Evaluation of hydrogen generation from feeder pipes of CANDU reactor by using CAISER code

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1. Introduction

CANDU has feeder pipes that differs from PWR, and this has recently raised issues regarding the possibility of hydrogen generation under severe accident conditions. Since 380 inlet and outlet feeder pipes, which is made of SAB106, are directly connected to 380 fuel channels in a core, a high temperature steam in a fuel channel can increase the temperature of feeder pipes to cause an oxidational reaction at feeder pipes.

Hydrogen generated in a core becomes to release to containment through a safety/relief valve, and it can increase the density of hydrogen in a containment, which can cause hydrogen explosion. Although the amount of hydrogen generated from ex-vessel by MCCI (Molten Corium Concrete Interaction) is typically larger than that from in-vessel, the hydrogen generated in a core is important in the perspective of early accident management of operators in a power plant.

The recent study [1] has evaluated the possibility of hydrogen generation from feeder pipes under SBLOCA scenario. Although the feeder pipes are made of Fe (SA106B), the previous study [1] had used Zr-steam oxidation model, instead of Fe-steam model, because of the lack of available experimental correlation for Fe-steam oxidation. And, as described in the previous paper [1], it did not consider the contribution of exothermal heat generation by Fe-steam oxidation reaction in the calculation of feeder pipes temperature. However, as revealed in the fuel rods temperature history under severe accident condition, the fuel rod temperature experiences a steep increase by the exothermal heat generation of Zr-steam oxidation reaction. Hence, the exothermal heat generation can have a strong effect on the temperature of feeder pipes, which then has feedback effects to the accelerated hydrogen generation in feeder pipes.

In this study, the hydrogen generation by feeder pipes oxidational reaction has been reevaluated by considering the unsolved modeling problems in the previous study.

2. Numerical Analysis Code

In this study, in order to examine the possibility of hydrogen generation in the inlet/outlet feeder pipes, CAISER (Candu Advanced Integrated SEveRe accident analysis code) has been utilized, which has been developed by KAERI (Korea Atomic Energy Research Institute), from the demands for an accurate and realistic severe accident code in the PHWR safety analysis. The main role of the CAISER code is to simulate overall severe accident progression in CANDU reactors, covering from core heatup to containment failure, by using more mechanistic modelling for the phenomena happening in severe accidents.

CAISER code is consisted of multiple codes, which are separately developed:

- CAISER-C code simulating the core degradation phenomena in the calandria vessel,
- MARS-KS code simulating the thermal-hydraulics of the Primary Heat Transport System (PHTS),
- CONTAIN code simulating the severe accident phenomena in the containment,

The CAISER-C code [2] simulates the core degradation phenomena occurring in the calandria vessel, which includes fuel rods uncover and heat-up, hydrogen generation due to steam-Zr oxidation, fuel rods slumping, fuel rods melting and relocation, the failure of pressure tube and calandria tube, the sagging of fuel channels, the debris bed formation caused by fuel channel failure, the molten pool formation, the calandria vessel failure caused by wall ablation and creep rupture and the fission product release from the fuel pellet. In the meantime, the coolant in a fuel channel is simulated by using the existing thermal hydraulic system code, MARS-KS [3]. That is, CAISER-C code simulates the solid parts in a core including feeder pipes, while MARS-KS deals with the thermal hydraulics in a coolant circuit, together with the fission product transport in a circuit. Hence, the above two codes are designed to communicate the relevant variables at every time step. For example, the CAISER-C code sends the convective heat transfer rate to MARS-KS, while it receives the coolant temperature and the convective heat transfer coefficient from MARS-KS.

On the other hand, the severe accident phenomena in a containment is simulated by using CONTAIN code [4], which deals with an in-containment thermal-hydraulics behavior including hydrogen combustion, the fission product behavior in the containment, MCCI, DCH (Direct Containment Heating), and engineered safety features such as spray and PAR (Passive Autocatalytic Recombiner). In the CAISER code, the CONTAIN code has been coupled with both MARS-KS and CAISER-C codes, in order to provide the information of the liquid and vapor discharge from the primary safety valve, and the corium discharge from the calandria vessel, together with a fission product transport from a primary circuit.

The detailed modelling for CAISER code has been described in a reference [5] with the simulation of the CS28-1 experiment. The CAISER code simulation for SBO severe accident scenario has also been compared with the other severe accident codes for CANDU reactor, such as MAAP-CANDU [6] and RELAP /SCDADSIM [7], in the IAEA-CRP study [8] which has been aimed for the uncertainty analysis of severe accident simulation.

3. Numerical modelling

According to the Wolsong-1 Refurbishment FSAR, a significant Zr-steam exothermic reaction on the fuel sheath as well as the inside surface of the pressure tube are known to occur for the large break LOCA with simultaneous loss of emergency core cooling (LBLOCA + LOECC) accident. In this study, SBLOCA severe accident scenario (RIH 2.5% break) with the moderator cooling system has been simulated. In this scenario, the moderator cooling system prevents the fuel channel failure through external cooling of fuel channel. This allows the high temperature steam in a fuel channel to increase the temperature of outlet feeder pipes.

Fig.1 & 2 show the CAISER-C and MARS-KS nodalization for this severe accident simulation. In this study, the cross-section of a calandria tank and feeder pipes have been nodalized with [I, J] = [4, 4], while the cross-section of a fuel channel has been nodalized of [M, N] = [2, 2]. The calandria tank and a fuel channel has been nodalized with 6 nodes in the flow direction, while the inlet and outlet feeders has been nodalized with 5, 6 nodes in the flow direction, respectively.

Since there are 380 fuel channels connected to 380 inlet feeder pipes and 380 outlet feeder pipes, with a checkerboard pattern of flow direction within these channels, each side of the fuel channel is equipped with 190 inlet feeder pipes and 190 outlet feeder pipes within an insulation chamber. An insulation chamber roles to prohibit the undesired heat loss from a hot heat structure to the environment in a containment. Since 380 inlet/outlet feeder pipes are installed in the confined space densely, without an extra insulation cover on outer surface of each feeder pipe, each feeder pipe has the radiation heat transfer with neighboring feeder pipes, which are inlet and outlet feeder pipes. Differently with the previous study [1], the radiation heat transfer among feeder pipes has been considered in this study.

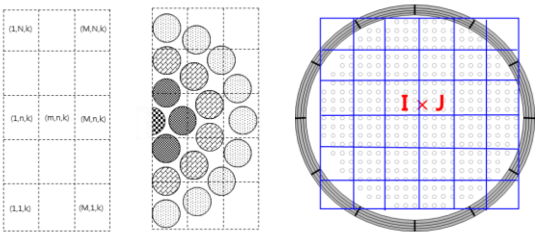

Fig.1 CAISER-C nodalization for core degradation

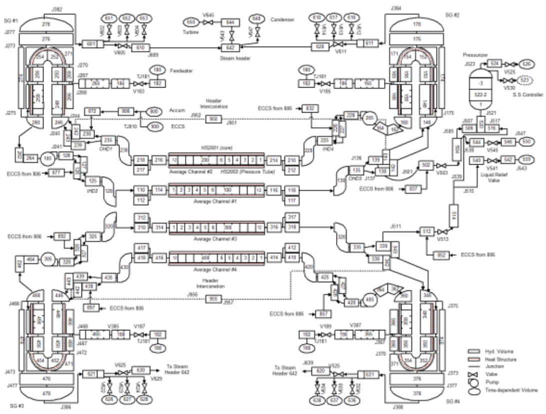

Fig.2 Plant nodalization of MARS-KS

The previous study [1] has used Zr-steam reaction model for the feeder pipe oxidation reaction because of the absence of Fe-steam oxidational model. Recently, for the purpose of examine the raised issue for the possibility of hydrogen generation in feeder pipes, the experimental work had been conducted [9] in Canadian National Laboratory (CNL). In this paper, the parabolic oxidational reaction model for SA106, which is the material of feeder pipe, has been developed in the temperature range of 800 ~ 1,100 °C. As noted in the study [9], the oxidation rate of SA106 was found to be a factor of about 5 to 10 greater than oxidation rate measured in 304L stainless steel. The study discovered that the weight gain due to the Fe-steam oxidation can be represented by the following equation.

$$W^2/t = 1.879 \times 10^5 \exp(-135{,}835 / RT) \qquad (1)$$

where W is the weight gain per unit area in mg/cm^2, t is time in seconds, R is the gas constants of 8.3145 J/gmol·K, and T is K.

And, under high temperature condition like severe accident, wustite(FeO) layer are known to be the dominant oxide as compared to hematite (Fe_2O_3) and magnetite (Fe_3O_4) [10]. Hence, the oxidational reaction in feeder pipes can be represented by

$$Fe + H_2O \rightarrow FeO + H_2 + Q_{ox} \qquad (2)$$

Where, Q_{ox} is the Fe-steam oxidational reaction heat having 0.56 MJ/kg.

4. Simulation Results

In this work, the oxidational reaction model for SA106B has been used in the calculations, together with the consideration of radiation heat transfer among feeder pipes.

Fig. 3 shows the accumulated hydrogen generation mass in a core. It reveals that the hydrogen mass generated from feeder pipes is about 500kg till 500,000 sec. Differently from the hydrogen generation by fuel rods, the hydrogen generation by feeder pipes continuously increases with time because of the available Fe mass for Fe-steam oxidational reaction, and it covers about 45% of the total amount of hydrogen generated in a core till 500,000 sec.

Fig. 4 shows the temperature of outlet feeder pipes. Because of the radiation heat transfer among feeder pipes, the temperature difference among feeder pipes is relatively small compared with the previous study [1], which did not consider the radiation heat transfer among feeder pipes. In the experiment of CNL [9], the hydrogen generation from SA106B oxidation reaction has been measured under the designed condition of 1,000°C steam exposure for 8 hours. However, Fig. 4 shows that the feeder pipes has been exposed for longer time with high temperature under the severe accident scenario considered in this study.

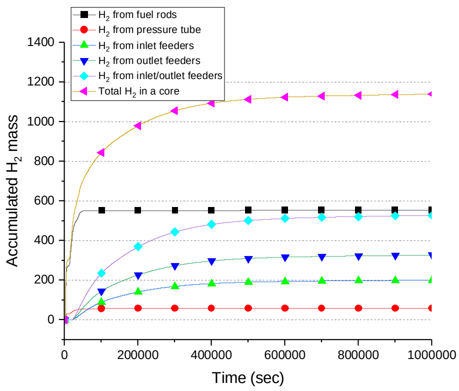

Fig. 3 Hydrogen mass generated in a core

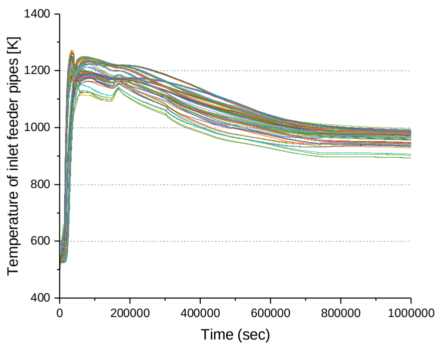

Fig. 4 Temperature of outlet feeder pipes

In the consideration of radiation heat transfer between two components, the exact value of radiation view factor is difficult to determine, especially in this analysis, because of the complicated structure among feeder pipes. Hence, the sensitivity study for the radiation view factor has been conducted. The radiation view factor, F, is varied between 0.05 ~ 0.25. The effect of radiation view factor on the hydrogen mass generated from inlet/outlet feeder pipe is shown in Fig.5. As the radiation view factor increases, the temperature of feeder pipes has more uniformly distributed among feeder pipes, resulting in the increase of the hydrogen mass generated.

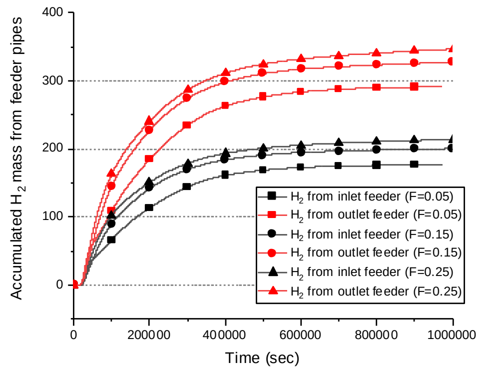

Fig. 5 Effect of radiation view factor, F, on the hydrogen mass generated from feeder pipes

Under severe accident conditions, the steam starvation can be occurred in a core by the oxidational reaction. For CANDU reactor where a feeder pipe is connected to a fuel channel and Zr-steam reaction occurs first before Fe-steam reaction, the feeder pipes undergo steam shortage or starvation. That is, steam shortage is accelerated due to the early Zr-steam reaction within the fuel channel and the late Fe-steam oxidational reaction in feeder pipes can accelerate this.

In this study, the steam starvation in a fuel channel caused by Zr-steam reaction has been counted for all cases. Meanwhile, the effects of steam starvation due to Fe-steam reaction in feeder pipes have been separately examined, as shown in Fig. 6. It reveals that the consideration of steam starvation in feeder pipes due to Fe-steam oxidational reaction can reduce the amount of hydrogen generation from feeder pipes by about 16%, but it still covers about 41% of the total amount of hydrogen generation in a core till 500,000sec.

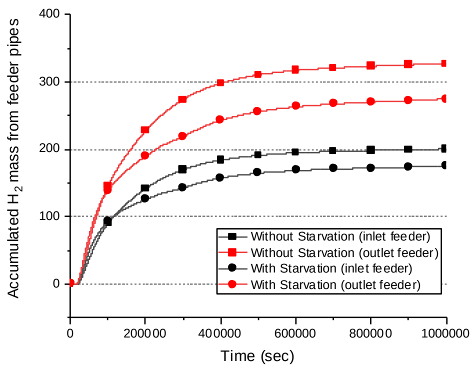

Fig. 6 Effect of steam starvation by Fe-steam oxidation reaction on the H_2 mass generated from feeder pipes

5. Discussions

In this study, the hydrogen generation by the oxidational reaction in the end-fitting has not considered because of small mass of end fitting. And, the geometric configuration of each of the 380 inlet and outlet feeder pipes, which varies in terms of the length and diameter in reality, is not considered. However, for the convenience of computational analysis, the representative value of the length and diameter has been used for 380 inlet and outlet feeder pipe, which needs to upgrade in the next work, together with the consideration of end-fitting component.

In CANDU, there is insulation chambers on both sides of the calandria tank, forming confined spaces. Any hydrogen generated from outside the feeder pipes has the potential to increase the local hydrogen concentration within the insulation chambers. This situation could lead to an unforeseen progression of accidents in a containment. The detailed analysis for the hydrogen distribution in a containment, especially for the insulation chambers, should be analyzed in the future work.

The existing severe accident codes for CANDU reactor in the world has not considered the possibility of a creep failure of feeder pipe even in a high pressure severe accident scenario (for example, SBO), as appeared in the IAEA CRP for the code-to-code comparison under SBO scenario [11]. Although the creep failure of feeder pipe is not considered either in this study, the feeder pipe has a possibility to experience the creep failure under high temperature and high pressure condition. Hence, it is also necessary to study in the future works since it can influence the hydrogen mass generated from feeder pipes as well as the accident progression under high pressure accident scenario.

6. Conclusion

For the severe accident scenario of SBLOCA with the moderator cooling system available, the hydrogen mass generated in the feeder pipes from oxidational reaction has been evaluated. The radiation heat transfer among feeder pipes and the Fe-steam oxidational reaction model has been considered. The hydrogen mass generated from feeder pipes is calculated to cover about 45% of the total amount of hydrogen generated in a core. Both the effect of steam starvation by Fe-steam oxidation reaction and the radiation view factor have also been examined in this study. For the future study, several important factors are presented including the effect of hydrogen concentration in an insulation chamber and the possibility of feeder pipes creep failure.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J.Y. Kang et al., "High temperature oxidation of the feeder pipe and its potential risk as the hydrogen gas management during SB-LOCA of CANDU reactor", *Transactions of the Korean Nuclear Society Spring Meeting*, Korea, May 12-14 (2021).
[2] Design of core heatup module for CANDU reactor, KAERI/TR-7409/2018
[3] MARS CODE MANUAL VOLUME II: Input Requirements Thermal-Hydraulic Safety Research Department, KAERI/TR-2811/2004.
[4] D.C. Williams et al. Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behaviour: Analysis and Calculations with the CONTAIN Code, NUREG/CR-4896, SAND87-0633, Sandia National Laboratories (1987).
[5] J. H. Bae et al., Numerical simulation of CS28-1 experiment by using CANDU severe accident analysis code CAISER, *Annals of Nuclear Energy* 150, 107820 (2021).
[6] Modular Accident Analysis Program 5 (MAAP5) Applications Guidance Desktop Reference for Using MAAP5 Software—Phase 3 Report, EPRI, Product ID # 3002010658, 2017.
[7] THE SCDAP/RELAP5 DEVELOPMENT TEAM, 1996. Code Manual. Volume II: Damage Progression Model Theory, NUREG/CR-6150 INEL-96/0422, Revision 1, October.
[8] J.H. Bae et al., "Uncertainty analysis for severe accident of CANDU reactor by using CAISER code", *Transactions of the Korean Nuclear Society Autumn Meeting*, Korea, Oct 19-21, (2022).
[9] A.D. Quastel et al., "Feeder pipe oxidation in the presence of steam during a nuclear reactor accident", High Temperature Corrosion of Materials (2023) 99:399-413
[10] C. Zhang, Oxide layer thickness modification. Masters Science thesis, Luleå University, Sweden (2012)

[11] IAEA TECDOC No. 1727 "Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications", (2013).