Development of CFD simulation methodology for the high temperature steam cladding oxidation phenomenon

Siwon Seo, Simanjuntak Armanto Pardamean, Simamora Benrico Fredi, Jaeyoung Lee [a*]
[a] School of Control and Mechanical Engineering, Handong Global Univ., Pohang, 37554, Korea
[*] *Corresponding author: jylee378@gmail.com*

1. Introduction

Since nuclear fuel cladding is the first physical barrier in the Defense-in-Depth concept for nuclear safety, studies on the cladding steam oxidation phenomenon that can occur due to nuclear power plant accidents have been extensively conducted [1-8]. The problem is that the oxidation model developed by these studies did not reflect the effect of steam flow rate. The models developed so far are only a function of temperature [9-13]. Therefore, an experimental study is being conducted at Handong Global University to study the effect of water steam convection on the cladding oxidation phenomenon. In this paper, a comparative analysis with an experimental result was performed to verify the validity of the 3D CFD analysis methodology developed through this research.

2. Methodology

2.1 Experimental Apparatus

In this study, an experimental apparatus was made to study the effect of steam convection on the cladding oxidation. The schematic of the experimental apparatus is shown in Figure 1. This can be classified into a high-temperature steam supply system, a test section, and a hydrogen measurement system.

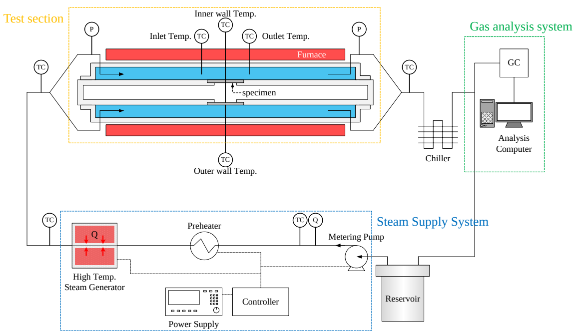

Fig. 1. Drawing of experimental apparatus for high temperature steam oxidation

The steam supply system is a system that supplies high-temperature steam to the cladding specimen at a constant rate. Water is supplied by the metering pump, and the entire water passes through the preheater and is heated with superheated steam. And this steam flows into the test section and is heated to the desired temperature. The steam heated to the desired temperature occurs an oxidation reaction by contacting the specimen installed at the rear part of the test section. After the oxidation reaction, superheated steam and hydrogen mixture is discharged through the outlet of the test section. After the high temperature steam and hydrogen mixture is cooled, the water is returned to the water supply tank and the light hydrogen flows into the above GC, where the hydrogen concentration is measured in real time. To verify the 3D CFD analysis methodology to be introduced in the next section, an experiment was conducted using the above experimental setup.

2.2 3D CFD Analysis Methodology

In this study, the analysis of the oxidation reaction was performed using ANSYS FLUENT 18.0, a commercially available 3D CFD code. As an analysis scheme, the pressure and velocity were determined through the SIMPLE (Semi-implicit method pressure linked equation) method, and the second-order finite difference method was used in consideration of the governing equations of continuity and momentum. The model for simulation was made as shown in Figure 2. The gray part in Figure 2 represents the part where steam flows, and the empty part in the middle is the part that simulates zircaloy and is modeled so that the oxidation reaction occurs on the surface of zircaloy.

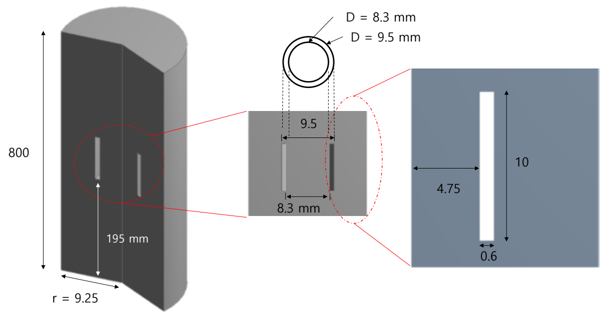

Fig. 2. Simulation Geometry

For this analysis, the cladding steam oxidation reaction was supplemented using UDF (User Define Function), and the heat flux generated by the oxidation reaction, the amount of hydrogen produced by the oxidation reaction, and the hydrogen diffusion equation in the cladding were calculated through the UDF. Each variable is expressed in the following formula, and the calculation flow chart for cladding oxidation analysis is shown in Figure 3.

$$\ddot{Q}_{ox} = 2.107 \times 10^{10} \times \frac{K_p}{\delta_z \rho_z^2} = 504.9 \frac{K_p}{\delta_z} \qquad (1)$$

$$H_t = 1.436 \times 10^5 (\delta_t - \delta_{t-\Delta t}) / \Delta t \quad (2)$$

$$\rho_{mix} D \frac{d\alpha_{H_2}}{dx} = Y_{H_2} = 3.362 \times 10^{-6} \frac{K_p}{\delta_z} \quad (3)$$

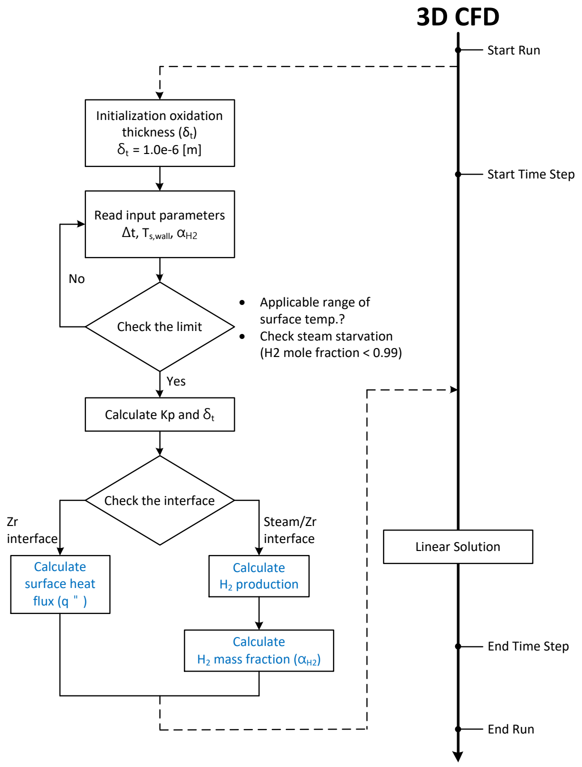

Fig. 3. Sequence of 3D CFD analysis for cladding oxidation phenomenon

Calculation conditions are as follow. A zircaloy cladding tube with a diameter of 9.5 mm and a length of 10 mm was installed in an alumina tube with a diameter of 18.5 mm, and steam at a temperature of 900°C was injected at a flow rate of 0.075 g/sec into the test section.

3. Experiment and Simulation Results

An experiment was conducted to verify the 3D CFD analysis methodology introduced in Section 2.2. The experiment was conducted under the conditions of a steam velocity of 1.58 m/sec, a specimen length of 10 mm, and a steam temperature of 900°C. 3D CFD analysis for the same conditions as this experiment was also performed. To confirm the validity of the analysis methodology, the cladding outer wall temperature measured in the experiment and the cladding outer wall temperature calculated in the analysis were compared. The analysis result calculated for 50 seconds is shown in Figure 4. As 900℃ steam was injected, an oxidation reaction occurred on the outer wall of the zircaloy cladding, and it was confirmed that the temperature around the outer wall of the cladding increased.

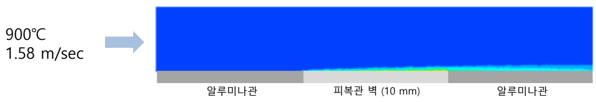

Fig. 4. Temperature distribution of 3D CFD

In addition, it was confirmed through CFD calculation that the thickness of boundary layer where the temperature rose around the cladding was only less than 1 mm (cladding thickness is 0.6 mm). This shows that in order to measure the temperature of the cladding exactly when performing the cladding oxidation experiment, a thermocouple should be brought into contact with the cladding. At 50 seconds, the maximum temperature of the cladding was 909.53°C, and the location of the maximum temperature was at the exit end of the specimen. In actual experiments, when measuring the temperature of the cladding, the thermocouple is placed in the middle of the 10 mm long cladding, and the thermocouple tip directly contacts the outer wall of cladding to measure the temperature accurately.

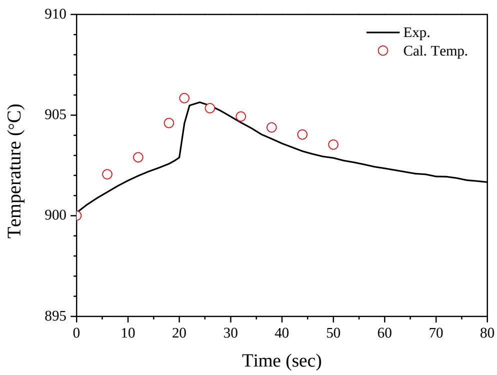

Fig. 5. Cladding outer wall temperature comparison between experiment and CFD simulation

Figure 5 compares the results of the high-temperature steam convection oxidation test and simulation for the cladding temperature. In the case of simulation calculations, an oxidation reaction occurs as soon as the calculation starts, and the temperature starts to rise immediately. In Figure 5, it can be seen that the calculated time of temperature rise, the time of reaching the maximum temperature, and the result of the maximum temperature are almost similar to the experimental results. The maximum temperatures of the cladding in the experiment and simulation are 905.64°C and 905.82°C, respectively. And a calculation error is only 0.02%. However, the temperature rise history shows a slight difference.

4. Conclusion

In this paper, a 3D CFD analysis methodology for cladding oxidation phenomenon was established prior to testing the steam convection effect on the cladding oxidation phenomenon. In addition, to confirm the validity of the analysis methodology, an experiment in one case was conducted. And the validity of the analysis methodology was confirmed through comparison with simulation results. The conclusions that can be drawn from this study are as follows.

- As a result of the analysis, the thermal boundary layer by the exothermic oxidation reaction is very thin. It means that in order to measure the temperature of the outer wall of the cladding precisely when performing the oxidation experiment, a thermocouple must be brought into contact with the outer wall.
- It was confirmed that the 3D CFD analysis methodology established through this study can simulate the experiment. As a result of only one case, additional analysis and experimental results are required to verify solidly the analysis methodology in the future.

Acknowledgement

This work was supported by Korea Hydro & Nuclear Power Co., LTD (No. 22-개념(후)-안전-3)

REFERENCES

[1] M. L. CARBONEAU, "Highlights of the OECD-LOFT LP-FP-2 Experiment, Including Hydrogen Generation, Fission Product Chemistry, and Transient Fission Product Release Fraction," Proc. OECD/LOFTMtg., Madrid, Spain, May 9-11, 1990, Organisation for Economic Cooperation and Development (1990)

[2] August W. Cronenberg, "Hydrogen Generation Behavior in the LOFT FP-2 and Other Experiments: Comparative Assessment for Mitigated Severe Accident Conditions", Nuclear Technology, 97:1, 97-112, (1992)

[3] J. Stuckert, M. Steinbruck, U. Stegmaier, "Sing rod Quench tests with Zr-1Nb cladding. Comparison with Zircaloy-4 cladding tests and modeling", Report FZKA-6604, Karlsruhe Institute of Technology (2001)

[4] M. Steinbruk, U. Stegmaier, T. Ziegler, "Prototypical experiments on Air oxidation of Zircaloy-5 at high temperatures", Report FZKA-7257, Karlsruhe Institute of Technology (2007)

[5] J. Stuckert, M. Grosse, M. Steinbruck, M. Walter, A. Wensauer, "Results of the QUENCH-LOCA experimental program at KIT", J. Nucl. Mater. 534 152143 (2020)

[6] P. von der Hardt, A. Tattegrain, "The Phebus fission product project", J. Nucl. Mater. 188 155-130 (1992)

[7] M. Schwarz, B. Clement, A. V. Jones, "Practical lessons from the first three PHEBUS FP tests", JAERI-Conf 2000-015

[8] J. H. Park, D. H. Kim, "Summary results from Phebus FPT-1 test and lesson learnt with MELCOR analysis", Korea, Republic of: M. p., (2005) Web.

[9] L. Baker, L. C. Just, "Studies of metal-water reactions at high temperatures; III. Experimental and theoretical studies of the zirconium-water reaction", Report ANL-6548, Argonne National Laboratory, (1962).

[10] J. V. Carhcart, R. E. Pawel, "Zirconium metal-water oxidation kinetics; IV. Reaction rate studies", ORNL/NUREG 17 (1977).

[11] V. F. Urbanic, T. R. Heidrick, "High-temperature oxidation of zircaloy-2 and zircaloy-4 in steam", J. Nucl. Mater. 74 (1978).

[12] J. T. Prater, E. L. Courtright, "Zircaloy-4 oxidation at 1300 to 2400℃", NUREG/CR-4889, PNL-6166 (1987).

[13] S. Leistikow, G. Schanz, "Oxidation kinetics and related phenomena of zircaloy-4 fuel cladding exposed to high temperature steam and hydrogen-steam mixtures under PWR accident conditions", Nucl. Eng. Des. 103, 65-84 (1987).