Development of Kartini Reactor Code to Support Nuclear Training Center and Safety Analysis

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***Abstract*—Development of a 100 kW Kartini research reactor code was carried out to support Nuclear Training Center and reactor safety analysis. The code has abilities of both simulating normal and abnormal conditions of the reactor. It was developed based on interaction among governing equations of mass and energy conservations, fuel rod heat conduction, and point kinetics. For simplicity, the code considers only one type of control rod rather than three types of control rods as used in the reactor. Calculation results of the power and axial coolant temperature distribution at rated power show a sufficient agreement with those of experimental data. Results of the plant dynamics analysis by using the code also show a correct plant's behavior as those of general light water reactors. Rough safety analysis of an excess reactivity insertion was carried out and the calculation results show that the limit of reactor safety is satisfied. It might improve the code by consideration of three types of control rods to decrease the calculation errors. However, the code was satisfied to be used as a tool for both supporting the nuclear training center and safety analysis.**

Keywords—Kartini reactor, nuclear training center, simulation code, safety analysis

I. INTRODUCTION

The Nuclear Training Center (NTC) is being the infrastructure of human resources development required by the international atomic energy agency (IAEA) regarding the plan of constructing a nuclear power plant in Indonesia [1,2]. One of facilities in the NTC is a Kartini research reactor of TRIGA Mark-II type. It is a 100 kW type research reactor located in Yogyakarta city, Republic of Indonesia, and provides as a resource for education and training on basic understanding of reactor physics and kinetics, operation, reactor instrumentation and control, as well as reactor utilization for elemental analysis. Several universities and high educational institutions surrounding the city, such as Polytechnic Institute of Nuclear Technology-BATAN, Gadjah Mada University, Bandung Institute of Technology, Sebelas Maret University, etc. have provided study programs related to nuclear field and have been using this reactor periodically for educational activities.

Recently, an internet reactor laboratory (IRL) based on the Kartini reactor is under development to expand the utilization of the reactor to remote educational institutions in the country, as well as in the regional area [3, 4]. In other place, the concept of the IRL was already proposed and developed based on Argentinian research reactor [5]. The basic idea of the IRL is allowing the remote students to perform the experiences as if they were in the Kartini reactor site. Therefore, it might lead to a more frequent utilization of the Kartini reactor for experiment courses. As part of the 19 infrastructures required by the IAEA, material related to reactor (nuclear) safety is important to be included in the courses. This material, however, is not considered in the courses yet due to difficulty of simulating an abnormal condition by experiment. Besides, according to the regulation of the Nuclear Energy Regulatory Agency mandated periodically operating license renewal, comprehensive safety analysis must be conducted to demonstrate that the Kartini reactor has inherently negligible risk. These matters should be addressed by providing a code of the Kartini reactor which has abilities of simulating both normal and abnormal (accidents) conditions. However, a code which has these abilities is not available yet. Therefore, development of the Kartini reactor code to support nuclear training center and safety analysis is important. Safety analysis of a similar reactor to that of Kartini reactor was conducted by using a code of PARET/ANL with the purpose to satisfy the requirement of the Nuclear Regulatory Commission (NRC) of the USA [6].

Previously a code for evaluation of core parameters of the Kartini reactor was developed [7]. The code, however, did not provide a facility for safety analysis. It was developed with purpose of providing a software for processing the data acquired by experiments in normal condition.

A code of supercritical accident and transient analyses (SPRAT) was developed and validated by the UT (University of Tokyo) and Waseda University for safety analysis of supercritical light water reactors (SCWRs) [8-16]. Features of the SCWR, however, are different from those of the Kartini reactor. The SCWR is a type of 1000 MW power reactor which uses forced cooling system [9]. The operating pressure is 25 MPa [9], much higher than the atmospheric operating pressure (0.1 MPa) of the Kartini reactor. However, both reactors use the same coolant of light water. Therefore, physical equations in the code should be applicable for the development of the Kartini reactor code. The purpose of this study is to develop a code of the 100 kW Kartini reactor. The code will be useful as the reactor facilities for education and training courses, and for

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preliminary safety analysis. In the future, the code is intended for comprehensive safety analyses which support the continuous operating permit from the Nuclear Energy Regulatory Agency.

II. DESCRIPTION OF THE KARTINI REACTOR

Kartini reactor was constructed in late 1974 and reached its first criticality on January 1979. It was inaugurated on March 1979 and still in operation until now. Currently, the reactor core consists of 69 standard fuel rods made by the General Atomic. Besides, several positions are filled with unfueled or "dummy" elements made of graphite equipped with 3 control rods. Fig. 1 shows the core structure of the Kartini reactor. The core characteristics are shown in TABLE 1.

Kartini reactor is equipped with two cooling systems of primary and secondary cooling systems. The primary cooling system is categorized as unforced cooling system. Primary coolant pumps are mounted but these pumps just circulate the coolant through two heat exchangers without forcing the coolant flow through the core. Besides, the primary coolant is also pumped through demineralizer to keep clean the coolant. The pump is also used for keeping the water level of the reactor through a makeup tank. The secondary cooling system circulates the secondary coolant from the heat exchangers to the cooling tower. The heat is released to open air by natural heat transfer. The schematic diagram of Kartini reactor cooling system is depicted in Fig. 2.

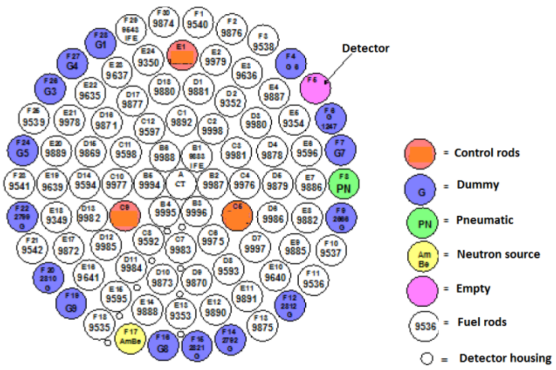

Fig. 1. Core structure of the Kartini reactor [7]

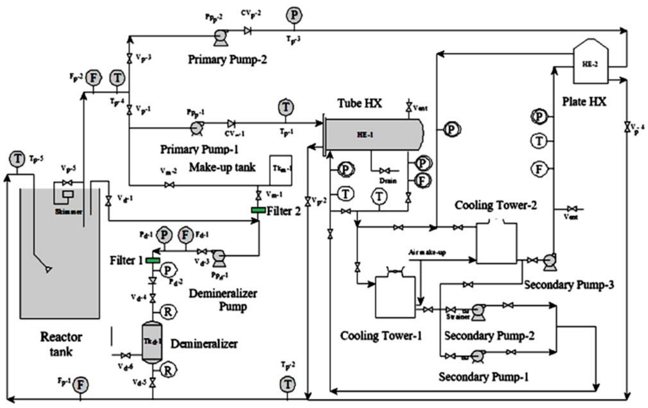

Fig. 2. Schematic diagram of Kartini reactor cooling system

TABLE I. CORE CHARACTERISTICS OF THE KARTINI REACTOR

Parameter	Value
Thermal power (kWth)	100
Operating pressure (atm)	1
Total height of core (cm)	76.2
Active core height (cm)	38
Numbers of fuel rods	69
Outer diameter of fuel rod (mm)	35.6
Gap of fuel (mm)	0.2
Outer diameter of cladding (mm)	37
Wall thickness of cladding (mm)	0.5

III. METHOD OF CODE DEVELOPMENT

The core characteristics of the Kartini reactor to be modeled are shown in TABLE 1. The calculation model is shown in Fig. 3. The Kartini reactor calculation model is divided into 3 parts. The first part is fuel channel where heat is produced, and numerically this part is divided into 36 meshes. The heat spreads out passively by conduction into the surrounding space which contains unforced water coolant. The second and the third parts are the lower and upper parts which contain only water without fuel, and each of these is divided into 10 meshes numerically.

The code calculations are based on the relation among the models of point kinetics, mass-energy conservations, and fuel rod heat conduction as shown in Fig. 4. The fuel pellet to coolant heat transfer calculation is carried out based on single channel model which the radial power distribution is assumed to be homogeneous by taking its average value as shown in Fig. 5. Axially, the power distribution is assumed in form of cosine function with total thermal power of 100 kW. The heat transfer consists of 2 steps. The first is heat transfer from the fuel to cladding and the second is heat transfer from cladding to coolant. Heat transfer calculation along the fuel is conducted based on the governing model as in Eq. (1) [9].

$$\rho V C_p \frac{dT}{dt} = Q_{in} - Q_{out} + Q_{product} \tag{1}$$

Where C_p is specific heat with constant pressure (J/kg.K), Q_{in} is heat flux-in into a node of fuel pellet (J), Q_{out} is heat flux-out from a node of fuel pellet (J), $Q_{product}$ is produced heat due to fission reaction (J), T is temperature of fuel pellet (K), V is volume of fuel pellet of each node (m^3), ρ is density of fuel pellet (kg/m^3)

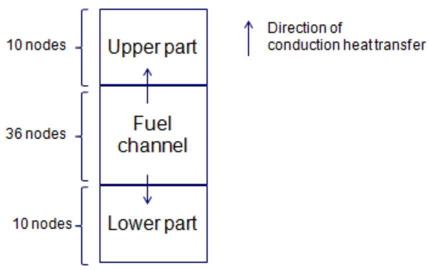

Fig. 3. Calculation model of the Kartini reactor

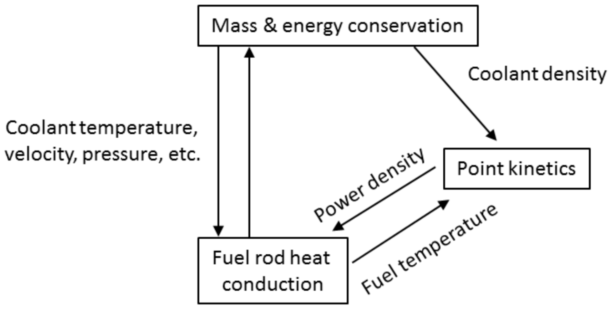

Fig. 4. Structure of the code [9]

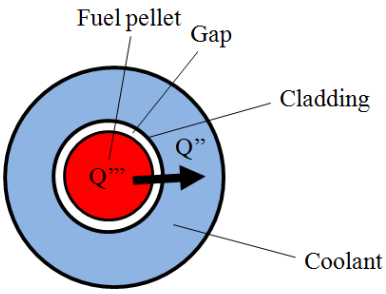

Fig. 5. Model of radial heat transfer from fuel pellet to coolant [9]

Calculation of the produced heat by fission reaction is carried out with accordance to the number of neutron n(t) by factor of conversion q_0 as shown in Eq. (2) [9].

$$Q_{product} = q_0 . n(t) \tag{2}$$

Heat transfer calculation from a node to another node of the fuel is carried out by using conduction model as in Eq. (3).

$$Q = \frac{2\pi \Delta Z K_{fuel}}{\ln\left(r_b / r_a \right)} \left(T_a - T_b \right) \tag{3}$$

Where $r_b > r_a$, K_{fuel} shows thermal conductivity of fuel pellet (W/m.K), r means radius of node (m), ΔZ means length of node (m)

Calculation of the fuel temperature average is carried out with accordance to Eq. (4) [9].

$$T_{ave} = \frac{T_1}{16} + \frac{3T_2}{16} + \frac{5T_3}{16} + \frac{7T_4}{16} \tag{4}$$

T_i (i=1, 2, 3, 4) is temperature of each mesh (K).

Calculation of the heat transfer from the fuel to the cladding is carried out according to heat conduction through the gap between the fuel and the cladding, and according to heat conduction through the cladding between the inside surface and outside surface of the cladding. Calculation of the heat transfer through the gap is carried out by using Eq. (5) [9].

$$q_g = \frac{2\pi \Delta Z (T_s - T_c)}{\frac{\ln\left(r_{fuel} / (7/8 r_{fuel}) \right)}{K_{fuel,4}} + \frac{1}{h_g \cdot r_{fuel}} + \frac{\ln\left((r_c - dx/2)/(r_c - dx) \right)}{K_c}} \tag{5}$$

With dx means cladding wall thickness (m), h_g means gap's thermal conductivity (W/m °C), K_c means cladding's thermal conductivity (W/m K), T_c means cladding inside surface temperature (K), T_s means cladding outside surface temperature (K), r_c means radius of cladding (m), and r_f means radius of fuel pellet (m).

Calculation of the heat transfer from cladding to coolant is carried out by Eq. (6) [9].

$$q_c = \frac{2\pi \Delta Z \left(T_c - T_{coolant} \right)}{\frac{\ln\left(r_c / (r_c + dx/2) \right)}{K_c} + \frac{1}{h_s \cdot r_c}} \tag{6}$$

Which $T_{coolant}$ shows coolant temperature (K) and h_s means heat transfer coefficient between the cladding and the coolant (W/m K).

Calculations of the thermal hydraulic are based on conservation laws of mass and energy which are shown in Eqs. (7-8) [9], respectivelly.

$$\frac{\partial \rho(z,t)}{\partial t} + \frac{\partial G(z,t)}{\partial z} = 0 \tag{7}$$

$$\frac{\partial \{\rho(z,t) h(z,t)\}}{\partial t} + \frac{\partial \{G(z,t) h(z,t)\}}{\partial z} = \begin{cases} \frac{1}{A_f} l_f Q_n''^{k}(z,t) & \text{.......(flow channel with fuel rods)} \\ 0 & \text{........(flowchannel without fuel rods)} \end{cases} \tag{8}$$

With ρ means density (kg/m^3), G means mass flux (kg/s.m^2), t means time (s), h means enthalpy (J/kg), z means position (m), l_f means mesh height (m), A_f means surface area of fuel pin (m^2), Q'' means heat flux (W/m^2)

Calculation of the neutron number is carried out based on the point kinetics models as shown in Eqs. (9-10)[9].

$$\frac{d}{dt} n(t) = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) \tag{9}$$

$$\frac{d}{dt} C_i(t) = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t) \tag{10}$$

Where n(t) shows the total number of neutron, $C_i(t)$ means the number of radioactive precursors producing delayed neutrons, $\rho(t)$ means reactivity ($), β means fraction of total delayed neutrons, Λ means prompt neutron generation time (s), λ_i means decay constant of the i-precursor (s-1)

Flowchart of the code calculation is shown in Fig. 6. Initial condition is assumed at normal rated power operation. Calculations are conducted in every time step in all nodes, starting from the lower part to the upper part through the fuel channel. An abnormal condition is assumed to happen during the rated power operation.

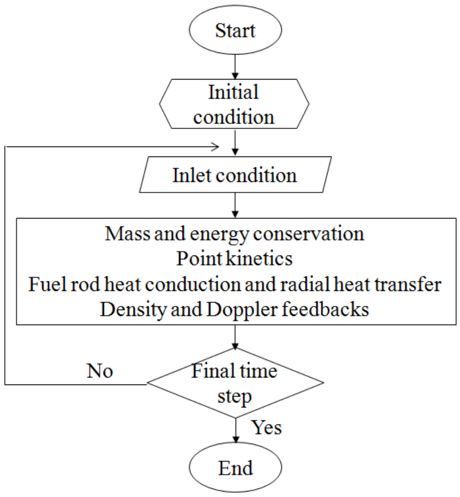

Fig. 6. Flowchart of thermal-hydraulic and neutronics calculation in the code

IV. CALCULATION RESULTS AND DISCUSSION

Experimental data of the Kartini reactor are used for validation of the code calculation. The data are the thermal power as function of control rod position and the coolant temperature distribution as function of axial position. Comparison of the results between the experimental data and the code calculation (simulation) of the reactor power is shown in Table 2. Graphically it is shown in Fig. 7. At low position of the control rod, the differences between experimental results and the code calculation are small, but these become larger when the control rod is further withdrawn. It might be due to the simplicity of using 1 bundle (type) of control rod in the code. In fact, there are three types of the control rods in the Kartini reactor. They are regulation control rod, compensation control rod, and safety control rod. However, calculation results of the code show a similar trend between the experimental data and the simulation.

TABLE II. COMPARISON BETWEEN EXPERIMENTAL DATA AND CODE CALCULATION OF THE THERMAL POWER

Control rod position (%)	Thermal power (kW)	
	Experiment	Code calculation (Simulation)
24	10	9
26	20	12
28	30	15
30	40	17
32	50	20
33.5	60	23
35	70	25
37	80	28
39	90	30
41.6	100	35

Comparison of coolant temperature distribution between the experimental results and the code calculation is shown in Fig. 8. It shows similar trend to the previous figure. At lower axial position of the core, the difference between experimental data and calculation results is low, but it increases at upper position. It might also be due to the assumption of using one type of control rod. Consideration of the three types of control rods in the code might address the large error. Besides, use of heat transfer correlation of pool boiling might improve the code calculation [9, 13].

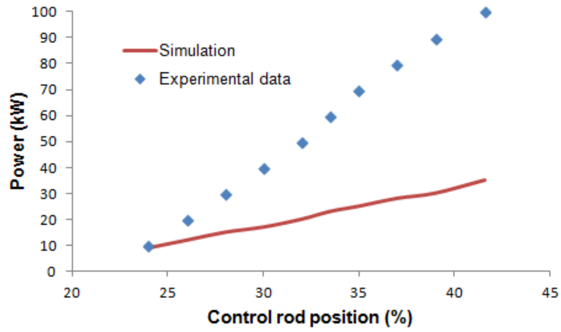

Fig. 7. Thermal power as function of the control rod position

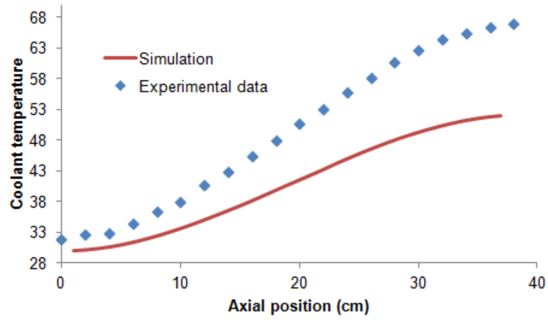

Fig. 8. Coolant temperature distribution

A plant dynamics analysis of the Kartini reactor was carried out by giving a stepwise decrease of the control rod position from 100% to 95%. Figs. 9-12 show the code's calculation results. Fig. 9 shows the change of the reactivity as results of the control rod insertion. The 5% stepwise decrease of control rod position inserts negative reactivity by about -0.013 $, so that the total reactivity is decreased leading to a decrease of the power as shown in Fig. 10. As a result, the average fuel temperature is decreased as shown in Fig. 11 and the coolant density is increased as shown in Fig. 12. These changes of fuel temperature and coolant density insert positive Doppler and density reactivity feedbacks which take the total reactivity to zero within about 180 s as shown in Fig. 9. Finally steady state conditions are achieved by all the operation parameters. Qualitatively, these plant dynamics show similar trend to those of plant dynamics characteristics of general light water reactors [8].

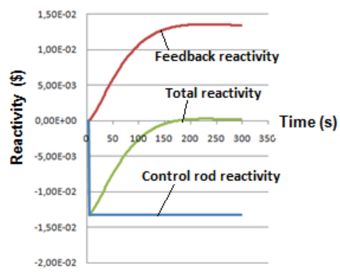

Fig. 9. Reactivity change due to a 5% stepwise decrease of control rod position

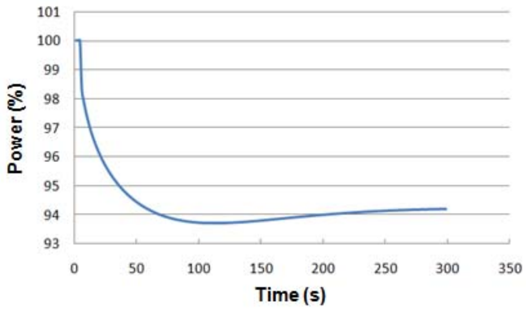

Fig. 10. Change of thermal power due to the 5% stepwise decrease of control rod position

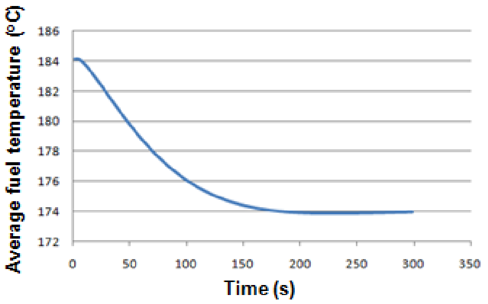

Fig. 11. Change of average fuel temperature due to the 5% stepwise decrease of the control rod position

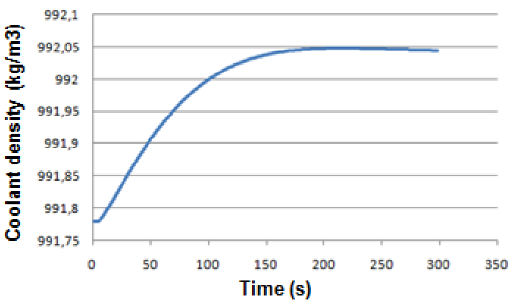

Fig. 12. Change of coolant density due to the 5% stepwise decrease of the control rod position

An excess reactivity insertion through control rod ejection was assumed to happen in the Kartini reactor, and safety analysis was carried out by using the code. The calculation results are shown in Fig. 13. None of safety and control systems was applied to provide conservative analysis. The total reactivity is suddenly increased due to the reactivity insertion leading to increases of the average fuel temperature to about 350 °C and the power to more than 200%, followed by the increase of cladding temperature to about 160 °C. Coolant temperature is increased to about 70 °C lower than the boiling temperature of water. The increases of fuel temperature and coolant temperature insert negative reactivity feedbacks which take the total reactivity to zero at about 110 s and all operation parameters are then kept constant. Criterion of safety limit of the fuel temperature of 530 °C is applied referring to that of similar training reactor of the University of Florida [6]. It is shown that the criterion is well satisfied due to the inherent characteristics of negative reactivity feedbacks.

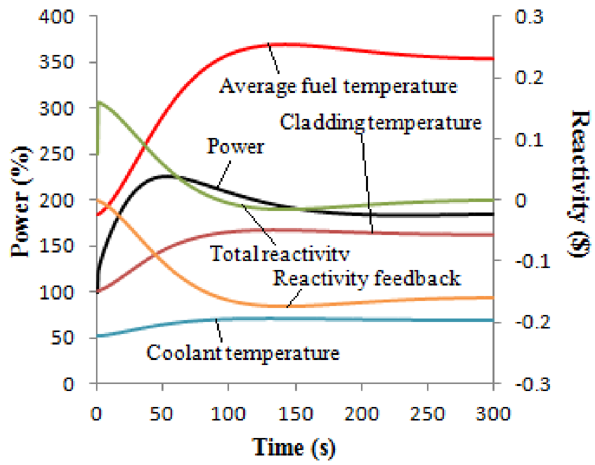

Fig. 13. Code calculations of an excess reactivity insertion by 1.1$

In the upcoming results, a comprehensive safety analysis might be conducted by using the improved code. Two major potential accidents of the Kartini reactor are expected to be analyzed: first, a Maximum Hypothetical Accident (MHA) and the second, a detail excess reactivity insertion accident. These major accidents refer to the safety analysis of the similar reactor of the University of Florida Training Reactor [6]. Other potential accidents might be also simulated and evaluated as a part of the educational activities. The safety analysis could be correlated with the experimental data as the challenge of discussion by the students.

V. CONCLUSION

A preliminary code with ability of calculating neutronics-thermal hydraulic of the Kartini reactor was developed. Qualitatively the calculation results show a sufficient agreement with those of experimental data of the Kartini reactor. However, the calculation error shows high value at particular condition. It is expected to improve the code by considering three types of control rods of the Kartini reactor. Besides, consideration of pool boiling heat transfer correlation might also improve the code. Calculation results of the reactivity, power, fuel temperature, and coolant density responses show similarity characteristics to those of plant dynamics of general light water reactors. It is expected that safety analysis and simulation could be carried out by the code in the future. Currently, the code is under improvement.

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