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Recent Domestic Research Trends of Natural Circulation Behaviors for Nuclear Reactor Safety

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1. Introduction

In 2011, severe accidents at the Fukushima nuclear power plants occurred according to loss of cooling ability for the reactor cores following station blackout (SBO) caused by the Tohoku earthquake and then tsunami. So it has been considered that one of the important reasons for the Fukushima accident is the failure of active cooling measures for core decay heat. According to the reason, verification of core coolability without electrical power supply has been becoming one of mainstreams for reactor safety studies after experiencing the Fukushima accident. In order to assess the cooling ability, many studies have been conducted to assess passive means of reactor core cooling. One of key factors for these studies is to generate driving force for coolant flows without supplying electrical energy.

In Heavy Water Reactor (HWR) including CANDU, the research topic is also very important because there is still a concern about core cooling in case of SBO accident at HWRs. In order to overcome the difficulty, natural circulation phenomena can be an answer because they are simply happened by density differences of a fluid. However, natural circulation flow in HWRs can be established hard because HWRs have horizontal fuel channels and these channel configurations result in considerable friction loss compared to vertical geometries. But there are few studies on natural circulation at HWRs.

In this paper as a preliminary study, major phenomena of SBO accident in CANDU are introduced and recent domestic research results over approximately twenty years (2000~present) for natural circulation are summarized regardless of reactor types because there are few papers about natural circulation as mentioned.

2. Major phenomena in SBO accident of CANDU

According to the previous technical paper[1], this section introduces the event progression for SBO accident in CANDU until core damage has just occurred [*]. The event is mainly divided into three steps which are reactor shutdown, steam generator dryout, and core damage sequentially.

First of all, when SBO accident occurs in CANDU all power is lost and then reactor is shutdown. Because of shortage of electrical power, forced circulation of the all active cooling systems in CANDU are stopped. After reactor shutdown, the core decay heat is moved to the inventory water of the steam generators through natural circulation flow inside heat transfer system. Without supplying feedwater the pressure and temperature in the steam generators rise rapidly, eventually the steam generators dry out. As a result, core damage begins due to the fuel channel dryout.

3. Brief summary on natural circulation studies

3.1 Heavy water reactor

Shin [2] conducted computational studies to predict integrity of the system using SOPHT. The numerical analyses were carried out according to accident conditions, which mean failures of shield cooling pumps and/or heat exchangers. According to simulation results, in case of concurrent failures of shield cooling pumps and heat exchangers, natural circulation resulting from boiling water was observed.

Although not domestic studies, two studies on natural circulation inside horizontal channels are introduced because of good explanation and analyzing of horizontal natural circulation flow. Zhou et al. [3] conducted numerical simulations to investigate the effect with or without water make-up to the steam generators in CANDU in case of SBO accidents. In order to achieve this, the input model of CANDU was created using RELAP5 and the fuel channels were divided into 20 groups according to their elevation and power. According to the simulation results, supplying water make-up to steam generators in the early stage of the SBO accidents assure the fuel and fuel channel integrity.

Lazarte et al. [4] studied flow oscillations in twin and parallel and inverted U channels numerically and theoretically. The computational input model was created using RELPA5 and theoretical analysis was conducted under some assumptions. According to the study, simulation results were able to reproduce natural circulation under this geometric condition and theoretical results were capable to predict the flow behaviors.

3.2 Light water reactor

More studies have been done on natural circulation of Light Water Reactor (LWR) compared to HWRs. These studies were mainly the assessment and verification for preventing core meltdown with External Reactor Vessel Cooling (ERVC) method. The brief summaries of the recent studies on natural circulation of LWR are as follows.

Park et al. [5] conducted experimental and numerical studies for natural circulation flow in the gap between the reactor vessel and the insulation(hereinafter referred to as “gap flow”) of APR1400 under external vessel cooling. The experiment study carried out using an 1/21.6 scaled test facility of the APR1400 reactor and the numerical study using the full-scale geometry for the APR1400 reactor showed that natural circulation flow fields formed in the experimental and numerical results. More specifically, as the heat flux inside the reactor vessel of the test facility increased from 0.06 MW/m² to 0.79 MW/m², the gap flow rates(kg/s) also rose. In addition, the gap flow patterns were irregularly fluctuated.

Ha et al. [6] experimentally studied two-phase natural circulation about gap flow in the same test facility [5] under external vessel cooling. Compared to the previous work [5], the authors attempted to study a position (lower/higher) effect of the coolant exit port and a difference between using electrical heating rods and injecting air bubbles equivalent to a heat flux by the heating rods. According to the experimental results, gap flow rates in the case of the higher exit port were larger than the lower exit port, and there were quite differences of gap flow rates between heating and non-heating(air bubble injection) experiments.

Kim et al. [7] conducted numerical studies using commercial CFD code (CFX-5.6) regarding air bubble injection rates and reactor geometries with or without shear keys, devices pinning the reactor and insulation each other. According to the simulation results, as an air bubble injection rate increased, a gap flow rate also rose. And under the same air bubble injection rate, gap flow rates with shear keys were higher than without shear keys.

Ha et al. [8] experimentally studied an effect of air bubble injection rates and generating positions of air bubbles on gap flow rates in the same test facility [5]. According to the authors, the air bubble injection rates had a proportional relation with the gap flow rates and the gap flow patterns were changed based on the generating positions of air bubbles.

Park et al. [9] conducted sensitivity analyses using RELAP5/MOD3 with respect to the heat flux inside the reactor vessel, position and area of coolant outlet, etc. The numerical input model was generated based on the full-scale APR1400 geometry. According to the authors, there was an critical value of the heat flux(1.0 MW/m²) having insignificant effect on increase of the gap flow rates over the value. In addition, as the area of the coolant outlet increased, the gap flow rates also rose. However there was no relation between the area of coolant inlet and the gap flow rates.

Park et al. [10] also carried out experimental and numerical studies to investigate the effect of air bubble injection rates, areas and position of the coolant outlet, etc. Compared to the previous works [5~9], a new test facility, T-HERMES-1D, was used for an experimental study and RELAP5/MOD3 for a numerical simulation. According to the authors, trends of the experimental and simulation results were similar to the previous studies [5~9]. However, there were slight differences between experimental and simulation results in some cases.

Ha et al. [11] conducted experimental studies to research natural circulation flow of the test facility [10] under ERVC. Compared to the previous works [5~9], it is revealed that there was no effect of the water level in the main tank.

Kim et al. [12] attempted to explain natural circulation behaviors of T-HERMES-1D under ERVC from the experimental and theoretical aspects. In order to achieve this, the authors analyzed gap flow rates using the one-dimensional drift flux model. According to the authors, the calculation results were matched to the experimental result [10,11] within the margin of error(15%).

Kim et al. [13] carried out experimental studies to investigate the effect of the wall heat flux on the test section of T-HERMES-1D on the gap flow rates. So, the authors used electrical heating rods instead of injecting air bubbles. In the experiments, it was found that vapor bubbles were formed periodically and the wall heat flux had proportional relation with vapor bubble generating and gap flow rates.

3.3 SMART-P

In addition to the above studies, there was another experimental study on natural circulation flow in Passive Residual Heat Removal System(PRHRS) of SMART-P. Park et al. [14] conducted experimental research to investigate heat transfer characteristics and natural circulation performance for PRHRS in SMART-P. According to the experimental results, it was found that natural circulation flow was formed and the maximum flow rate was 0.03 kg/s.

5. Conclusion

In this paper, major phenomena of SBO accident in CANDU are introduced and recent domestic research trends of natural circulation for a variety of reactor types are summarized. The previous studies are mainly focused on the vertical flow of natural circulation, while few studies have been made for horizontal natural circulation flow. Based on the previous studies, a numerical study on natural circulation flow in horizontal channels will be conducted in the future work.

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REFERENCES

[1] Canadian Nuclear Safety Commission(CNSC), Sever Accident Progression Without Operator Action, CNSC Online Article, 2015.

[2] J.C. Shin, HWR Shield Cooling Natural Circulation Study, Journal of Energy Engineering, Vol.21, No.3, pp.221-227, 2012.

[3] Feng Zhou, David R. Novog, RELAP5 Simulation of CANDU Station Blackout Accidents with/without Water Make-Up to The Steam Generators, Nuclear Engineering and Design, Vol.318, pp.35-53, 2017.

[4] Alejandro I. Lazarte, J.C. Ferreri, A Verification Problem for Thermal Hydraulics Systems Codes Dealing with Twin, Parallel-Boiling and Inverted U-Tubes Condensing Channels, Annals of Nuclear Energy, Vol.68, pp.163-171, 2014.

[5] R.J. Park, K.S. Ha, S.B. Kim, H.D. Kim, Analysis of Coolant Flow in the Reactor Cavity under External Vessel Cooling, Transactions of the Korean Nuclear Society Autumn Meeting, 2002.

[6] K.S. Ha, R.J. Park, H.Y. Kim, S.B. Kim, H.D. Kim, An Experimental Study on the Two-Phase Natural Circulation Flow through an Annular Gap between Reactor Vessel and Insulation under External Vessel Cooling, Proceedings of the Korean Society of Mechanical Engineers 2003 Spring Conference, pp.1897-1902.

[7] H.M. Kim, J.W. Seo, K.Y. Kim, R.J. Park, K.S. Ha, S.B. Kim, A Numerical Study on the Two-Phase Natural Circulation Flow in Reactor Cavity under External Vessel Cooling, Proceedings of the Korean Society of Mechanical Engineers 2003 Autumn Conference, pp.781-785.

[8] K.S. Ha, R.J. Park, Y.R. Cho, S.B, Kim, H.D. Kim, A Non-Heating Small-Scaled Experimental Study on the Two-Phase Natural Circulation Flow through an Annular Gap between Reactor Vessel and Insulation, Proceedings of the Korean Society of Mechanical Engineers 2004 Spring Conference, pp.1927-1932.

[9] R.J. Park, K.S. Ha, S.B. Kim, H.D. Kim, Analysis of Two Phase Natural Circulation Flow in the Reactor Cavity under External Vessel Cooling, Proceedings of the Korean Society of Mechanical Engineers 2004 Spring Conference, pp.2141-2145.

[10] R.J. Park, K.S. Ha, J.C. Kim, S.W. Hong, S.B. Kim, One-Dimensional Analysis of Air-Water Two Phase Natural Circulation Flow, Proceedings of the Korean Society of Mechanical Engineers 2007 Spring Conference B, pp.2626-2631.

[11] K.S. Ha, J.C. Kim, R.J. Park, S.B. Kim, S.W. Hong, Natural Circulation Flow Investigation in a Rectangular Channel, Proceedings of the Korean Society of Mechanical Engineers 2007 Spring Conference B, pp.3086-3091.

[12] J.C. Kim, K.S. Ha, R.J. Park, Y.R. Cho, S.B. Kim, S. Kim, 1-DTwo-Phase Investigation for External Reactor Vessel Cooling, Transactions of the Korean Society of Mechanical Engineers B, Vol.31, No.5, pp.482-490, 2007.

[13] J.C. Kim, K.S. Ha, R.J. Park, S.W. Hong, S. B. Kim, Preliminary Experimental Study on the Two-phase Flow Characteristics in a Natural Circulation Loop, Proceedings of The 5th National Congress on Fluids Engineering(2008), pp. 308-311.

[14] H.S. Park, K.Y. Choi, S. Cho, C.K. Park, S.J. Lee, C.H. Song, M.K. Chung, Experimental Studies on Heat Transfer Characteristics and Natural Circulation Performance of PRHRS of the High Temperature and High Pressure Thermal-Hydraulic Test Facility, Transactions of the Korean Nuclear Society Autumn Meeting, 2003.