Micro-Integral Effect Test of URI-LO with Infrared Imaging Technique of Drone

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1. Introduction

The 4th industrial revolution technologies represented by big data processing technology [1], artificial intelligence [2, 3], drone [4], and 3D printing are widely applied to engineering fields for the benefits in terms of safety and economy. Application of the above-mentioned technologies to nuclear power plants will remarkably reduce the potential risk factor (human error) with enhancing the construction and operation efficiencies. Although there are many research activities advancing safety features [5-7] and considering application of the 4th industrial revolution technologies, test beds evaluating feasibility of some innovation concepts are insufficient because conventional integral effect test loops are too large and heavy to adopt new ideas like operating power plants. Therefore, micro-integral effect test facility with a small and light scale was developed to overcome such limits of large-scale test beds. The UNIST reactor innovation loop, URI-LO which is a scale-down model (1/12 diameter ratio and 1/8 height ratio) of the APR-1400 was designed based on the three-level scaling method. The URI-LO is designed to have enough simulatability of three major accidents of reactor coolant pump seizure accident, station blackout, and loss of feedwater accident of the reference power plant. The refrigerant, FC-72 with a lower boiling point (~56 °C) is determined as a working fluid to simulate the operating conditions of the reference power plant with relatively low pressure and temperature conditions. To exhibit the performance as integral effect test facility, main components, such as heater, reactor coolant pump, and steam generator, must be validated whether they collaborate each other with exhibiting appropriate system behaviors under various operating conditions. Therefore, a series of experiments was conducted to confirm the functionality. In this paper, the experimental results demonstrating performance of test facility is introduced with application of drone as a representative technology of 4th industrial revolution.

2. Design Specification of URI-LO

URI-LO is a scale-down facility of APR-1400 designed by three-level scaling methodology to conserve the system behavior of reference power plant. Three-level scaling approach, suggested by Ishii and Kataoka [8], is an appropriate approach for design of URI-LO, because this methodology conserves the thermal-hydraulic phenomena of the reference system providing the disadvantages of linear and volumetric scaling methods. According to this approach, scaling ratio in height and diameter could be varied, and reduction of height provides good simulatability on multi-dimensional phenomena. Therefore, three-level scaling approach was used in scaling analysis of URI-LO, that must have noticeably reduced height scale.

For single-phase natural circulation, mass, momentum, energy conservation equations regarding fluid and solid are nondimensionalized with boundary conditions according to three-level scaling approach. Dimensionless numbers, Richardson number, Stanton number, time ratio number, heat source number, and Biot number, representing the thermal-hydraulic phenomena, are deduced in the nondimensionalization. Conservation of the deduced nondimensional numbers is a key analysis step to conserve the thermal-hydraulic phenomena of reference system with scaled facility [9].

In case of scaling of two-phase flow, non-dimensional numbers, such as phase change number, subcooling number, Froude number, Drift-flux number, Friction number, and Orifice number, deduced from one-dimensional drift flux model and transfer functions, were matched. After analyses of global scaling, boundary and inventory scaling, and local phenomena scaling were conducted.

Table I: Global scaling parameters and scaling ratios for single natural circulation of URI-LO [9]

Parameters	Scaling ratio	URI-LO
Length (height)	l_{oR}	1/8
Diameter	d_{oR}	1/12
Core temperature rise	dT_{oR}	1/2
Velocity	$l_{oR}^{1/2}$	1/1
Time	$l_{oR}^{1/2}$	1/1
Richardson number	1.0	
Friction number	1.0	
Time ratio number	0.84	
Stanton number (laminar)	0.66	
Stanton number (turbulent)	0.50	
Biot number (laminar)	0.80	
Biot number (turbulent)	0.64	
Heat source number	0.72	

URI-LO was scaled by 1/8 reduced-height and 1/12 reduced-diameter. To simulate the system behavior under the high pressure and high temperature condition of reference model in reduced pressure condition (due to mechanical strength of transparent material), all-round scaling analyses were conducted based on thermal-hydraulic properties of simulant fluids.

FC-72 was determined as a simulant fluid considering the boiling temperature, compatibility with material, and scaling distortions of reference velocity and heat transfer coefficients. Although there is remarkable distortion of heat transfer coefficient, the distortion effect was preserved by adjusting the heat transfer areas of components (number of heater and steam generator u-tube). The overall scaling ratios and global scaling parameters of URI-LO is listed in TABLE I.

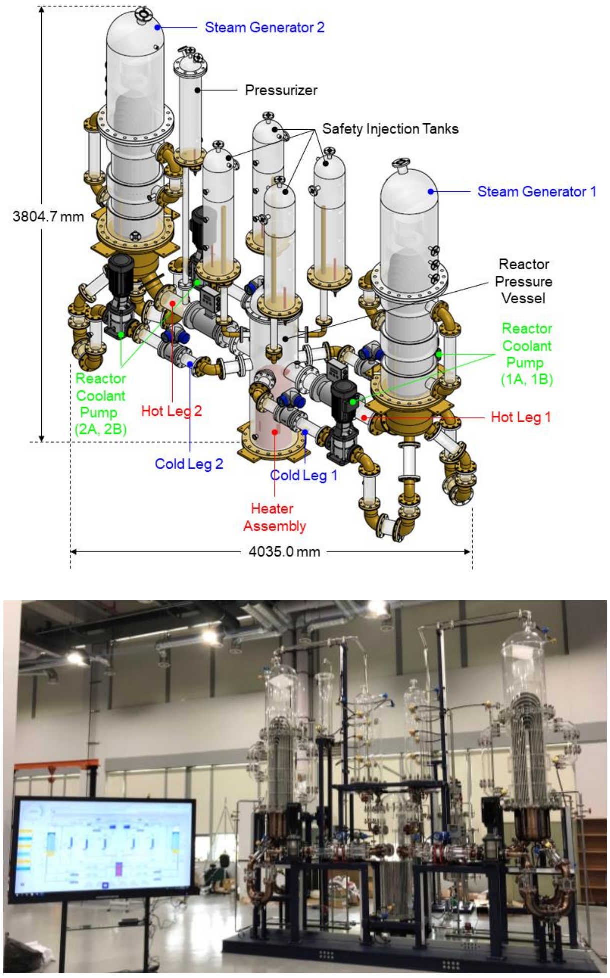

Fig. 1. Overall design feature and image of URI-LO [9]

Total height and width of URI-LO are 3.8 m 4.04 m, respectively. Fig. 2 is an overall design feature of URI-LO and Fig. 3 is a photo of constructed URI-LO. Numbers of heater and steam generator u-tube were further reduced to preserve the distortion effect of heat transfer coefficient as depicted in previous section. Reactor coolant system includes reactor pressure vessel having downcomer, heater assembly with maximum heat capacity of 200 kW, pressurizer, 2 hot legs, 4 cold legs (4 intermediate legs with loop seals), and 4 reactor coolant pumps (RCPs). Safety injection tanks consists of container, heater, pressure valve, and fluidic device were installed with direct vessel connection as a fundamental passive safety system. Two steam generators consist of u-tubes, steam dryer, steam separator, main feedwater system with recirculation pipeline, and auxiliary feedwater system were constructed. Total 40 thermocouples, 16 pressure transducers, and 12 mass flowmeters measure the system behaviors during the tests. The measured data will collaborate with visualization data to provide comprehensive understanding on multi-dimensional behaviors and complex thermal-hydraulic phenomena.

3. Functional Test of URI-LO

In general, physical system behaviors with specific thermal-hydraulic phenomena are indicators of performance of integral effect test facility. To evaluate the performance indicator, a series of experiments was conducted. A heating test under natural circulation condition was carried to demonstrate that the system behaviors under natural circulation phase is valid. In addition, overall system behaviors were observed under forced convection condition varying the flow rate and power of the heaters. All of experiments were conducted under the condition that a single steam generator is filled with coolant (rest SG is empty) as a stagnant liquid pool to observe resolution toward asymmetric behaviors.

4. Results and Discussion

4.1. Heating test (Natural circulation)

Temperature difference between cold legs and hot legs of the loops, and steam generator temperatures when all of reactor coolant pumps (RCPs) do not operate and power of 75 kW was applied to heater are plotted in Fig. 2.

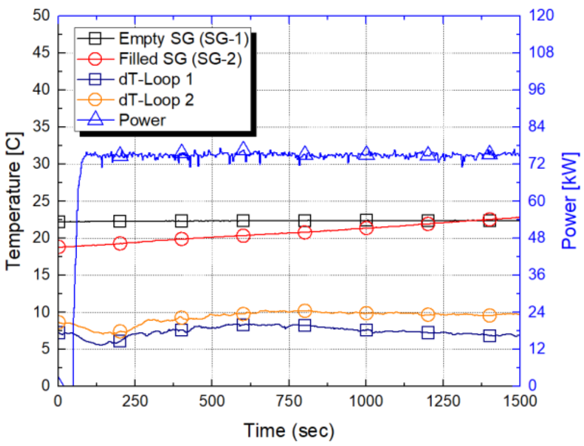

Fig. 2. Variations of temperature differences between hot legs and cold legs, and SGs of the loops with empty and filled SGs under natural circulation phase.

The temperature difference between cold leg and hot leg of the loop having coolant-filled SG (Loop 2) was higher than that of opposite loop (Loop 1) owing to heat removal through steam generator as indicated by increase of temperature of steam generator 2. In addition, the temperature difference between cold leg and hot leg of the loop 2 was nearly constant during heating test period, in opposite, temperature difference of the loop 1 decreases due to absence of heat sink. In terms of reactor coolant flow rate, the flow rate of the loop 2 was higher than loop 1, because higher buoyancy force of the loop 2 was exerted by higher temperature difference under equal height difference between thermal centers (core and steam generator u-tubes).

In a physical viewpoint, it was confirmed that system behaviors inside the URI-LO under natural circulation condition is valid and the facility has appropriate simulation capacity for integral effect test related to natural circulation.

4.2. Forced convection test

The temperatures of SGs and temperature difference between hot leg and cold legs according to loops when all of RCPs operated at the equal heat input condition with natural circulation test were plotted in Fig. 3. As the coolant flow rate increases, SG2 temperature increased with sharper slope than natural circulation condition, because heat transfer rate from primary system to secondary system was increased through increased convective heat transfer. The reduction of reactor coolant temperature after operation of RCPs proves the heat removal through SG 2. However, constant SG 1 temperature indicates negligible heat removal.

The temperature differences between cold legs and hot legs were decreased to below 1 °C, compared to natural circulation condition due to increased reactor coolant flow rates.

The change of system behaviors when the coolant flow rate was varied were demonstrated in Fig. 4. As the coolant flow rate decreased, the temperature difference between cold legs and hot leg of the loop 2 was higher than loop 1, because of different heat removal rate through SGs. After increasing the coolant flow rate, temperature differences of the loops converged. Based on temperatures of steam generators, the heat transfer rates from primary system to secondary system were calculated. As shown in Fig. 4, the heat removal rates through SG 1 and 2 were 0.25 % and 4.5 %, respectively.

The comprehensive data regarding system behaviors under single phase circulation supports the appropriate test performance of URI-LO. In addition, it was proven that URI-LO has resolution about asymmetric behaviors of the loops. Therefore, various system behaviors related with single-phase circulation under integral effect tests are expected to be analyzed by URI-LO appropriately.

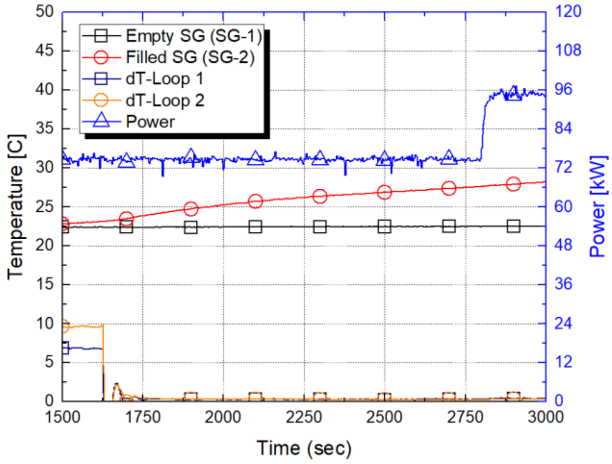

Fig. 3. Variations of temperature differences between hot legs and cold legs, and SGs of the loops with empty and filled SGs under forced convection phase.

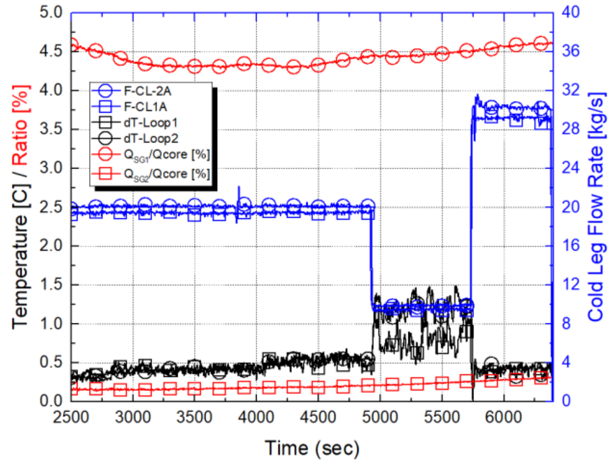

Fig. 4. Variations of temperature differences between hot legs and cold legs, and SGs of the loops and SG`s heat removal rates.

4.3. Infrared observation with drone

Drone is a representative technology of 4th industrial revolution and being widely investigated to adopt nuclear power plant for inspection and maintenance. For improvement of the technical quality, feasibility study is necessary by utilizing the device in plant environment. As a feasibility study of plant inspecting drone, IR camera-equipped drone (160x120 resolution, 12 um fixel, 10 % of maximum uncertainty from -10~140 °C) was utilized during the experiment.

Temperature fields according to various operating conditions were taken as shown in Fig. 5 and 6. The recorded IR images exhibited significant resolution toward coolant inventory inside the system including water level, temperature distribution across the loop, and overall operating condition of the facility. Figure 5 depicts the temperature difference between hot leg and cold leg. Relatively low temperature field (blue) was observed along the intermediate leg, cold leg, and downcomer of RPV, even though, upper head of RPV, hot leg, and SG lower plenum. The asymmetric operating condition could be also distinguished by IR image as shown in Fig. 6. The observed temperature field of SG 1 was nearly room temperature and SG 2 temperature was higher than 35 °C.

The applicability of drone for nuclear power plant was briefly evaluated, and the results showed it could be utilized as inspection device by measuring temperature field, leaking coolant, visual data, and so on. The branch research adopting drone to plant environment will be advanced and continuously evaluated in the future.

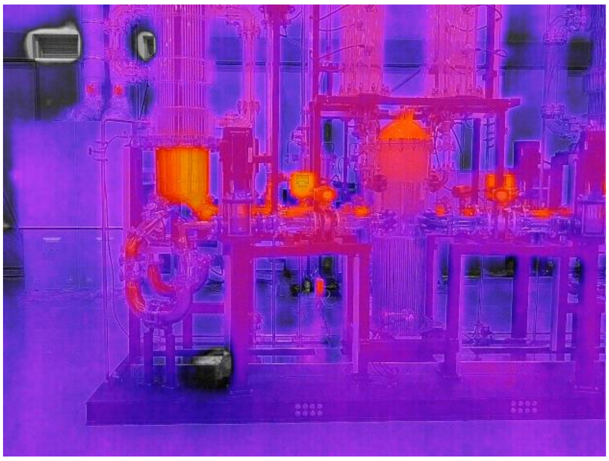

Fig. 5. Temperature field exhibiting different temperature between cold leg and hot leg of URI-LO.

Fig. 6. Overall temperature field of URI-LO during forced convection condition.

5. Conclusion

Micro-integral effect test facility, UNIST reactor innovation loop (URI-LO), was designed and constructed as a test bed for new innovative technologies. Based on three-level scaling approach, URI-LO was designed to have remarkable reduced scales; 1/8 height ratio and 1/12 diameter ratio in respect of APR-1400. Utilizing simulant fluid and appropriate scaling analysis, the facility was comprised with transparent components.

To observe that the constructed URI-LO has appropriate performance as a thermal-hydraulic integral effect test facility, preliminary test evaluating performance of main components and system behaviors including resolution for asymmetric behaviors was carried out. A series of experiments consisting of heating test and forced convection test with various operating conditions were conducted. The comprehensive analysis on experimental data supported that URI-LO has significant capacity as IET facility with provide the physically valid phenomena.

In the future, integral effect tests will be conducted for quantitative design validation with utilization of simulant fluid. Consequently, the research activities of URI-LO contributing to improve technical quality of innovative technologies will be performed.

ACKNOWLEDGEMENT

This work was supported by Korea Hydro & Nuclear Power Company through the project "Nuclear Innovation Center for Haeorum Alliance".

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