Experimental and Analytical Studies on Thermal-Hydraulic Performance of a Vacuum Vessel Pressure Suppression System in ITER

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Abstract An integrated ICE (Ingress-of-Coolant Event) test facility was constructed to demonstrate that the ITER (International Thermonuclear Experimental Reactor) safety design approach and design parameters for the ICE are adequate. Major objectives of the integrated ICE test facility are to estimate the performance of an integrated pressure suppression system and obtain the validation data for safety analysis codes and clarify the two-phase flow behavior under vacuum. The integrated ICE test facility simulates the ITER components with a scaling factor of 1/1600. The modified TRAC-PF1 code is used to verify the integrated ICE experimental results. From the present study the effectiveness of the ITER pressure suppression system was verified experimentally and analytically, and then, it was clarified quantitatively that the prediction accuracy of the modified TRAC-PF1 code is very high.

1. Introduction

Thermal-hydraulic characteristics in a fusion experimental reactor under an ingress-of-coolant event (ICE) were investigated by Takase, et al. [1] using a preliminary ICE apparatus and led controlling factors on the pressure rise. Since the preliminary ICE apparatus did not simulate the actual shape of ITER, however, it was difficult to estimate the ITER safety at the ICE from the results of the preliminary ICE experiments. Furthermore, the maximum pressure during the ICE is affected by the condensation in a suppression tank and the two-phase flow pressure drop at a divertor, whose effects strongly depend on the configuration of ITER components. Until now, however, there are no quantitative data about the maximum pressure available to the safety analysis codes of fusion reactors. Based on these backgrounds an integrated ICE test facility was constructed referring to the ITER components to examine whether a concept of the ITER pressure suppression system is adequate. On the other hand, the numerical analyses with the modified TRAC-PF1 code [2] were performed and its prediction accuracy was verified using the quantitative and qualitative results of the integrated ICE experiments.

2. Pressure Suppression System in ITER

Figure 1 shows a concept of the vacuum vessel pressure suppression system (VVPSS) in ITER [3]. The ITER VVPSS mainly consists of relief pipes, suppression tank (ST), drain tank (DT), drain pipe and rapture disks. Three relief pipes are installed to the side of the VV in ITER and connected to the ST. The DT is connected to the bottom of the VV through a drain pipe. The double rapture disks are settled to each relief pipe and also the drain pipe. The water is injected from the cooling tubes into the plasma-facing component (PFC) and a great amount of vapor generates due to the flashing and boiling, and then, the pressure inside the PFC increases. Because of the pressurization the double rapture disks at each relief pipe are broken and then the vapor flows into the ST through the relief pipes. The ST initially holds water under low temperature and pressure (around 30∞C and 3 kPa). Therefore, the vapor is condensed, and consequently, the pressurization in the PFC is suppressed. The remained water in the PFC flows to the bottom of the VV and goes to the DT after the double rapture disks at the drain pipe are broken. According to the ITER design, the design pressure of the rapture disk at the relief pipe is 150 kPa and that at the drain pipe is 110 kPa.

3. Integrated ICE Test Facility

3.1. Structural Components

Figure 2 shows an outline of an integrated ICE test facility. The integrated ICE test facility simulates the ITER structural components with a small-scale model of 1/1600 and mainly consists of a plasma chamber (PC), divertor, VV, relief pipes, ST, DT and drain pipe. The PC simulates the PFC volume of ITER and has a volume of 0.6 m^3. The VV simulates a simplified VV in ITER and has a volume of 0.34 m^3. The divertor simulates the simplified divertor cassette section in ITER and its dimensions are a width of 120 mm, height of 162 mm and length of 1200 mm. A plate with four slits is installed into the divertor to simulate the ITER evacuation slits. The slit dimensions are 5 mm in width, 80 mm in length, 15 mm in depth and 100 mm in pitch, and those values are determined based on the ITER design values. The ST volume is 0.93 m^3 and the initial water volume is less than 0.5 m^3. The ST is connected to the PC by three relief pipes with an inner diameter of 35 mm. A magnetic valve is installed to each relief pipe instead of the double rapture disks in case of ITER. The magnetic valve is opened when the PC pressure reaches 150 kPa after the injection of water as same as the ITER design value. The DT with a volume of 0.4 m^3 is located below the VV and connected to the VV with the drain pipe with an inner diameter of 12 mm. A magnetic valve is also set up to the drain pipe instead of the double rapture disks in ITER. Three sets of water injection nozzles were installed to simulate the multiple first wall pipe break event in ITER. A diameter of the water injection nozzle is 7.3 mm. The total cross-sectional area of three water injection nozzles corresponds to the supposed maximum failure area in ITER based on the scaling factor of 1/1600.

3.2. Experimental Conditions

Experimental conditions are as follows: water temperature 125-150°C; water pressure 2-4 MPa; PC wall temperature 230°C; VV wall temperature 100-230°C; initial pressure inside the test facility less than 100 Pa; number of used water injection nozzles 3; injection time period of water 45 s; and number of relief pipes 1-3. The total amount of water (i.e., 0.26 m^3) which is injected into the PC by the combination of 3 water injection nozzles and 45 s injection time period corresponds to 1/1600 of the supposed total injected water volume (i.e., 420 m^3) in ITER during the ICE.

4. Results and Discussion

Figure 3 shows an example of the pressure transients obtained by the ICE experiment. The solid, dashed, dotted and one-pointed solid lines represent the pressures in the PC, VV, relief pipe (RP) and ST, respectively. The experimental conditions are as follows: water temperature 125°C; water pressure 2 MPa; PC wall temperature 230°C; VV wall temperature 100°C; and two relief pipes were used. The pressures in the PC and VV increase very quickly due to the flashing and boiling just after the injection of water. The pressure rise at the relief pipe comes late in comparison with those at the PC and VV because of the magnetic valve opening. The pressure increase in the ST is quite small because of the condensation of vapor.

Figure 4 shows an effect of the number of relief piping on the pressure rise in the PC during the ICE. The solid, dashed and dotted lines represent the experimental results when the number of relief piping is 1, 2 and 3, respectively. Experimental conditions satisfy the ITER conditions mostly as: water temperature 125°C; water pressure 2 MPa; PC wall temperature 230°C; and VV wall temperature 100°C. Moreover, the injected water flow rate and the water leakage area simulate the ITER multiple first wall pipe break condition. The pressure decreases with increasing the number of relief piping. This reason is that the condensation of vapor is enhanced with the increase in a cross-sectional area of the relief piping. Therefore, by adjusting the cross-section area it is possible to reduce the maximum pressure.

Figure 5 shows a comparison of the experimental and analytical pressure transients in the PC during the ICE. Here, the experimental result corresponds to the dotted line in Fig. 4. In order to predict numerically the pressure rise and heat transfer characteristics during the ICE with high accuracy, it is important to grasp the water and vapor distribution in the test facility precisely. Then, the authors carried out three-dimensional computations with the modified TRAC code using the fine mesh model. The predicted maximum pressure (211 kPa) agreed well with an error less than 1 % with the measured maximum pressure (210 kPa).

Figure 6 shows the predicted void fraction distributions in the integrated ICE test facility just after the injection of water. Here, Fig. 6(a) is a case that one relief pipe is operated and Fig. 6(b) is a case that three relief pipes are operated. In Fig. 6, the void fraction larger than 0.9 is shown at the relief piping section, and then, the void fraction smaller than 0.9 is shown at the test facility components except the relief piping. In the color map of the void fraction, the red means 100% vapor and the blue means 100% water. Calculated conditions are as follows: water temperature 125°C; water pressure 2 MPa; PC wall temperature 230°C; VV wall temperature 100°C; water injection time 45 s; and, water injection nozzle diameter 7.3 mm. In case of Fig. 6(a) the water in PC flows through the divertor to the VV and to the drain tank, and then, the vapor in the PC goes through the relief pipe to the ST and is condensed there. On the other hand, in case of Fig. 3(b) the remained water in the PC is much larger than that of Fig. 6(a) and the remained water in the VV is much smaller. From these results it was predicted numerically that the two-phase flow characteristics during the ICE receives strongly the effect of the cross-sectional area of the relief pipe.

5. Concluding Remarks

The present experimental and analytical results are summarized as follows:

1) The ITER VVPSS is very effective to reduce the pressurization during the ingress of water into vacuum;
2) The pressure decrease inside the PC caused by the condensation of vapor in the ST depends on the cross-sectional area of the relief pipe because the amount of vapor from the PC to the ST depends on that;
3) The modified TRAC-PF1 code can predict the maximum pressure in the PC during the water injection with sufficient accuracy to the integrated ICE experimental results; and,
4) The present three-dimensional numerical analysis with the modified TRAC-PF1 code is very useful to clarify quantitatively the water-vapor two-phase flow characteristics in the fusion reactor during the ICE.

References

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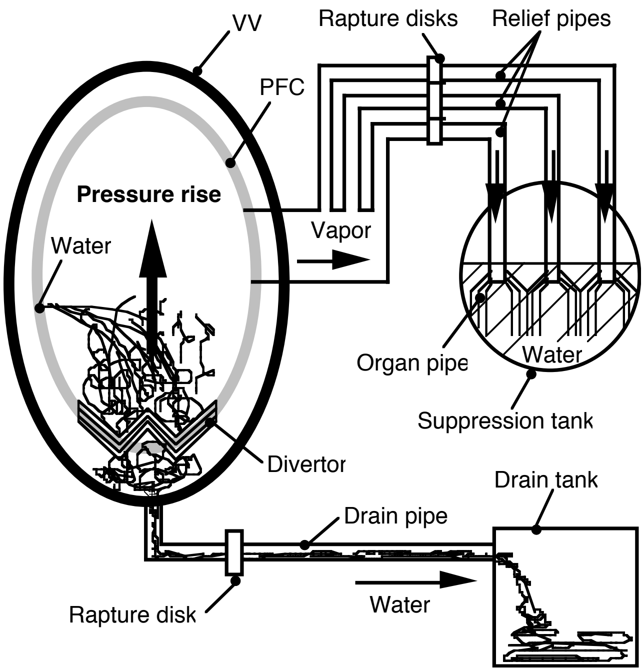

FIG. 1. A concept of a vacuum vessel pressure suppression system in ITER.

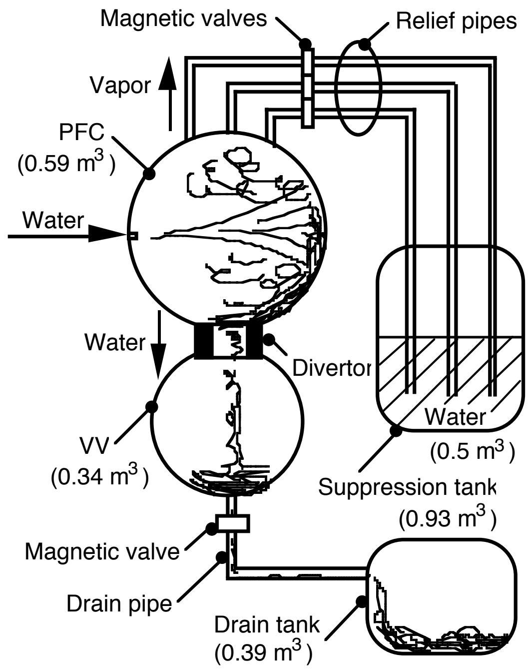

FIG. 2. Outline of an integrated ICE test facility, which simulates the components of ITER VVPSS with a scaling factor of 1/1600.

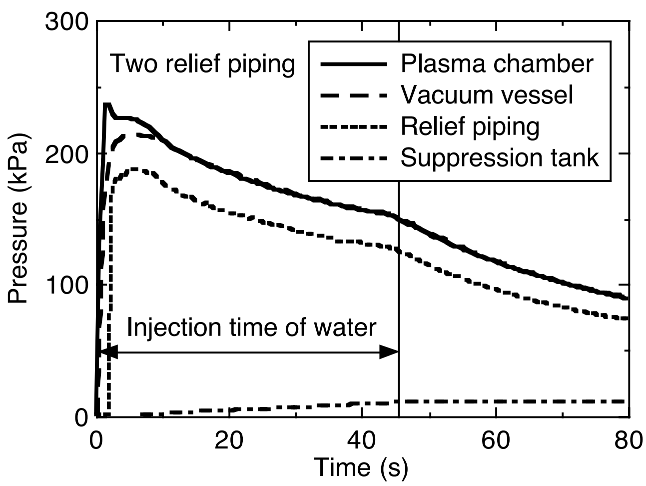

FIG. 3.Pressure transients in the test facility obtained by the ICE experiment.

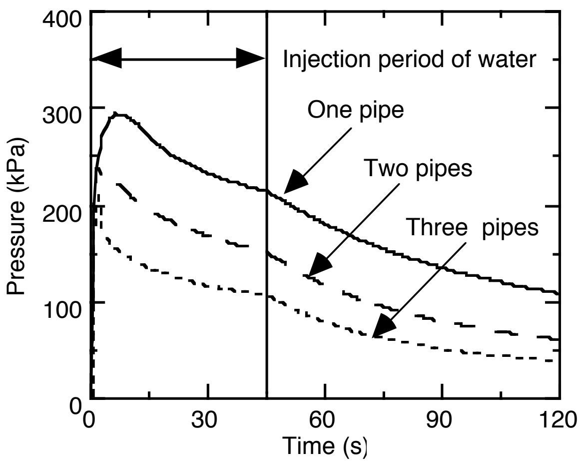

FIG. 4. Effect of the number of relief piping on the pressure rise in PC during the ICE.

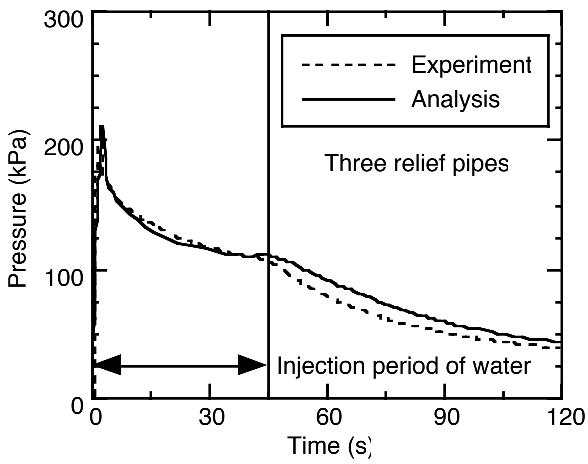

FIG. 5. Experimental and analytical results on the pressure rise in the PC

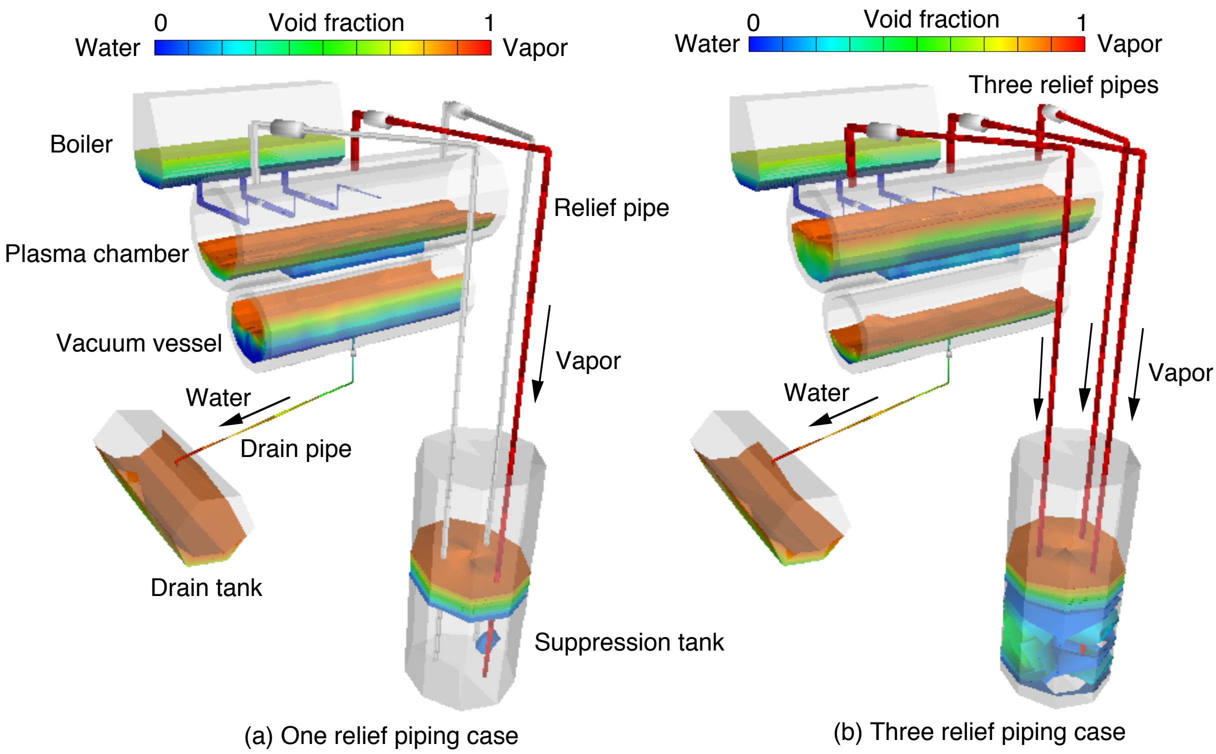

FIG. 6. Void fraction distributions just after the injection of water predicted by the modified TAC-PF1 code