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TRIGA PUSPATI reactor: model analysis and accuracy

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ABSTRACT

There are many challenging issues with research reactor, such as time variation and uncertainty. Since its first criticality in 1982, the biggest changes in TRIGA PUSPATI Reactor system is the replacement of instrumentation and control console system from analogue to digital in 2013. Apart from providing methods of controlling the power reactor via the control rod movement, the Instrumentation and Control Console System also provides monitoring and display for all reactor parameters to protect the reactor from undue influences or abnormal circumstances. Meanwhile, the simulation model of the TRIGA PUSPATI Reactor system has been developed in the Simulink-MATLAB. The simulation model development is based on the research reactor mathematical representatives and the real plant parameters of TRIGA PUSPATI Reactor. However, the performance of this simulation model needs to be evaluated. Since there is no report or paper work found on the performance of the simulation model to represent the real system of RTP, the present study aims to carry out an analysis for more rigorous understanding of the TRIGA PUSPATI Reactor model simulation through validation and verification methods. After analysing the result, it was found that the simulation model has a good representation of a real plant.

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1. INTRODUCTION

Nuclear reactor kinetics refers to the characteristics of power reactor that are altered when the position of the rod control and temperature are changed. This change is unique for each reactor; the power reactor level changes upon the changes in the reaction rate of neutron absorption and reactor temperature. Meanwhile, a control rod is used to absorb the neutrons in the reactor core; when the control rod is withdrawn, the power reactor will increase due to the decreased rate of neutron absorption, resulting in the reactor to be in a supercritical condition. On the other hand, once the control rods are inserted into the storage banks, the rate of neutron absorption increases. Thus, the power reactor level decreases and becomes subcritical [1]. The power reactor goes into a critical condition when the power level of the reactor achieves a steady-state level. At this point, the control rod movement will be manipulated in an up-and-down manner in order to maintain the power level; this is illustrated in Figure 1.

The reactor control manages the core reactivity and power distributions simultaneously [2-4]. Apart from achieving reliable power level demand, the power level control is also very important to ensure the operational safety of a plant. The RTP is a TRIGA MARK II research reactor type with multipurpose function that provides maximum thermal power of one megawatt (MW). In addition to producing neutron, RTP also provides beam experiment, isotope production, neutron activation analysis, and training. A demineralised light water has been used as a coolant to reject heat and act as a moderator to slow down the neutron speed [5, 6].

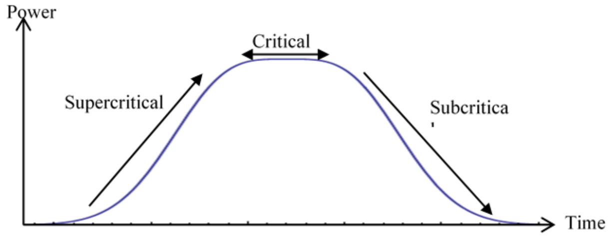

Figure 1. The relation between core condition and power in time

The RTP involves complex and nonlinear process, which are significantly related to the power reactor level control. Since its first criticality in 1982, the biggest changes in the RTP system would be the replacement of Instrumentation and Control Console System (ICCS) from analogue to digital in 2013 [7]. Apart from providing methods of controlling the power reactor via the control rod movement, the Instrumentation and Control Console System also provides monitoring and display for all reactor parameters to protect the reactor from undue influences or abnormal circumstances. Thus the development of modelling for RTP system is crucial in order to represent the real system before any changes has to be made. There are many methods to do so such as Support Vector Machine integrated with Multi Output Modelling for analog circuit [8] and Finite Element Modelling to model Pulsed Eddy Current to investigate the specimen and the transient magnetic field problem [9]. Meanwhile to predict energy consumption, baseline energy model was developed under Artificial Neural Network integrated with bootsrap and cross validation [10].

In the meantime, the simulation model of the TRIGA PUSPATI Reactor system has been developed in the Simulink-MATLAB. The simulation model development is based on the research reactor mathematical representatives and the real plant parameters of TRIGA PUSPATI Reactor. Since converted into ICCS, there are numerical study and investigation on the topic of RTP and the studies are providing the issues of neutron and neutronics, fuel, thermal-hydraulic, power generation and many more topic related with physics and chemicals issues. Numerous works have attempted to reveal the neutron flux studies such as neutron flux effect, neutron distribution and neutron irradiation has been done for RTP. For example, the model of neutron flux was using MCNPX Ver. 2.7 has been studied on how far neutron flux gave the impart burn-up effect onto irradiated fuel [11]. In other study, thermal neutron flux distribution by using Monte Carlo code MCNP was examined the agreement between calculation and measurement to be met [12]. Meanwhile, both TRIGLAV and MCNP code has been used in investigation of the design and verification for RTP core by manipulation neutron flux calculation [13]. In the same way, the study of neutron flux had been performed to determine parameters and measurement by exploiting cd-ratio multi monitor method and self-powered neutron detectors respectively [14, 15].

Beside neutron flux study, the fuel of RTP also is one of the hot topic to discuss among researchers. Previous investigation into RTP fuel have reported in various papers. From transfer cask modelling for fuel element [16] to the spent fuel investigation for safety critical analysis had been done using MCNP technique [17]. This is consistent with [18], which had been using Adaptive Network based Fuzzy Inference System (ANFIS) to estimate fuel temperature reactivity coefficient in RTP. Not to forget the study bringing about neutronics and thermal-hydraulic of RTP that had been done by few researchers. They used TRIGLAV and MCNP code in order to do calculation of neutronics and to find the correlation between neutronics and thermal hydraulics [7, 19]. On the other hand, few researchers investigated Departure of Nucleate Boiling Ratio (DNBR) and the pattern of temperature profiles in thermal hydraulics system by utilizing PARET code [20]. The equally important topic in RTP is the power generation. At the present time, there are few papers associated to this topic where the authors had been use mitigation technique to investigate the quality issue [21] and Particle Swarm Optimization to improved response signal [22]. Meanwhile Model Reference Adaptive Control and Self Tuning Control had been used in controller part to improve the power tracking and to regulate reactor power [23, 24].

As mentioned above, the simulation model of the TRIGA PUSPATI Reactor system has been developed in the Simulink-MATLAB in order to simulate the power generation in RTP. So far however to the best of author knowledge, there is no report or paper work found on the performance of the simulation model to represent the real system of RTP to verify the real representation of the RTP system. After analysing the result, it was found that the simulation model has a good representation of a real plant. Therefore, before the deep study of RTP proceeds any further, this paper aims to share a study to prove that the accuracy of the first principle model simulation is a valid standard or representation of the real RTP.

2. MODELING OF TRIGA PUSPATI REACTOR (RTP)

Generally, the main reactor system includes the cooling and reactor systems. Since the conversion of neutron count into power reactor is not considered as part of the neutronic model in a reactor, therefore, it is excluded and the whole reactor system is portrayed in Figure 2. The RTP cooling system is divided into two loops; the primary loop is a heat rejection from the core in the tank, while the secondary loop is the reject heat that flows from the pool tank into the heat exchanger.

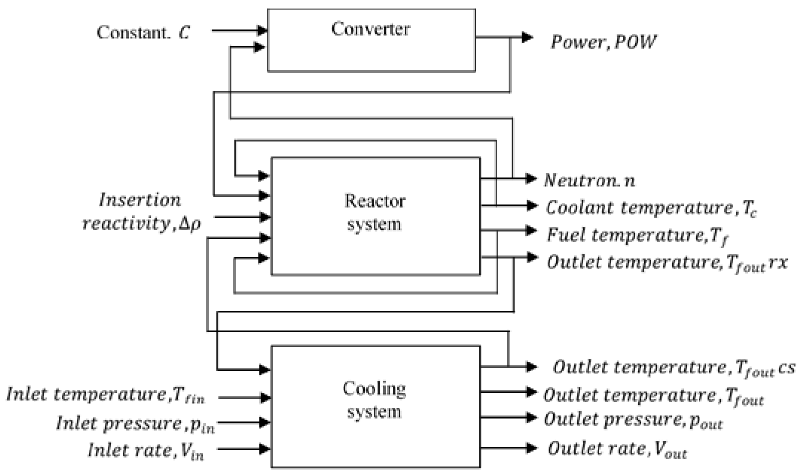

Figure 2. Block diagram of the RTP system

The general block diagram for the RTP reactor system shows three subsystems, which are the thermal hydraulic model, the neutron point kinetic model, and the reactivity model that integrate with each other, as shown in Figure 3. It is worth noting that the outlet temperature parameter of the cooling system, $T_{fout}cs$, is also the inlet temperature of reactor system. All three models describe the behaviours of the associated temperatures, fission products, neutron and precursors, heat dissipation by coolant in the reactor system.

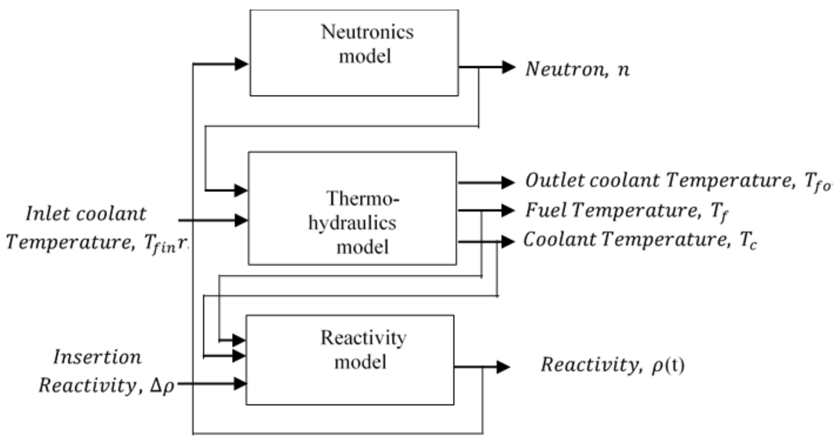

Figure 3. Block diagram of the reactor model

2.1. Neutronic model

The neutron fission process can be described as once the neutron hits the U^{235} nuclide and is absorbed, it will trigger fission at a certain rate of neutron generation, which produces new neutrons as 'child'. These 'child' neutrons will become 'parent' neutrons when it bombards other nuclides. The number of neutrons and delayed neutron precursor will determine the neutron production, which is also called as a point reactor kinetic [1, 25, 26] that is described as:

$$\frac{dn(t)}{dt} = \frac{\rho(t)-\beta}{\Lambda} n(t) + \sum_{i=1}^{6} \frac{\beta_i}{\Lambda} C_i(t) \quad (1)$$

$$\frac{dC_i(t)}{dt} = \lambda_i n(t) - \lambda_i C_i(t)\ i = 1, \ \dots, 6 \quad (2)$$

where, n is the number of neutrons, C_i is the number of delayed neutron precursor in group i, βi is the delayed neutron fraction of group i, λ_i is the decay constant, k_{eff} is the effective multiplication factor, Λ is the prompt neutron lifetime, and ρ is the reactivity.

2.2. Thermal-hydraulic modeling

The thermal-hydraulic modeling comprises a few parameters, as shown in Figure 4:

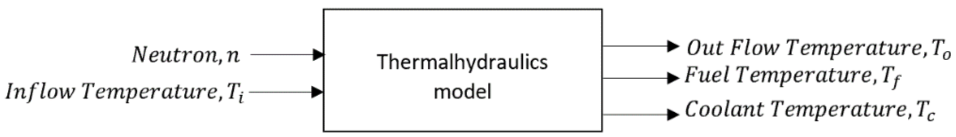

Figure 4. Block diagram of the thermal-hydraulic modeling

The temperature drops between the fuel and the coolant is compared with the temperature rise of the coolant.

$$\frac{\bar{T}_f - \bar{T}_c}{\bar{T}_o - \bar{T}_i} = R_f W c_p \quad (3)$$

The difference of powers appears as the rate at which the internal energy is added to the coolant within the core, thus increasing the rate of internal energy.

$$M_c c_p \frac{d}{d\tau} T_C(t) = \frac{1}{R_f}\left[T_f(t) - T_C(t)\right] - 2W c_p [T_C(t) - T_i)] \quad (4)$$

M_c is the coolant mass within the core, c_p is the specific heat, $\bar{T}_o$ is the outlet coolant temperature, $\bar{T}_i$ is the inlet coolant temperature, R_f is the reactor core thermal resistance, and W is the coolant mass flow rate:

$$\frac{d}{dt} \bar{T}_c(t) = \frac{1}{\tau'}\left[\bar{T}_f(t) - \bar{T}_c(t)\right] - \frac{1}{\tau''}[\bar{T}_c(t) - \bar{T}_i] \quad (5)$$

$$\tau' = \frac{M_c c_p}{M_f c_f} \text{ and } \tau'' = \frac{M_c c_p}{2W c_p} \quad (6)$$

The nuclear fission produces heat that needs to be transferred. The temperature drops in power reactor from fuel to coolant, which is proportional to the linear heat rate, can be described as:

$$T_f(r,z) - T_c(r,z) = R_f P f_r(r) f_z(z), \text{where}, P = \frac{\bar{T}_f - \bar{T}_c}{R_f} \quad (7)$$

With consideration of cooling were cut off entirely, all of the heat produced would result in the adiabatic heating of the fuel:

$$M_f c_f \frac{d}{dt} \bar{T}_f(t) = P(t) \quad (8)$$

The approximate lumped-parameter model for thermal transients can be described as:

$$M_f c_f \frac{d}{dt} \bar{T}_f(t) = P(t) - \frac{1}{R_f}\left[\bar{T}_f(t) - \bar{T}_c(t)\right] \quad (9)$$

$$\frac{d}{dt}\bar{T}_f(t) = \frac{1}{M_f c_f} P(t) - \frac{1}{\tau}\left[\bar{T}_f(t) - \bar{T}_c(t)\right] \text{ where } \tau = M_f c_f R_f \quad (10)$$

The summarised thermal-hydraulic modeling is as below [27, 28]:
For coolant temperature,

$$\frac{dT_C}{dt} = \frac{P(1-f)}{\tau_C K} + \frac{T_f - T_C}{\tau_C} - \frac{c_c}{\tau_C K w}\Gamma(T_C - T_i) \quad (11)$$

For fuel temperature,

$$\frac{dT_f}{dt} = \frac{Pf}{\tau_f K} + \frac{T_f - T_C}{\tau_f} \quad (12)$$

Where:

$$T_C = wT_o + (1-w)T_i \, and \; \Gamma = \sqrt{\frac{\delta_{in} g L v}{\alpha_2 w}}(T_C - T_i) \quad (13)$$

2.3. Reactivity model

The reactivity model is shown in Figure 5.

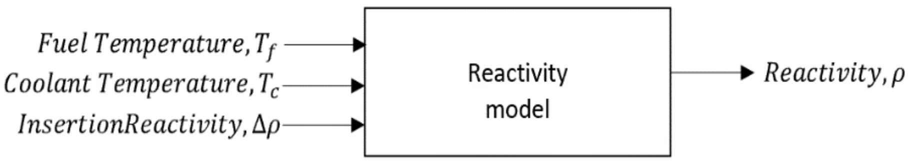

Figure 5. Block diagram of the reactivity model

The imbalance measurement of neutron removal and neutron production of the entire core is called reactivity.

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \quad (14)$$

Where, k is the multiplication factor, $\rho > 0$ is supercritical, $\rho = 0$ is critical, and $\rho < 0$ is subcritical. When the rod control moves up and down, the neutron (or power) population changes accordingly. This condition will change the temperature of the reactor and affect the reactivity and multiplication factor. Thus, this change in power reactor is called the reactivity feedback effect. The reactivity can be expressed as [29]:

$$\rho(t) = \delta\rho_{ext}(t) + \delta\rho_f(t) \quad (15)$$

$$\rho(t) = \alpha_h \Delta h_{cr} + \alpha_m (T_m - T_m^0) + \alpha_f (T_f - T_f^0) \quad (16)$$

$$\rho(t) = \alpha_h \Delta h_{cr} \quad (17)$$

Since the initial temperature and current temperature for both fuel and coolant almost equivalent to zero, then (17) has been simplified as $\rho(t) = \Delta\,\rho$. According to [16], the importance of validation and verification of the simulation model is to ensure the accuracy and reliability of a model prior to its implementation. The validation and verification of the model are two different processes and both do not imply each other. Validation is to establish that the exact model is developed, while verification is to prove that the model was developed exactly in the way that it is supposed to. This is consistent with the paper from [30] which claimed that the validation of a model refers to a developed model that satisfies the accuracy range of the real plant and/or model, while the verification of a model refers to a model that is transformed and developed into a simulation model that is exactly as the conceptual model. Meanwhile, the author of [31] claimed that validation is a degree of accuracy for a model to capture the system behaviour or degree to which the model would be able to represent the real system accurately. To validate the simulation model that has been developed exactly as that of a real plant, the mean and standard deviation for eight cases of experimental and simulation model were obtained. For the purpose of analysis, the mean residual percentage was assessed; the equation is described as (18):

$$Mean\ Residual = \frac{\mu_{real\ plant} - \mu_{simulation\ model}}{\mu_{real\ plant}} \times 100\% \tag{18}$$

3. RESULTS AND DISCUSSION

Before the RTP power reactor level data are acquired, all of the experimental setups were done, including the initial reactor setup, the safety margin setup (including maximum power test), and the core access measurement. The data were collected at the TRIGA research reactor of the Malaysian Nuclear Agency. These eight sets of data collection will have the same initial value variable, such as the height of fuel elements, and uncontrolled variables, such as the fuel temperature and the coolant temperature. A wide range of power level was selected to cover both the lowest and highest power of the RTP. The power demand chosen were 250 kW, 500 kW, 570 kW, and 1000 kW, with two sets of data for each level. The initial power demand or set point is 15 watts, with identical height of three control rods, i.e., transient, shim, and safety. Meanwhile, the regulator control rod depends on the core access measurement for each experimental work. These continuous data collections were obtained from operational and non-operational plants. For non-operational plant, the data collection will be stopped once the steady state of power is achieved after 30 minutes. The condition for non-operational is the same as that of the operational plant. Figures 6 to 9 show the detailed comparison between power demand, real plant, and simulation output for each data set at four different power levels, i.e., 250 kW, 500 kW, 750 kW, and 1 MW. Although the entire simulation model can follow the real plant profile, the higher the power demand, the tougher the tracking of real plant and simulation model will be. Nevertheless, the higher the power demand, the lesser the overshoot of output of the real plant and simulation model will be. As shown in Figure 10 the plot shows the residual between the real power plant value and the simulation of power generation for each data set. Can been seen that the higher the power generation, the higher residual become.

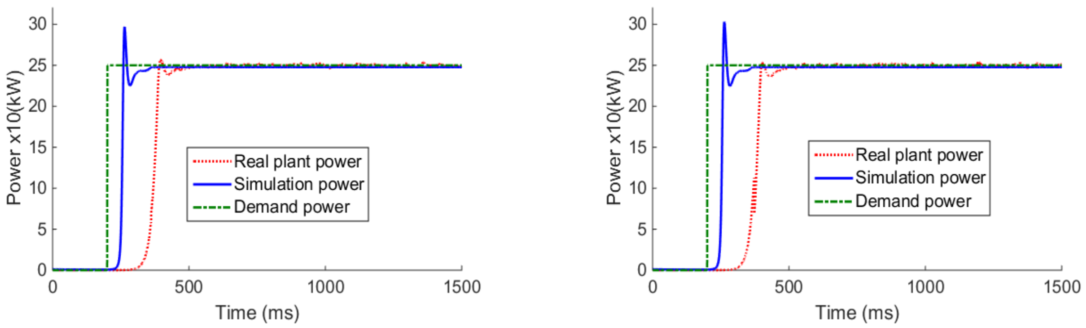

Figure 6. Power reactor output of 250 kW (Left: Set 1; Right: Set 2)

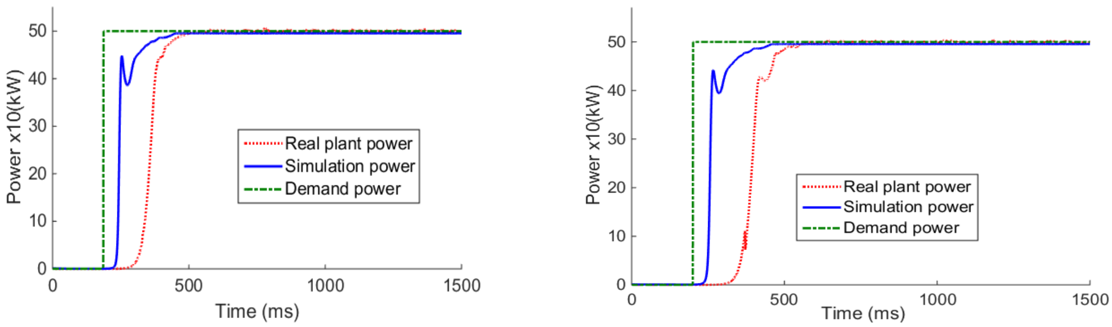

Figure 7. Power reactor output of 500 kW (Left: Set 1; Right: Set 2)

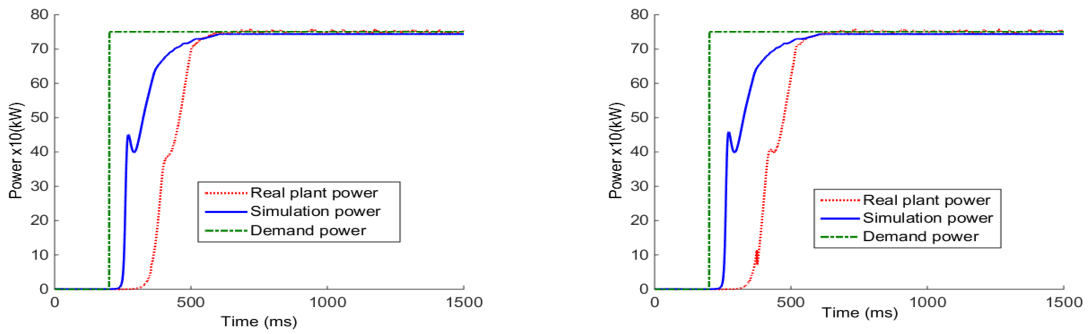

Figure 8. Power reactor output of 750 kW (Left: Set 1; Right: Set 2)

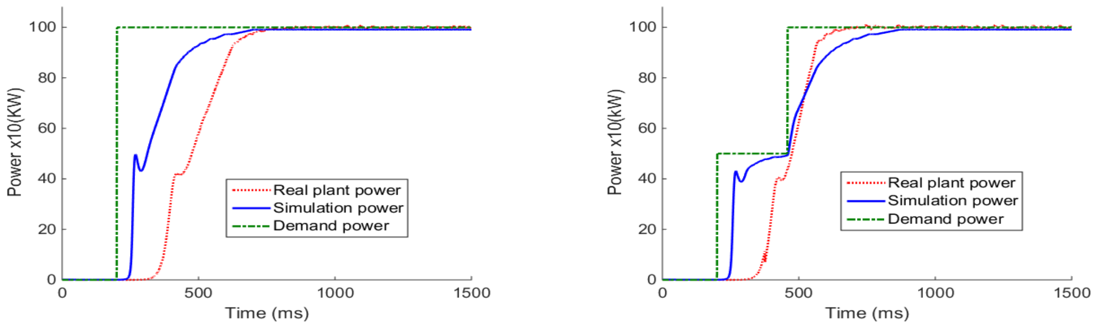

Figure 9. Power reactor output of 100 kW (Left: Set 1, Right: Set 2)

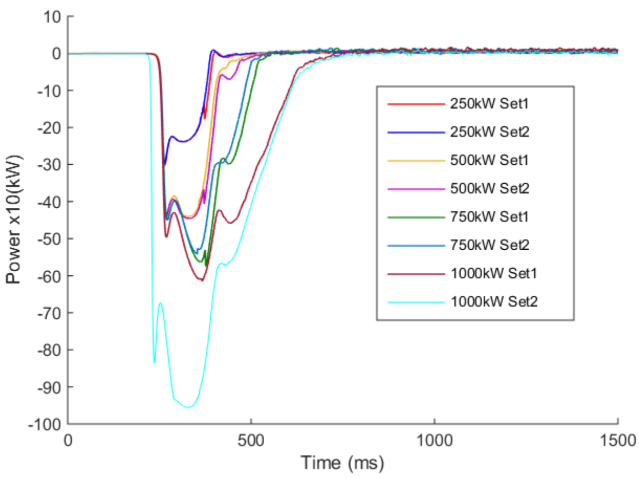

Figure 10. Power residual between real plant and simulation model for all set power

The model accuracy was analysed by comparing the simulation results and the real data acquired from the real plant of TRIGA PUSPATI. As illustrated in Table 1, it presents the relativity between the simulation data and the real plant data. In general, the simulation time to run was similar for all types of power demand. The simulation results for four types of power demand were run with Intel core i5, 2.7 GHz CPU with 8.00 GB memory. Meanwhile, the real data were run at the research reactor from the abovementioned TRIGA PUSPATI plant. Although many papers related to RTP have been published, there has been little discussion about the residual properties data. This paper attempts to provide a more detailed investigation regarding the residual properties of the simulation data and the measurement of the real plant data. Then, it is essential to determine the model accuracy benchmark, where several attempts have been made to realize the aim. According to [32], model accuracy is rated as A (less than 10%) or D (more than 50%), indicating the smallest and largest measured points, respectively. This means that A and D are the limits for quantifying and the variances in between are rated as B and C. A B rating is given if the residual falls between 20%–30%, while rating C is given for the rest of the residual.

Table 1 shows that all of the data sets are ranked A, which represents good performance. In comparison, Data Sets 1 and 2 at 250 kW and 1 MW power levels, respectively, have a residual mean of more than 1%; while the remaining data sets have it below 1%.

Table 1. Summary of the performance of the RTP model

Power level (kW)	Data set	Residual mean (%)	Ranking
250	Set 1	2.3264	A
	Set 2	0.5093	A
500	Set 1	0.1640	A
	Set 2	0.1785	A
750	Set 1	0.4517	A
	Set 2	0.4853	A
1000	Set 1	0.8819	A
	Set 2	1.0490	A

A = good, B = acceptable, C = marginal, D = poor

4. CONCLUSION

In general, the goal of this paper is to establish the performance of the RTP simulation model through multiple power levels. This can be done by addressing the analysed residual between the real plant and the first principle simulation model. There are four power demand levels with two sets of data each. Although the requirement of two data sets is quite unconventional, all of residual mean percentage are below 10%, which is the benchmark level of the model. This leads to good model performance since allof the power levels are ranked good. Consequently, the findings of this study are considered significant.

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