The Simulator Development for RDE Reactor

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Abstract. BATAN is proposing the construction of experimental power reactor (RDE reactor) for increasing the public acceptance on NPP development plan, proofing the safety level of the most advanced reactor by performing safety demonstration on the accidents such as Chernobyl and Fukushima, and owning the generation fourth (G4) reactor technology. For owning the reactor technology, the one of research activities is RDE’s simulator development that employing standard equation. The development utilizes standard point kinetic and thermal equation. The examination of the simulator carried out comparison in which the simulation’s calculation result has good agreement with assumed parameters and ChemCAD calculation results. The transient simulation describes the characteristic of the simulator to respond the variation of power increase of 1.5%/min, 2.5%/min, and 3.5%/min.

1. Introduction
BATAN is proposing the experimental power reactor (RDE reactor) for pursuing the public acceptance on NPP development plan, proofing the safety level of the most advanced reactor by performing safety demonstration on the accidents such as Chernobyl and Fukushima, and owning the generation fourth (G4) reactor technology. RDE reactor is a High Temperature Gas Cooled Reactor (HTGR) with thermal power of 10 MWe that employed pebble bed fuel and helium coolant [1-2]. The reactor has planned to be constructed at Serpong, Tangerang Selatan, Indonesia, close to RSG-GAS reactor with thermal power of 30 MWt [3]. For owning the reactor technology, the research activities are the standard code verification and validation, transient calculation for safety analysis, as well as the simulator development.

The development of NPP simulator could be grouped in four classification level based on the simulator objective. The simulator objective is for basic study, classroom teaching, engineering and full scale for NPP staff operator training. The conventional full scale simulators based on analog/digital technology is dedicated for NPP operators. The engineering simulator is for initial training of the operator [4]. An example of engineering scale simulator has been developed by implementing a standard code of RELAP [5] and MELCOR [6]. The commercial NPP simulator such as PCTRAN is utilized for transient analysis [7]. Those developed simulators are mostly dedicated for understanding the accident process. However, the previous studies of method development [8-10] are a basic method for either normal and accident operation simulation. Therefore, the development of basic or classroom scale simulator with normal operation simulation is important to be done before carry out accident simulation.

The objective is to develop a RDE reactor simulator that employs neutronics, core thermal, and Nuclear Steam Supply System (NSSS) modules for simulating the transient reactor. The code
development utilized LabVIEW software developer and Personal Computer for implementing the coupled kinetics-thermal calculation. The standard calculation of HTGR core used Germany standard of KTA [11]. The simulation demonstration followed the power increase arrangement by regulator and has a reactor operating pattern for avoiding shutdown by developed Reactor Protection System (RPS). Moreover, the reactor control employs PID and advanced technology to control the reactor, helium circulator, feedwater pump and steam valve in once time. Therefore, the normal and accident operation could be simulated with the developed RDE simulator including Reactor Core Cavity System (RCCS). The designed RCCS contains of three trains of cavity pipe, evaporation tank, and smaller cooling tower. The main cooling tower is utilized by the reactor for normal operation. For enhancing the user interaction, the simulator utilized three computer screens to show the reactor control, Balance of Plant (BOP), and RCCS.

2. Theory

2.1. RDE Reactor
The reactor main components consist of reactor vessel, blower, steam generator, turbine, secondary pump, condenser, cooling tower, and deaerator. The design of RDE reactor is assumed to approach the reactor HTR-10 [11] with several differences such as more number of small ball absorber, straight pipe for fuel discharge system, and unavailability of irradiation channel as showed in Fig. 1. Therefore, the number of control rod and small ball absorber holes are ten that arranged in side reflector. Consequently, the neutron balance will be different as well. The neutron flux is controlled symmetrically by 10 Control Rod (CRs) that could be inserted in CRs channel with speed of 10 mm/s in normal condition.
2.2. Reactor equation

The reactor module utilizes point kinetics for neutron flux calculation and reactivity. The equation of point kinetics is described below [12]:

\[
\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{\infty} \lambda_i C_i(t) + S(t)
\]  

(1)

\[
\frac{dC_i(t)}{dt} = \frac{n(t)}{\Lambda} - \lambda_i C_i(t)
\]  

(2)

where:

- \(n(t)\): neutron population at time \(t\) (n/cm\(^3\).s)
- \(C_i(t)\): precursor for delayed neutron in energy group of \(i\) and time of \(t\) (n/cm\(^3\))
- \(S(t)\): neutron source production at time of \(t\) (n/s)
- \(\Lambda\): neutron generation time (s)
- \(\beta\): delayed neutron fraction for energy group of \(i\) (\(\cdot\))
- \(\lambda_i\): Decay constant of delayed neutron precursor for energy group of \(i\) (s\(^{-1}\))
- \(\rho(t)\): Reactivity at time \(t\) (pcm)

The reactivity value form control rod is calculated by using designed control rod data. Therefore, the total reactivity in the core could be summed from all contributed reactivity as below:

\[
\rho_{Total} = \rho_{excess} + (\rho_{CR} + \rho_{Xe} + \rho_{T})
\]  

(3)
\[
\rho_{CR} = \sum_{i=1}^{10} \rho_{CR_i}
\]  

where:

- \( \rho_{\text{Total}} \): total reactivity (pcm)
- \( \rho_{\text{Excess}} \): excess reactivity from fuel (pcm)
- \( \rho_{\text{CR}} \): total control rod reactivity (pcm)
- \( \rho_{\text{Xe}} \): poison reactivity from Xenon (pcm)
- \( \rho_{\text{Sm}} \): poison reactivity from Samarium (pcm)
- \( \rho_{\text{T}} \): negative temperature reactivity from Doppler effect (pcm)
- \( \rho_{\text{CR_i}} \): control rod reactivity from control rod number \( i = 1 \text{-} 10 \) (pcm)

### 2.3. KTA standard equation

The simulator development for RDE reactor is based on empirical standard equation. The implemented equation that standardized in KTA [13] is heat transfer \( Q \) in a pebble bed fuel to surrounding below:

\[
Q = \alpha A_k (T_k - T_g)
\]  

\[
\alpha = \frac{Nu \lambda}{d}
\]  

\[
\lambda = 2.682 \times 10^{-3} T^{0.71(1.0 - 2.0 \times 10^{-6} P)} (1.0 + 1.123 \times 10^{-5} P)
\]

where:

- \( A_k \): fuel wall area (m\(^2\))
- \( T_k \): average temperature for pebble fuel (K)
- \( T_g \): temperature helium gas (K)
- \( \alpha \): heat transfer coefficient for fuel wall (W/m\(^3\)K)
- \( \lambda \): thermal heat conductivity for helium gas (W/mK)
- \( Nu \): Nusselt number (-)
- \( d \): outer diameter for pebble bed fuel (m)
- \( P \): pressure (kPa)
- \( T \): temperature (K)

### 3. Methodology

The development for RDE simulator processes a modeling based on the assumed operation values of RDE reactor. The modeling includes the main component such as the reactor, steam generator, blower, turbine, deaerator, condenser, pump, and cooling tower. The next step of the development is coding development using LabVIEW developer tool with three main user interface screen. The main screens contains of reactor, NSSS and RCCS control. Therefore, the simulator development requires three screens to visualize the screen for reactor, NSSS, and RCCS controls. The comparison of steady state condition is required by utilizing the data taken from HTR-10 [13] and RDE assumed parameters [1] as well as ChemCAD calculation results. However, the engineering adjustment was done to reach the assumed outlet temperature of helium reactor coolant of 700°C and steam generator of 530°C. The adjustment considers the ChemCAD calculation results for variation of designed temperature inlet [14]. The maximum inlet steam temperature of 160°C is assumed to obtain good thermal performance.

The transient simulation starts from 0% to 100% power level with variance of power increase of 1.5%/min, 2.5%/min, and 3.5%/min. The examination of the RDE simulator carries out calculation result comparison and transient analysis in which the comparison includes the assumed parameter and ChemCAD calculation results. The transient analysis examines the control rod movement to follow the regulation of power increase and study the respond of control rod and blower controls.
4. Result and Discussion

4.1. Design Reference Comparison
Table 4 shows a comparison of the calculation result of the developing simulator and assumed parameters. The averaged value was calculated for 7200 s. The comparisons examine the difference of reactor outlet temperature at 10% and 100% power and include the calculated value from ChemCAD. The calculation method of simulator is similar with ChemCAD on mass and energy balance. Therefore, the difference of steam flowrate for assumed parameters could not be analyzed due to unknown explanation for assumed parameters in the conceptual document. However, the difference could be justified by comparing to the ChemCAD calculation results. The engineering adjustment based on ChemCAD calculation corrects the values for primary coolant and steam flowrate of 4.27 kg/s and 3.55 kg/s respectively. The consideration for the adjustment is to set the outlet temperature close to the assumed parameters.

### Table 1. Comparison of the calculation result of the developing simulator and assumed parameters.

| Parameter                        | HTR-10 Value[13] | RDE Parameters |
|----------------------------------|------------------|----------------|
|                                  | Assumption[1]    | ChemCAD        | Simulator     |
| Reactor Power (MWt)              | 10.00            | 10.00          | 10.00          |
| Primary coolant inlet temperature (°C) | 250.00          | 250.00         | 250.00         | 243.49 |
| Primary coolant outlet temperature (°C) | 700.00          | 700.00         | 700.00         | 701.43 |
| Primary coolant pressure (bar)   | 30.00            | 30.00          | 30.00          | 30.00  |
| Primary coolant flowrate (kg/s)  | 4.32             | 4.40           | 4.27           | 4.32   |
| Steam-generator outlet temperature (°C) | 450.00          | 530.00         | 530.00         | 529.89 |
| Steam flowrate (kg/s)            | 4.00             | 4.00           | 3.55           | 3.55   |
| Steam pressure (bar)             | 60.00            | 60.00          | 60.00          | 60.00  |
| Feedwater temperature (°C)       | 145.00           | 145.00         | 145.00         | 145.50 |
| Feedwater pressure (bar)         | -                | -              | 71.2           | 71.5   |

4.2. Benchmarking
The modeling of NSSS was done by using ChemCAD for steady state calculation that is shown in Fig. 2. Based on developed model, the similar model was developed for Simulator that the RDE reactor has main NSSS components such as steam generator, deaerator, turbine, condenser, and secondary pump. The transient simulation was started from reactor power 0% to 100%. The regulation of power increase was simulation in variance of 1.5%/min; 2.5%/min; and 3.5%/min.
Figure 2. The steady state modelling of NSSS using ChemCAD.

Fig. 3 shows the transient simulation based on power increase of 1.5%/min. The reactor power increases from 0 MWt to 10 MWt by control rod withdrawal. The early simulation until t=300 s, control rod was withdrawal for reaching the maximum reactivity that is permitted by Reactor Protection System. The limit for minimum reactor period is 20 s. However, the warning in the simulator will actuated if the minimum reactor period of 40 s was exceeded. The figure cropping at t=4500s shows that the control rod has to adjust in reactivity insertion and correction to maintain the power increase surrounding 1.5%/min. The reactivity insertion and correction affect the increase and decrease of the reactor power in the same time frame. This power increase pattern continues until the power level reached 100% power with a small over shoot in Fig. 3.

The power increase rule that is stated by power plant regulation is commonly different between countries. Fig. 4 shows the transient simulation based on power increase variation of 1.5%/min, 2.5%/min, and 3.5%/min. The variation determines the reactor startup time from 0% power level to reach 100% power level. With power increase 2.5%/min or 3.5%/min, the 100% power level could be reached less than an hour. However, the 100% power level with power increase 1.5%/min could be reach in longer time, more than two hours.
The development also finished the simulator screen creation for (i) reactor, (ii) NSSS, and (iii) RCCS controls. Fig. 5 shows the developed simulator screen for reactor control. The screen is responsible for arranging the control rod position and Helium flow rate by blower. The reactor indicators that useful for reactor control is control rod positions, reactor period, reactivity, power level, etc. The brief operation of reactor startup in a manual mode, the early step of the operation is withdraw the control rod to increase the neutron flux in a safe condition showed by the parameters of total reactivity or neutron period. After reactor power increases significantly and affects to the Helium outlet temperature increase, the control rod position must be maintained so that the total reactivity or neutron period keep below the operation limit. The operation limit value considers the adequate margin to safety limit.
5. Conclusion
The simulator development has finished the development of main code of reactor module that employed point kinetic method. The examination of the simulator carried out comparison in which the simulation’s calculation result has good agreement with assumed parameters and ChemCAD calculation results. The variation of power increase was studied to determine the reactor startup time from 0% power level to reach 100% power level.

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