Simulation System for PeLUIt 150 MW Nuclear Reactor by using vPower

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Abstract. In developing the PeLUIt 150 MW nuclear power plant based on the High Temperature Gas-cooled Reactor (HTGR) technology, with the helium-coolant and output thermal power of 150 MW, the PeLUIt simulator is also developed for training the operators and educating other technical personnel. Referred to the balance of plant (BOP) design of the PeLUIt, the simulator utilized the vPower simulation platform to simulate the secondary loop for power generation with a water-steam Rankine cycle. The paper focuses on developing the secondary loop's main components: steam generator, steam turbine, condenser, deaerator, and feedwater pump. The reactor module in the primary loop is simplified as a heat source with 150 MW output. The steam generator that connects the primary and secondary loops is modeled with the heat exchanger module by transferring heat from helium to water/steam. Meanwhile, pressure and flow parameters can also be simulated for both helium and water/steam flows in steady-state and transient operating conditions. The steady-state simulation results are almost the same as the design data. The differences in the main steam temperature, feedwater pressure, and feedwater temperature, are 0.03%, 0.53%, and 0.02%, respectively. Meanwhile, the transient condition carried out in the loss of coolant accident showed a decrease in flowrate of 43.31 kg/s and an increase in temperature of feedwater and main-steam of 52.32 and 15.38 °C, respectively. In addition, there was a pressure drop of around 10.37 (feedwater) and 10.16 MPa (main-steam).

1. Introduction
Related to the development of Pembangkit Listrik dan Uap untuk Industri 150 MW or referred to PeLUIt 150 MW Nuclear Reactor based on High-Temperature Gas-cooled Reactor, one of the things that need to be prepared is the development of a nuclear reactor simulator. Nuclear reactor simulators are needed as a means of education and training for operators of the nuclear reactor. Training with this simulator is essential to improve the safety of nuclear reactor operations. Therefore, as part of developing large-scale nuclear reactors and SMRs design in Indonesia, it is necessary to develop a nuclear reactor simulator design in preparing human resources as a nuclear power plant operator.

Development of nuclear reactor simulators has been carried out both for PWR type reactors that operate a lot around the world as well as some advanced reactor designs such as High-Temperature Gas-cooled Reactors (HTGR) and Lead-cooled Fast Reactors (LFR) [1]–[8]. Various platforms or software are used for the development of nuclear reactor simulator designs, such as the merger between RELAP5 and LabVIEW [9], the use of SAS4A / SASSYS-1 and SIMULINK safety analysis codes in modeling the LFR reactor core simulator [1], and THERMIX / BLAST and the vPower used in the HTR-PM
Compared with various software for simulators, vPower is a simulation platform based on power generation, object-oriented components or modules, and an easy-to-use graphical interface.

In this research, a nuclear reactor simulator system will be developed by using the vPower platform. vPower is a new generation of simulation software that supports various power generation systems, including nuclear power plants. The vPower system covers developing simulation systems, including simulator design, modeling, testing, training, operations, and maintenance. The vPower platform library provides various thermohydraulic, control, and electrical-related modules that can meet various power plants' simulation requirements. vPower is also able to do modeling accurately with mathematical modeling, which includes the equilibrium of mass, momentum, and energy. In addition, vPower provides graphical configuration-based modeling, network communication, and database management in real-time and others [4].

This research focuses on developing simulators for modeling secondary cooling systems, including major components such as steam generators, steam turbines, condensers, deaerators, and water pumps. The development of this secondary system is based on the BOP from the design of a nuclear reactor. As for modeling on primary systems, nuclear reactors are modeled as a simple module of heat generation. The modeling will simulate nuclear reactors' conditions in full operation and transient conditions such as the Loss of Cooling Accident (LOCA) accident.

2. Design of PeLUIt 150 MWt Nuclear Reactor Simulator

2.1. Balance of Plant of PeLUIt 150 MW Nuclear Reactor

Development for the 150 MWt Nuclear Power Plant Simulator is focused on the secondary system of conceptual design that was previously simulated using ChemCAD software. The parameters obtained from the design will then be simulated using the vPower simulation platform. The nuclear reactor's main components consist of reactor vessels, blowers, steam generators, steam turbines, pumps, condensers, cooling towers, and deaerators. General installation data from a 150 MWT nuclear reactor is shown in Table 1 and power conversion system data is shown in Figure 1.

| Reactor parameter                                  | Value     |
|---------------------------------------------------|-----------|
| Thermal power (MW)                                | 150       |
| Helium inlet/outlet temperature (°C/°C)           | 250/700   |
| Helium pressure (MPa)                             | 7         |
| Helium mass flowrate at full power (kg/s)         | 96        |

As shown in Figure 1, this simulator's design is divided into 2 main systems 2, namely the primary and secondary systems, where the secondary circuit is further divided into 4 schemes. In the primary circuit consisting of a reactor as a heat generator, a blower as a regulator of helium flow and a steam generator as a steam generator used to drive a turbine. The secondary system is divided into 4 schemes. Each scheme represents the secondary system's main components, including the turbine, condenser, deaerator, and steam generator components. In this secondary system, water is converted into steam in the steam generator and flows to the turbine that is connected to an electric generator. In addition to converting water to steam, steam generators also function as heat exchangers between the primary and secondary systems.

2.2. Modelling of Secondary Loop System

The simulation modules developed in the secondary system of the 150 MWt nuclear power plant design use modules contained in the vPower simulation platform [5]. In general, the secondary system's main components include main-steam flow system, cooling water circulation system, condensate water flow system, and feed water flow system.
In this modeling and simulation with vPower, there are 2 parts, namely solving the thermal fluid network equation and simulating the main components of the system. The thermal fluid network is an essential part of a power plant simulation. In this platform, the components in the thermal fluid network include Node: the intersection of two or more branches where pressure is an unknown parameter that must be resolved in a fluid network, Branch: A channel of the direct flow of fluid, where the mass flux is an unknown parameter, boundary: a special node where pressure is applied, and Branch equipment: components of the branch such as pumps, valves, and others.

The model of the thermal fluid network can be explained as follows:

The fluid models on a node:

\[
\frac{d(\rho V)}{dt} = \sum_{i=1}^{n} w_i - \sum_{j=1}^{m} w_{m+i} + w_{LE} + w_{LL}
\]  

where,
\[
\begin{align*}
\rho & = \text{density of the node} \\
V & = \text{volume of the node} \\
n & = \text{number of nodes that connect with the node} \\
m & = \text{number of upstream nodes} \\
w & = \text{mass flux of the upstream or downstream branch} \\
w_{LE} & = \text{leakage mass flux into the node} \\
w_{LL} & = \text{leakage mass flux out of the node};
\end{align*}
\]

The fluid model on a branch:

\[
p_1 - p_2 + f(w) + \rho g \Delta z = \frac{1}{\rho C_v} |w| w
\]  

where,
\[
\begin{align*}
p_1, p_2 & = \text{pressure of the upstream node and the downstream node, respectively} \\
f(w) & = \text{increased pressure of the pump equipment} \\
w & = \text{mass flux of the branch} \\
\rho & = \text{density of the upstream node} \\
C_v & = \text{flow resistant factor of the branch};
\end{align*}
\]
The thermal energy conservation model of the node

\[ M \frac{dh}{dt} = \sum_{i=1}^{m} w_i h_i - \sum_{j=1}^{n-m} w_{m+j} h_{m+j} + Q \]  

(3)

where,

- \( M \) = mass of the node
- \( h \) = enthalpy of the flow
- \( Q \) = heat transfer to the node.

3. Methodology

This simulation is carried out under normal conditions at full power operation and transient under conditions of loss of the cooling system or loss-of-feedwater (LOFW) accident. From the secondary system scheme, there are modules of the primary and supporting components, including steam turbine with high-pressure and low-pressure, deaerator, condenser, feed water pump, check and single valve, vacuum pump, and components of a convection system on a steam generator as shown in Figure 2.

Under normal conditions, the simulation results with vPower will be verified with BOP data (as shown in Figure 1) to see the level of accuracy of the simulator system that has been made. In general, the simulation results on the 150 MWt nuclear power plant simulator that will be verified are the power conversion system data. Under normal conditions, the reactor design shows that the flow rate of steam on the secondary system is 59.5 kg/s with pressure at SG inlet about 14.9 MPa and SG outlets 14 MPa. Likewise, in the LOFW condition simulation, the energy conversion system data will be further analyzed when the primary and secondary cooling systems.

Figure 2. Secondary loop system of PeLUIt 150 MW Nuclear Reactor.
4. Result and Analysis

4.1. Simulation of Steady States with 100% Rated Power

The simulation results on the PeLUIt 150 MWt Nuclear Reactor carried out at full power are shown in Table 2. The parameters shown in Table 2 are a comparison between the simulation results and the design value. This research focuses on the secondary system so that the data obtained is also a part of the steam generator connected to the secondary system. The power of the reactor is set such that the parameters obtained from the simulator approach the design value. As shown in Table 2, the relative error between the simulation value and the design values is not more than 2% which means the design is reliable [4][5].

| Parameters                  | Design (superheated) Steam | Simulation (superheated) Steam | Relative Error |
|-----------------------------|----------------------------|--------------------------------|----------------|
| Working fluid               | Steam                      | Steam                          |                |
| Main Steam flowrate (Kg/s)  | 59.50                      | 59.50                          | 0.00%          |
| Main Steam Pressure (MPa)   | 14.05                      | 14.05                          | 0.00%          |
| Main Steam Temperature (°C) | 539.32                     | 539.18                         | 0.03%          |
| Feedwater Flowrate (Kg/s)   | 59.5                       | 59.5                           | 0.00%          |
| Feedwater Pressure (SG inlet) (MPa) | 14.95 | 14.87 | 0.53% |
| Feedwater temperature (°C)  | 200                        | 200.04                         | 0.02%          |

4.2. LOFW Accident Scenario

Besides steady-state conditions, the PeLUIt 150 MWt Nuclear Reactor Simulator is also applied to simulate transient conditions and accidents. In this part, the loss of feedwater accident scenario was simulated which the secondary system loses the cooling flow system. This loss of coolant is caused by pump damage which results in a decrease in pump performance. The scenario is started from full power condition as the initial condition and followed the process of decreasing the pump's performance causes the water flow to decrease gradually. A decrease in feedwater flow occurs for almost 150 seconds until it reaches saturation flow. This change in feedwater flow results in changes in flow rate, temperature, and pressure of main-steam. Figure 3-5 shows the curve of dynamic parameter changes in the simulation process.

![Figure 3. Flow rate of feedwater (left) and main-steam (right)](image-url)
Figure 3 shows the change in the flow of feedwater and main-steam. When the pump fails, resulting in a decrease in flow in the feedwater as shown in Figure 3 (left), it causes the flow to decrease from 59.5 Kg/s to around 16.19 Kg/s. The decline in feedwater flow rapidly occurred at 30 s, and after that, it began to saturate up to 150 s. In this simulation, even though there was a pump failure, up to 280 s, the feedwater's residual flow did not stop quickly. Meanwhile, the decrease in the feedwater flow causes a decrease in the steam flow, which takes place gradually to form an exponential curve pattern. Up to 280 s, the steam generator's main-steam flow is almost the same as the feedwater flow. The difference in flow between main-steam and feedwater after the accident was minimal, around 0.13 s.

Meanwhile, the decrease of feedwater flow increases the feedwater temperature, i.e., about 52.32 ℃, followed by an increase in main-steam temperature, around 15.38 ℃ given in Figure 4. The decrease in flow in feedwater which is very significant at 100 s, results in a significant increase in temperature. After that, the temperature begins to saturate after the process is running 150 s.

Figure 5 shows the pressure change during the LOFW process. From this figure, it can be seen that there is a pattern of changes in pressure that is almost the same between feedwater and main-steam gradually. In feedwater, there was a decrease in pressure from 14.87 MPa to 4.14 MPa. Meanwhile, main-steam decreased from 14.05 MPa to 3.89 MPa. However, the overall data cannot be further verified because there is no supporting experimental data.
5. Conclusion
The Simulator of PeLUIt 150 MWt Nuclear Reactor using the vPower platform is applied to simulate the steady state condition and loss of feedwater accidents. The results analysis of this simulation shows that that is agreed with the design value. In steady-state conditions, the relative error between the simulation value and the design values is not more than 2%. It can simulate normal and also accident conditions. In LOCA condition, there is a decrease in flow rate and pressure and an increase in temperature. This simulator will be developed, validated, and verified with the other data of PeLUIt nuclear reactor design, especially in any accident condition.

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