.621
E	2000	2600	3600	5600	5800	7400

A. Core diameter (m), B. Average porosity (ε_b), C. Void flow area (m^2), D. Pebble fraction, E. Amount of pebbles

The core diameter is calculated from the middle core (1^{st} core) and the areas of the core rings (2^{nd} to 6^{th} core). The diameter data is used to calculate the average porosity on each core based on the Equation (1) and therefore the void flow area and the volume fraction of the pebble, which is one minus the average porosity. From the pebble fraction data, the number of the pebble of each core can be estimated. The number of the pebbles in this case is approximated on each core to be close with the EPR design of around 27,000 pebbles.

The core power in the EPR core sections have to represent a certain power distribution axially and radially, which are determined by neutronic analysis. Based on the EPR concept design, the core neutronic were analyzed for two modes of pebbles circulation through the core, which are once-through-then-out (OTTO) mode and multi-pass mode. For this analysis, power density distributions for OTTO mode are used, which are calculated using GAVROSH code [9]. The radial power distribution is estimated for the 6 core sections to represent the radial power fractions. For each of the 6 core section having its own radial fraction, an axial power fraction is set for the 10 axial segments having characteristic of the axial power distribution. Fig. 3 and 4 shows the determined radial and axial (elevation) power fractions used to model the core power in the RELAP5.

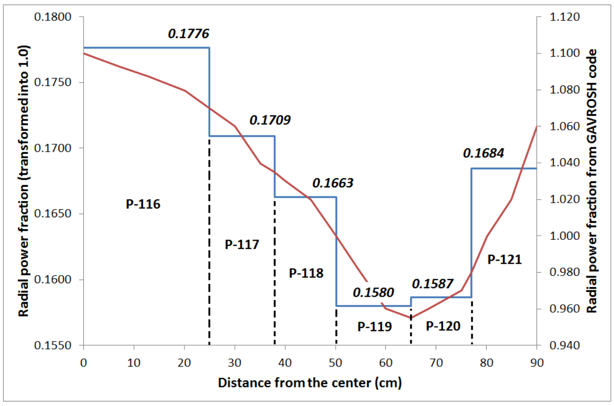

Fig. 3. Radial power fraction for the core power modeling using RELAP5

The total value of the 6 radial power fractions should be 1.0 to be correlated with the total core power of 10 MWt. Each of 6 radial power fractions is correlated with the axial power fraction divided into 10 segments of the all core sections segments. The left and right axes on the 2 figures are related to the modified values obtained from the data of GAVROSH code, respectively. In addition, each of 6 radial power fractions has the number of pebbles as calculated in Table 1. For instance, the middle core section (P-116) has 2000 pebbles having 0.1776 power fraction of the 10 MWt core power.

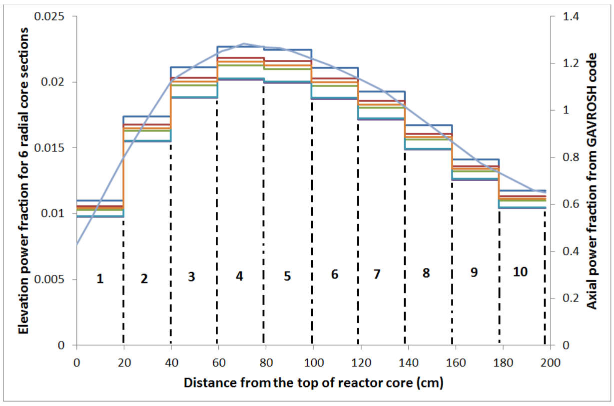

Fig. 4. Axial power fraction for the core power modeling using RELAP5

Simulation of the EPR model is objected to calculate the helium gas temperature in the core outlet and pebble temperature distribution in the 6 core sections to be compared with the design data under 10 MWt core power. The first simulation is performed based on the pebble bed model only without heat loss to the reflector with the nominal helium mass flowrate of 4.27 kg/sec as designed. Fig. 5 shows the increase of the helium temperature after absorbing heat in the core calculated in the outlet volume (P-130 of Fig. 2). The helium temperature measured in the inlet core (B-115 of Fig. 2) is basically similar with the helium temperature determined in the TV-300 of 250 °C. The steady-state helium temperature in the outlet core is achieved after 40,000 second simulation to the value of 589 °C. If the helium temperature is measured in the hot duck volume (P-400), an increase to 702 °C is observed due to the mixed heated helium gas from the hot helium plenums. Those values are close with the design parameter of 700 °C as included in Table 2. The measured mass flow rate in the inlet core (B-115) is around 3.873 kg/sec, which is about 90 % of the rated helium mass flow rate of 4.27 kg/sec provided by the primary blower (PMP-355 of Fig. 2). The value is slighly lower than the target downrate of 87 %, which depends on the determined flow loss entering the bypass volume of P-600.

The pebble temperatures in the 6 core sections (pebbles inside the P-116 to P-121) are shown in Fig. 6 after 40,000 seconds simulation, in which the temperature on each axial segment is homogenized for the 10 segments. The pebble temperature should not exceed the limit temperature in the SiC layer of 1,620 °C [4, 9, 13]. The highest pebble temperature is observed in the lower core section of P-116 even it is still below the pebble temperature limit.

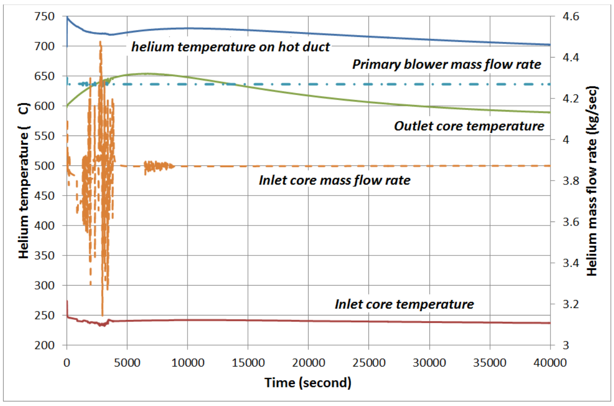

Fig. 5. Calculated helium temperature at inlet and outlet core and helium mass flow rate of EPR

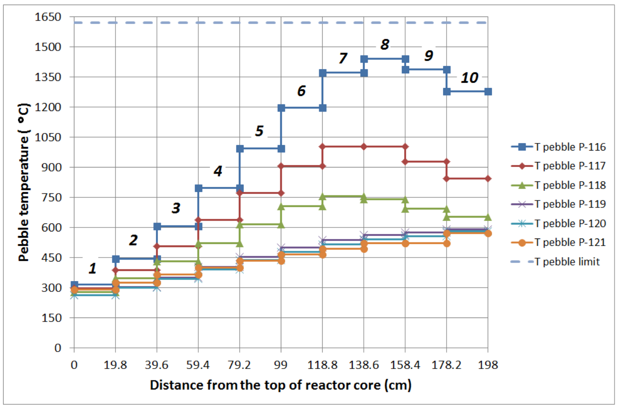

Fig. 6. Calculated pebble temperatures for the 6 core sections in axial direction

The highest value can be traced back to the highest radial power factor as indicated in Figure 5. The results on Fig. 6 are based on the heat transfer mechanism of convection from the pebbles into the helium gas and conduction inside the pebbles. Other heat transfer mechanism to be considered is the radiation among the pebbles, which has to be specified in the RELAP5 input data. Due to the complexity of the radiation heat model among pebbles in the RELAP5, the radiation heat transfer is represented by the effective thermal conductivity, which is applied in the homogeneous section or in the near wall-region of the pebble bed [14]. The results of RELAP5 simulation shows that the pebble temperatures in the outest core section (connected to P-121) become higher than those without considering radiation by 7 degree. The results shown in Fig. 6 are much different than the preliminary simulation results conducted based on the different core model [15], in which the pebble temperature in the middle core was much higher than the pebble temperature limit even with rated mass flow rate of helium entering the core. The anomaly was compensated then by setting a different loss coefficient in the middle core. Some differences with the previous model are the modelling of more hot pipes after the core section (P-130, P-140, and P-142), more core radial division from 4 to 6 sections with all similar loss coefficients, and similar height for all 6 core sections to allow uniformed cross-flow between segments. Those allow a much more distributed helium flow out of the core to simulate the real condition closely.

The EPR reactor design incorporates the installment of graphite reflectors and carbon bricks surrounding the pebble bed core. The graphite reflectors serve as neutron reflector, whereas the carbon bricks as thermal insulator and neutron absorber. To simulate the role of the graphites and carbon bricks structures on the pebble temperatures, another simulation was carried out by modeling additional heat structures around the pebble bed core consisting of the graphite and carbon brick structures and reactor pressure vessel in the side direction only. Related material properties for the graphite and carbon brick structures are availble in the IAEA document [8]. Therefore the core heat in the helium coolant will be also absorbed by the side reflectors, helium in the annular space, vessel wall, and the air gap of the reactor cavity cooling system (RCCS). Fig. 7 shows the schematic design of the EPR reflector and RCCS to be modelled using the RELAP5. It is assumed, that the heat dissipation from the core occurs in the outermost core ring (P-121) to the adjoined reflectors and finally to the RCCS air space as the ultimate heat sink. The results of simulation with reduced core mass flow rate are shown in Fig. 8 for the pebble temperatures.

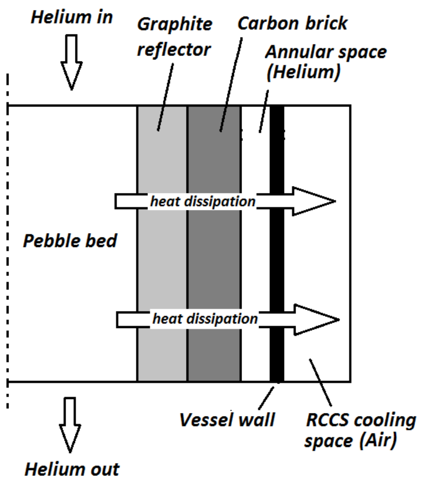

Fig. 7. Mechanism of core heat loss into surrounding reflectors and RCCS in the EPR model

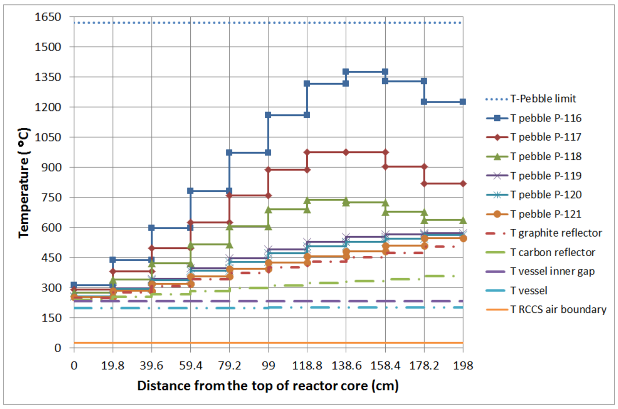

Fig. 8. Calculated temperatures in the core, reflector, and vessel wall with RCCS heat sink

From the Fig. 8, the calculated pebble temperatures are in general lower than those of Fig. 6 since the heat loss to the reflector and vessel wall and into the environment are considered. The highest pebble temperature is calculated on the 8 segment of the middle core (P-116) for the core model without reflector at 1440 °C and for the core model with reflector of 1375 °C. A gradual decrease of temperature is calculated in the reflector (graphite and carbon bricks), vessel annular gap, vessel, and finally in the air outside the vessel. The air outside the vessel is a simplified representation of the RCCS function, in which the temperature is kept constant at around 25 °C. The results show the importance of the reflectors and RCCS to affect the pebble temperature in the EPR core below the limit. On the other side, the heat loss modeling contributes in reducing the helium temperature at the hot gas duct from the 702 °C to 698 °C.

To assess the accuracy of the pebble temperature calculation using the RELAP5 model, a benchmark analysis is carried out by comparing the simulation results with the calculation in the EPR document [9]. The EPR document contains the calculated pebble temperature in average in radial direction as function of the core height as shown in the Fig. 9.

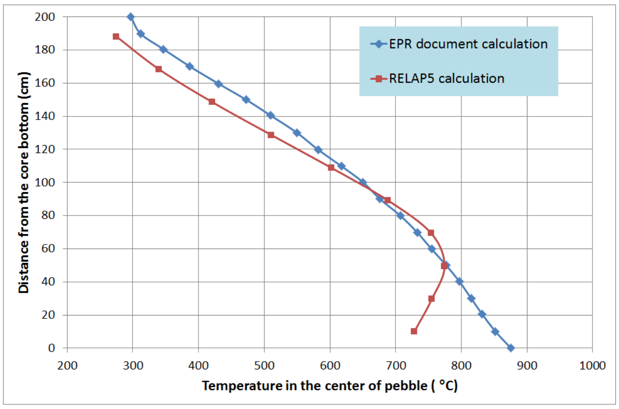

Fig. 9. comparison of pebble temperature calculation using RELAP5 and EPR document

From that figure, the average radial pebble temperature between RELAP5 and EPR calculation are close each other particularly in the upper core to the half of the core height from the bottom. Almost in the core bottom, there are a little deviation of the pebble temperature, which might be caused by the non-uniformity of the core flow on that sections. Until now, there are not many detail descriptions regarding the core model of the EPR in the document. Several data are described in the EPR document for discussion such as that the thermal power released to the RCCS achieves the value of 76.5 kW. The RELAP5 calculation results in the total thermal power released to the RCCS air gap of 54.65 kW, which is achieved by the convective heat transfer only. The RELAP5 code can accomodate the radiation heat transfer model, which is not yet applied in the current EPR model, that might cause the calculation difference. Another parameter is the maximum pebble temperature, which is obtained in the reactor core outlet based on the EPR document, of 875 °C. By considering the divergence of parameters from nominal values, the pebble temperature can reach maximum 1,015 °C. RELAP5 calculation results in the maximum pebble temperature of 1,375 °C, which is occured in the middle core section. Even this value is below the pebble temperature limit, it is in general still high, if the HTR-10 calculation is also used as reference. For instance, the range of maximum fuel temperature can achieve from 919 to 988 °C [8, 16]. The reason for the higher maximum pebble temperature in the RELAP5 model can be caused by the helium flow distribution on that segment, that does not cool the pebbles effectively, the unavailability of bottom reflector in the model, and the effect of the pebbles in the fuel discharge tube with the additional reflector around it to dissipate the heat from the pebble bed, which is not yet considered. A further investigation is still needed to obtain more representative results of the pebble temperature especially in the bottom part of the core.

5. CONCLUSION

Development of model of the EPR design using the RELAP5/SCDAP/Mod3.4 has been carried out in order to study the RELAP5 capability in determining the most representative model for further safety analysis. The model development involves several stages from the study of the HTR-10 design, which is compared with the EPR design document to the nodalization of the helium flows inside internal structures of the reactor pressure vessel, inside pebble bed in the core zones, and finally the simulation under different boundary conditions. The developed EPR model results in output parameters, which confirm the main thermal data of the EPR. In term of calculation of pebble temperatures, a further investigation is still needed to obtain more representative results especially in the bottom part of the core. For safety analysis, the EPR model can be used under nominal core flow condition, which produces more conservative results by paying attention on the RELAP5 specific modules for the pebble bed-gas cooled system.

ACKNOWLEDGMENT

This work was funded by Ministry of Research, Technology and Higher Education of the Republic of Indonesia under Flagship-INSINAS research project of the year 2018, which has been managed by Center for Nuclear Reactor Technology and Safety (PTKRN) of Indonesia National Nuclear Energy Agency.

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