Preliminary Analysis of PIUS-type Experimental Apparatus with Hot/Cold Fluids Interface for Inherently Safety

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1. Introduction

In recent years, nuclear reactor safety has become increasingly important due to several accidents at nuclear power plants. In response, safety concepts such as passive safety and inherent safety have gained prominence with the aim of reducing the probability of accidents and improving safety in nuclear power plants. The PIUS (Process Inherently Ultimate Safety) concept, which was first proposed by the ABB-ATOM of Sweden in the 1980s, involves submerging the reactor in a large tank filled with cold high-borated water [1]. A schematic of the PIUS-type reactor is shown in Fig. 1.

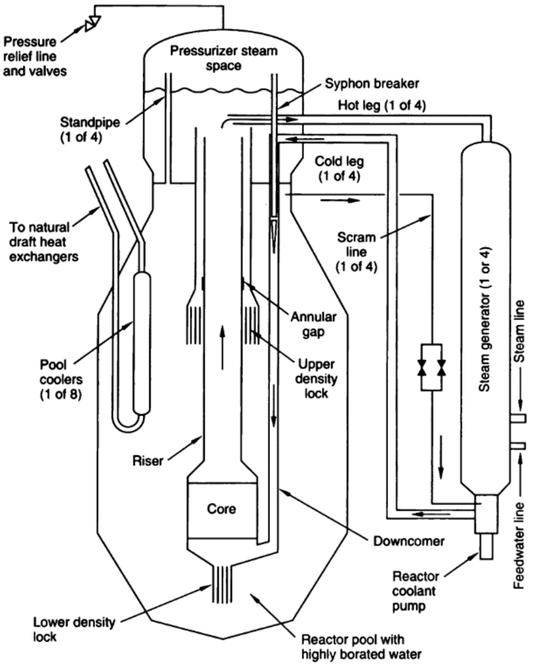

Fig. 1. Schematic of PIUS-type reactor [1].

The volumetric flow rate is controlled by reactor coolant pumps to prevent the abnormal influx of boron acid water, which serves to control the core reactivity without requiring control rod driving mechanisms. This can be achieved through the basic principle of a density lock; whereby hot and cold fluids are stratified as illustrated in Fig. 2.

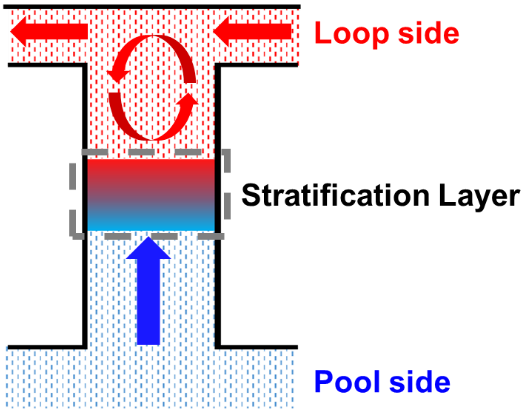

Fig. 2. Stratification principle in a density lock.

The PIUS design provides a complete solution to control rod ejection accidents by removing the need for control rod driving mechanisms. This design ensures inherent safety by allowing the inflow of cold-borated water, resulting in a negative reactivity coefficient even under accident conditions [2].

Previous studies have conducted several thermal-hydraulic experiments on a scaled-down model of the PIUS-type reactor. Tasaka et al. conducted an atmospheric-pressure small-scale experiment of the PIUS-type reactor in various transient conditions, where they proposed a pump speed control system for the stable operation of the reactor [3]. Sibamoto et al. analyzed the dynamic response of hot/cold fluid interfaces to pump speed perturbation in the EARTH (Experimental Apparatus for Reactor Thermal-Hydraulics) facility [4].

However, the instability of the hot/cold fluids stratification inside the density lock of PIUS-type reactors has not been extensively studied. As a result, an experimental apparatus was designed to visualize and analyze the stratification instability. A preliminary analysis of the thermal-hydraulic phenomena of the experimental apparatus was performed using the MARS-KS code, which is the standard nuclear safety regulation numerical analysis code in Korea.

2. Numerical Simulation Modeling

As illustrated in Fig. 3, the experimental apparatus used is designed to replicate the density lock and was modeled for the MARS-KS code simulation. The experimental setup comprises a pressurizer, a cold water tank, a heater, a riser, a downcomer, and two density locks. With a total height of approximately 3.3 m from the ground, the Upper Density Lock (UDL) and Lower Density Lock (LDL) are arranged at the top and bottom, respectively. The coolant pump, arranged at the end of the downcomer, provides working fluid at a specific flow rate to counterbalance the hydrostatic pressure caused by the temperature difference between the loop side and the pool side.

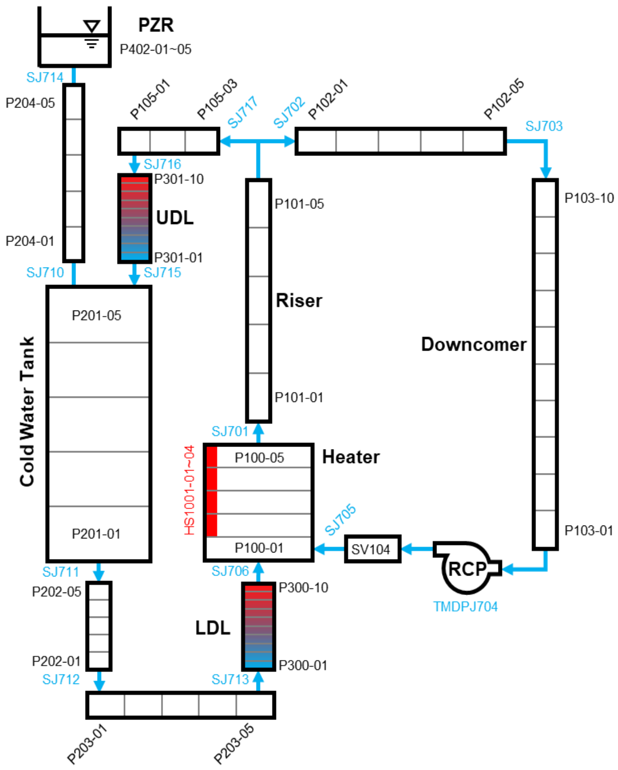

Fig. 3. Nodalization of the experimental apparatus.

During transient states, the hydrostatic pressure balance inside density locks was disrupted, causing the fluid interface to collapse, and resulting in the inflow of low-temperature water into the loop side. To ensure the experimental apparatus operates at atmospheric pressure, the pressurizer is open to the atmosphere. The temperature of the loop side is limited to 80 ℃, which is within the temperature range allowed for acrylic material, to enable the visual observation of the thermal-hydraulic phenomena inside the apparatus.

3. Simulation Results

Prior to the detailed design of the experimental apparatus, preliminary simulations were performed using the MARS-KS code, which is based on the one-dimensional momentum equation. Simulations focused on start-up, pump trip, and pump power ramping scenarios, which were considered significant transient conditions for this study.

3.1. Start-up Simulation

To generate the hot/cold fluids stratification interface inside the density lock from the initial state, a specific start-up procedure must be required [3]. This procedure is not only necessary for the initial start-up but also for the restart process of the PIUS-type reactor. The code analysis was conducted to verify whether the cold water enters the primary side of the small-scale experiment. In the start-up simulation, the heater power and the pump flow rate were simultaneously increased at 2.0 kW and 0.53 m/s for 1200 sec, respectively.

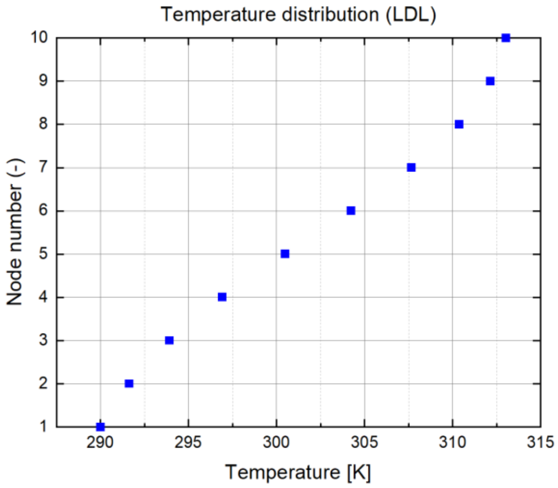

Fig. 4. Axial temperature distribution in the LDL (P300) in a steady state.

After 1200 seconds, the temperature of each node of the LDL increased and successfully formed the interfacial layer, as presented in Fig. 4. The temperature gradient increases as it approaches each side from the center of the LDL, indicating that the longer the linear section from the center, the greater the stratification instability. The Richardson number is used as an evaluation criterion for stratification instability, where a fluid interface is considered stable when the Richardson number is greater than 0.25. The Richardson number in this simulation and the previous study [3] have a similar value of 0.231.

3.2. Pump Trip Simulation

In the normal operation of the PIUS-type reactor, the stratification inside the density lock is maintained by controlling the pump speed. However, in the event of a pump trip, which could potentially lead to a nuclear reactor accident, the reactor must be protected. Fig. 5 illustrates the thermal-hydraulic phenomenon in the pump trip simulation after 2000 sec. The volumetric flow rate in the loop side decreases, causing the collapse of the hot/cold fluids interface. This leads to the inflow of cold water into the primary side through the LDL.

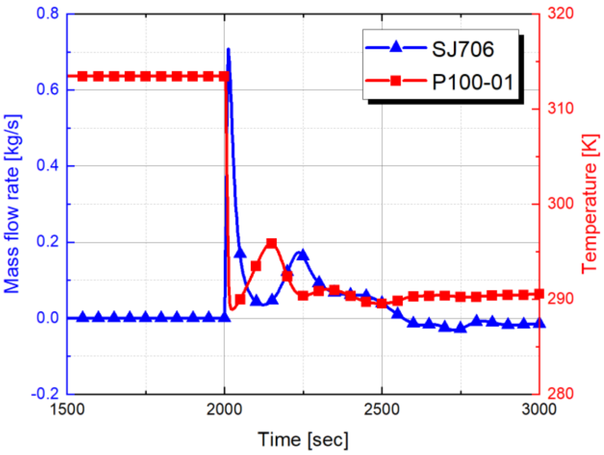

Fig. 5. Mass flow rate through the LDL and primary side temperature behavior in the pump trip simulation.

The cold water was then mixed with the hot water and exited to the water tank through the UDL. In the actual-scale of the PIUS-type reactor, passive pool coolers arranged in the large water pool cools the hot coolant that flows into the pool through the natural circulation path of the coolant and removes the decay heat ensuring long-term cooling process.

3.3. Pump Power Ramping Simulation

Preserving the hot/cold fluids interface in the density lock during normal operation requires feedback control based on the elevation of the stratification layer [3]. Thus, pump feedback control is essential for ensuring the normal operation of the PIUS-type reactor. However, mechanical failure or malfunction of the pump may cause the loss of pump control, leading to the continuous high flow rate of the working fluid and a collapse of pressure balance for the stratification. This high flow rate also results in an internal pressure drop, affecting the reactor power.

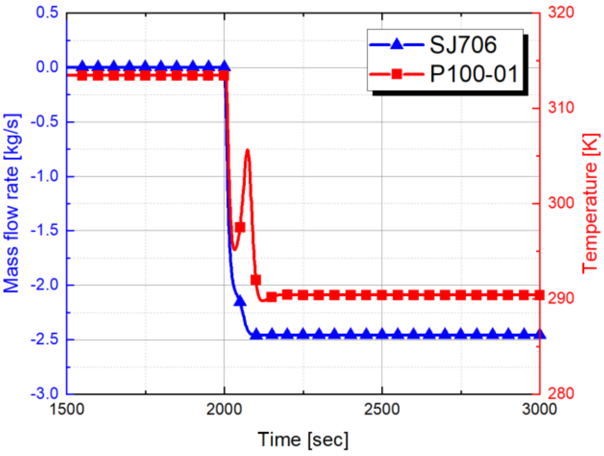

Fig. 6. Mass flow rate through the LDL and primary side temperature behavior in the pump power ramping simulation.

The pump power ramping simulation in this study imitates the uncontrolled conditions with the pump speed twice as high as normal operation. Fig. 6 shows that pump power ramping leads to the high mass flow and the flow of hot water on the primary side out to the pool side through the LDL. It means that the outflow of the primary coolant through the LDL and the inflow through the UDL generate the natural circulation path, which has the opposite direction in the previous pump trip simulation. Notably, the pool surrounding the reactor contains cold water that is highly enriched with boron acid for reactivity control. These results underscore the inherent safety feature of the PIUS-type reactor, emphasizing its ability to ensure safe shutdown even in the face of unexpected events.

4. Conclusion

An experimental apparatus was designed to visualize and analyze the instability of the hot/cold fluids stratification within the density lock of a PIUS-type reactor. In this study, the thermal-hydraulic phenomena of an experimental apparatus were preliminary investigated using the MARS-KS code.

Simulations were conducted for start-up, pump trip, and pump ramping scenarios. The results showed that the start-up procedure successfully generated hot/cold fluid stratification inside the density lock. The pump trip simulation revealed that the hydrostatic pressure balance inside the density lock was disrupted, causing the fluid interface to collapse, and resulting in the inflow of low-temperature water into the loop side. The pump power ramping simulation showed that the thermal-hydraulic phenomenon was stable with the inherently safety feature. These simulation results provide valuable insights into the instability of the hot/cold fluid interface in the density lock of the small-scale experimental apparatus and can aid in the design of safer nuclear reactors.

Further experimental studies are needed to validate the simulation results and improve the understanding of the thermal-hydraulic phenomena in PIUS-type reactors.

ACKNOWLEDGMENTS

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