Experimental Verification of Integrated Pressure Suppression Systems in Fusion Reactors at In-Vessel Loss-of -Coolant Events

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Abstract. An integrated ICE (Ingress-of-Coolant Event) test facility was constructed to demonstrate that the ITER safety design approach and design parameters for the ICE events are adequate. Major objectives of the integrated ICE test facility are: to estimate the performance of an integrated pressure suppression system; to obtain the validation data for safety analysis codes; and to clarify the effects of two-phase pressure drop at a divertor and the direct-contact condensation in a suppression tank. A scaling factor between the test facility and ITER-FEAT is around 1/1600. The integrated ICE test facility simulates the ITER pressure suppression system and mainly consists of a plasma chamber, vacuum vessel, simulated divertor, relief pipe and suppression tank. From the experimental results it was found quantitatively that the ITER pressure suppression system is very effective to reduce the pressurization due to the ICE event. Furthermore, it was confirmed that the analytical results of the TRAC-PF1 code can simulatet the experimental results with high accuracy.

1. Introduction

If cooling tubes installed into plasma-facing components (PFCs) in a Tokamak vacuum vessel are broken, water under high temperature and pressure in the cooling tubes will be discharged into the vacuum vessel (VV). Then, the discharged water will impinge on the hot surface of the PFCs and evaporate. As a result, the VV will be filled with vapor and the pressure in the VV will increase rapidly. This is called an Ingress-of-Coolant Event (ICE).

Takase, et al. [1] investigated physical phenomena during the ICE event using a preliminary ICE apparatus and led controlling factors on the pressure rise. Since the preliminary ICE apparatus did not simulate the ITER configuration, it was difficult to estimate the ITER safety at the ICE event from the results of the preliminary ICE experiments. However, the quantity of the ICE behavior and the verification of the safety analysis codes are very important for the safety design of fusion reactors. Then, an integrated ICE test facility was planned and constructed referring to the ITER pressure suppression system, and the adequacy of the ITER pressure suppression system was investigated quantitatively. Furthermore, numerical analyses with the TRAC-PF1 code, which is a safety analysis code for light water reactors, were performed and the prediction accuracy of the TRAC-PF1 code was verified.

2. Experimental Study

2.1 Pressure Suppression System in ITER

Figure 1 shows a concept of the pressure suppression system in ITER-FDR [2]. The water injected from the cooling tubes into the PFC flows through the divertor slits to the bottom of the VV and the accumulated water in the VV goes through a relief pipe to a suppression tank (ST). At this time a great amount of vapor generates due to the flashing under vacuum and boiling heat transfer from the plasma-facing surfaces, and then, the pressure inside the PFC and VV increases. Because of the pressurization a couple of rapture disks which are settled at the relief pipe are broken and the water under high temperature and vapor flow into the ST. The ST initially holds water under low temperature and pressure (around 25°C and 2300 Pa). Therefore, water under high temperature and vapor can be cooled down and condensed inside

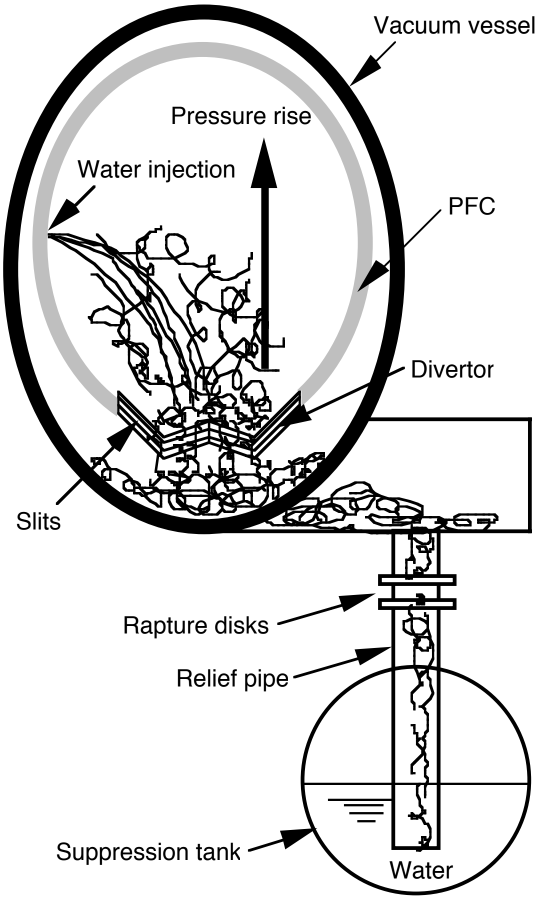

FIG. 1 ITER pressure suppression system.

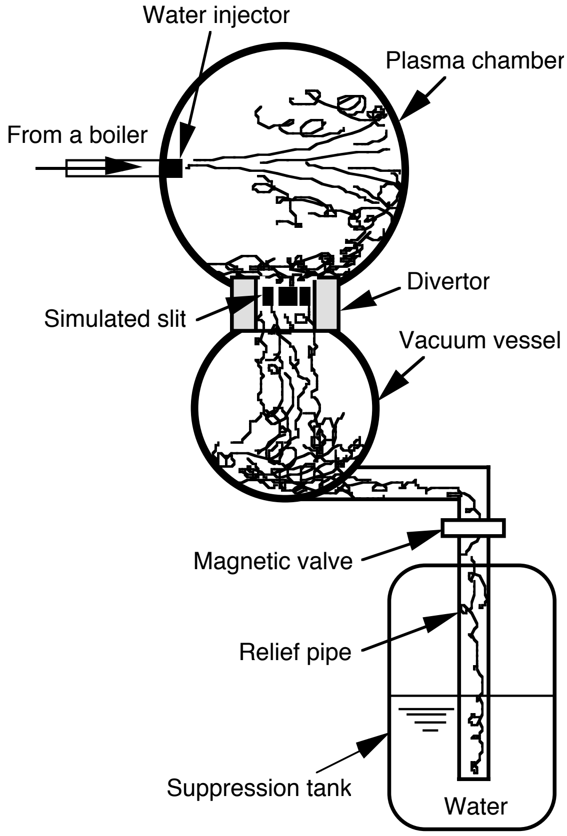

FIG. 2 Outline of an integrated ICE test facility.

the ST, and consequently, the pressure in the ITER can be decreased.

In the current design of the pressure suppression system in ITER-FEAT [3], a few relief pipes are installed at the upper region of the VV and connected to the ST and a drain tank is settled at the bottom of the VV with a drain pipe. This new design concept on the pressure suppression system using the ST and drain tank was considered to enhance the condensation performance in the ST by separating the vapor and water from the mixture at the ICE events.

2.2 Integrated ICE Test Facility

Figure 2 shows a schematic drawing of an integrated ICE test facility. The integrated ICE test facility simulates the ITER components with a small-scale model of 1/1600 and mainly consists of a plasma chamber (PC), divertor, VV, relief pipe, ST, water injection nozzle and boiler.

The PC simulates the volume of PFC in ITER and has a volume of 0.6 m^3. The VV simulates a part of VV in ITER and has a volume of 0.34 m^3. The divertor simulates the 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 multiple 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, 100 mm in pitch and 12 in total number, and those values are determined based on the current ITER design values. Compensation heaters are set to the outside of the PC, divertor and VV to control the outer temperature.

The ST has a volume of 0.93 m^3 and the initial water volume is less than 0.5 m^3. A maximum diameter of the water injection nozzle is 10 mm and three water injection nozzles were set up to simulate the multiple pipe rupture conditions in ITER. Water in the boiler is pressurized by nitrogen gas to maximum 4 MPa and heated by the heaters up to maximum 250℃. The water pressure in the boiler during the injection of water is controlled by nitrogen gas to keep at a constant value because the injected water flow rates from the water injection nozzles do not change with time.

2.3 Experimental Conditions

Three kinds of the integrated ICE experiments were carried out: Case 1, Case 2 and Case 3. In Case 1 the injection time of water was 10 s and the ST is not available. In Case 2 it was also 10 s but the ST is available. In Case 3 it was 30 s and the ST is available. The effectiveness of the ST to reduce the pressure rise during the ICE event was evaluated from the results of Case 1 and 2. Furthermore, the effect of the injection time on the pressurization was investigated from the results of Case 2 and 3.

Common experimental conditions for each test case were: water temperature of 150°C; water pressure of 2 MPa; wall temperature of 230°C; initial pressure inside the test facility less than 100 Pa; water nozzle diameter of 10 mm; water nozzle number of 3. In addition, the initial pressure inside the ST was set to around 2300 Pa, and therefore, the initial temperature inside the ST was the saturation temperature which is determined by the pressure.

In Case2 and 3 in which the ST is available, a magnetic valve at the relief pipe is opened when the pressure in the PC reached 0.15 MPa after the injection of water, and then, the ST is connected to the bottom of the VV through the relief pipe.

3. Analytical Study

The TRAC is an advanced, best-estimate computer program to calculate the transient behavior of a pressurized water reactor (PWR). The TRAC-PF1 code [4], which is one of a series of TRAC codes, uses a two-phase two-fluid model for the incompressible fluid flow. Detailed governing equations and empirical correlations for the two-phase flow analysis are shown in Ref.[5].

A nodalization diagram of the analytical model is shown in Fig. 3. Here, the PC, VV, divertor, ST and boiler were modeled using a VESSEL component in the TRAC code, and similarly, the relief pipe and water injection nozzle were modeled using PIPE and VALVE components, respectively. In addition, gas and water piping at the boiler was modeled with a PIPE component and a pressure controller was modeled with a BREAK component. The boiler maintains at constant pressure by the BREAK component to simulate the experimental condition. In the present numerical analysis a three dimensional model was chosen for the VESSEL component.

The mesh division numbers in the radial, circumferential and axial directions in the VESSEL component are 38x13x1 at the PC, 24x2x1 at the divertor, 34x5x1 at the VV, 3x3x1 at the boiler and 1x4x1 at the ST. Each mesh division number was decided based on the results of sensitivity calculations. The initial pressure in the present numerical study was set to 1 kPa based on the assumption of continuity of the fluid. Analytical conditions are the same as the experimental conditions mentioned in Section 2.3.

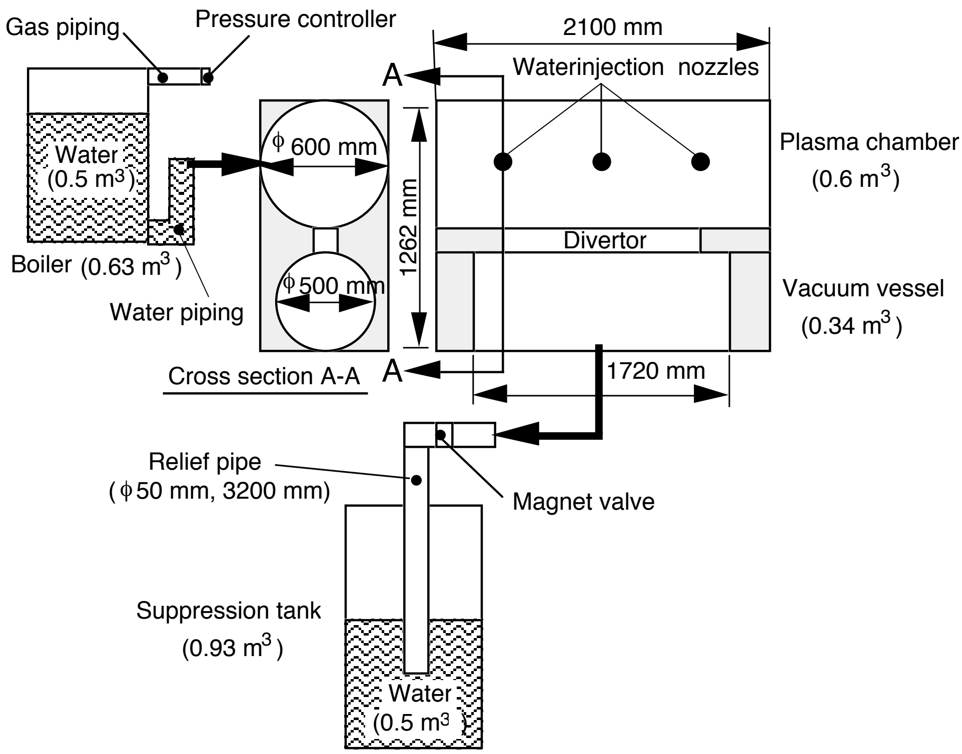

FIG. 3 Nodalization diagram of the analytical model with TRAC-PF1 code.

4. Results and Discussion

Figure 4 shows the pressure transients inside the PC and is the result of Case 1. Here, the solid and dashed lines indicate the experimental and analytical results. The pressure increases due to flashing just after the injection of water. When the injection of water ends, the pressure increases gradually up to the saturation pressure determined by temperature. The analytical result agrees well with the experimental result up to 80 s and is slightly overestimated after 80 s. The difference between both results after 80 s depends on the overestimation of the supposed heat transfer rates from the component walls in the analytical model.

Figure 5 shows the pressure transients inside the PC and is the result of Case 2. Here, the solid and dashed lines indicate the experimental and analytical results. As soon as the injection of water completes, the pressure decreases drastically and reaches less than atmospheric pressure because of the condensation effect with the ST. The predicted maximum pressure is in good agreement with the maximum pressure obtained by the experiment. An error between both maximum pressures was only 3.4%. It was verified from the present results that the ST system is very effective to reduce the pressure rise at the ICE events and the maximum pressure in the PC during the injection of water can be predicted numerically with sufficient accuracy.

Figure 6 shows the pressure transients inside the PC and is the result of Case 3. Here, the solid and dashed lines indicate the experimental and analytical results. In comparison with Fig. 5, the time which the pressure represents the highest value is lengthened because the injection time of water is longer. The maximum pressure value at the PC during the injection of water when the ST is available depends on the average temperature in the PC which is determined by the water temperature and wall temperature inside the PC. The analytical result showed underestimation at the early stage with the experimental result and overestimation at the final stage during the injection of water, however, the analyzed maximum pressure was in good agreement with the experimental result within an error of 1.5%.

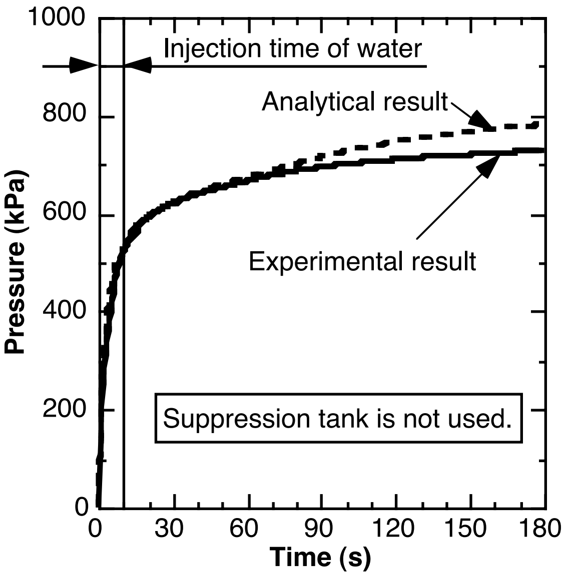

FIG. 4 Pressure transients in the PC at Case 1.

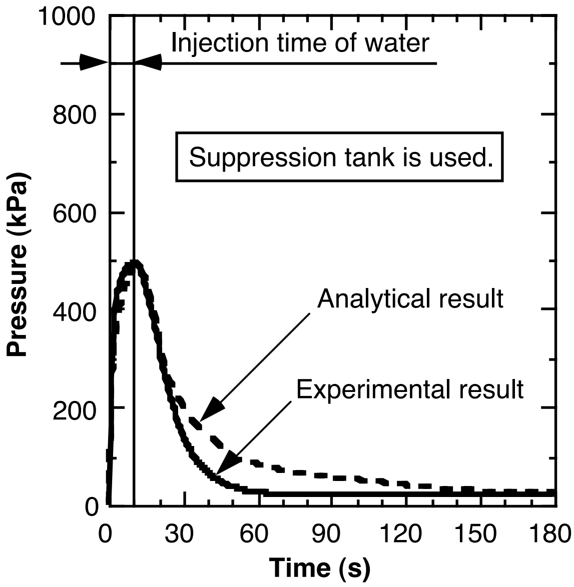

FIG. 5 Pressure transients in the PC at Case 2.

5. Conclusions

From the results of the integrated ICE experiments, the pressure rise characteristics in ITER during the ICE event were clarified quantitatively, and then, the analytical results of the TRAC-PF1 code were verified with the experimental results. It was concluded from the present study that the ITER pressure suppression system is very effective to reduce the pressurization due to the ingress of water and the analytical results with the TRAC-PF1 code can simulate the experimental results with high accuracy.

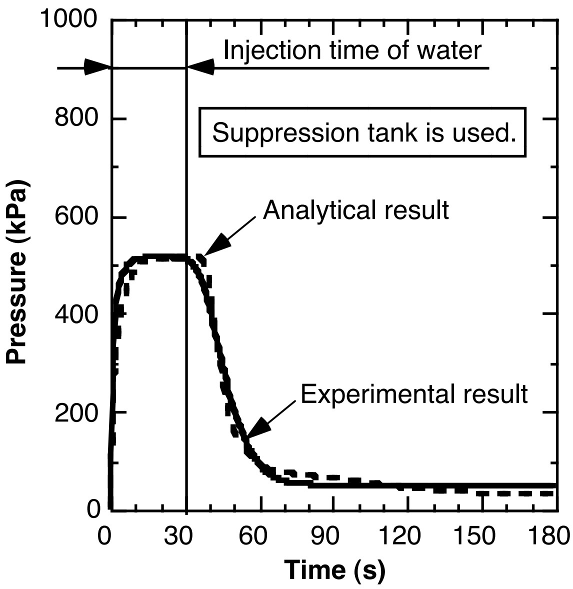

FIG. 6 Pressure transients in the PC at Case 3.

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