Analysis of the Ingress of Coolant Event tests performed in the upgraded ICE facility aimed at the ECART code validation

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The activities on the validation of the ECART code against the eight Ingress of Coolant Event (ICE) tests performed in the upgraded ICE facility are discussed. These analyses have been carried out to extend the ECART validation to incidental sequences related to future fusion plants, specifically - in the case of ICE - versus Loss Of Coolant Accident (LOCA) in volumes with near vacuum conditions. The upgraded ICE facility consists of a boiler, injecting water at high pressure inside a low-pressure tank simulating the Plasma Chamber (PC). This PC is in turn connected to the Vacuum Vessel (VV) through the divertor, and to the pressure Suppression (ST) by means of several relief pipes. Finally, the VV is connected with the Drain Tank (DT). Eight tests were performed investigating different numbers of relief pipes, different initial PC and VV temperatures, and different injected water mass flow rates, pressures and temperatures. The ECART results show an overall good agreement with the experimental data, confirming that ECART is also a valuable tool for the safety analysis in future fusion plants, as already pointed out in previous works.

Keywords: ICE facility, ECART, Pressure Suppression System, Fusion Safety.

1. Introduction

Several efforts on the validation of computer codes to be utilized in safety analysis were performed in the ITER design frame during the last years [1] [2]. The ECART code was one of these codes, and the present work summarizes the efforts performed to extend the ECART validation versus LOCAs in near vacuum volumes analyzing 8 tests performed in the upgraded ICE facility [3]. Similar ICE based validation activities were published in the past for different codes [4].

The employed ECART code, initially developed for fission plants [5] and then employed for safety analysis of fusion reactors [6], [7], couples 3 modules: thermal-hydraulics, aerosol-vapor transport phenomena, and chemistry. However, only the thermal-hydraulic section was activated in the present work due to the ICE tests characteristics.

The upgraded ICE facility (1/1600-scale model of ITER) was realized at the Naka Laboratories of the Japan Atomic Energy Research Institute (JAERI) to obtain experimental data on the effectiveness of the ITER suppression system [8]. The facility consists in a PC tank in which high-pressure liquid water is injected, connected to a VV tank through a channel-like pipe reproducing the divertor. Three relief pipes at the top of the PC discharge the formed steam into a ST. In turn, the water falling down from the PC to the VV is finally collected inside a DT.

Due to the compact size of the facility, two combined phenomena were mainly investigated by ECARTs: the jet impingement of the injected water and the heat transfer between the fluid and the walls. The former is needed to effectively reproduce the ICE facility thermal-hydraulic behavior, whereas the latter is also significant for ITER.

2. The Upgraded ICE facility

Figure 1 shows a schematic of the major components of the upgraded ICE facility. It includes a boiler (not represented) and 5 main volumes: the PC, the divertor, the VV, a DT and the ST. The boiler is connected to the PC by 1 or 3 injection lines (with an internal diameter of 10 mm), running from the bottom of the boiler to the side of the PC. The maximum water volume stored in the boiler is about 0.2 m^3, kept to a constant pressure during the tests to maintain a constant mass flow to the PC.

The PC and the VV are insulated cylindrical steel tanks with a thickness of 10 mm. The PC has a diameter of 0.6 m and it is 2.1 m long while the VV has a diameter of 0.5 m and a length of 1.72 m. Up to 1 MPa and 250 °C can be reached inside the PC and the VV, both at a very low initial pressure (~500 Pa). A channel-like structure (162 mm high, 120 mm wide, 1.2 m length) represents the divertor and connects the PC with the VV. A removable steel plate, with 4 evenly spaced slits, is installed inside the divertor (flow area 1.6x10^{-3} m^2).

The DT is a horizontal cylinder of about 0.383 m^3, connected to the bottom part of the VV through a drain line (inner diameter 16.1 mm). No water is present inside this DT at the beginning of the tests and a magnetic valve, having a set point of 0.11 MPa, initially closes the drain line.

The ST is a vertical cylindrical vessel (diameter 0.8 mm, length 1.96 m), connected with the PC upper part by 3 relief pipes (inner diameter 35.5 mm) and initially contains about 0.4 m^3 of subcooled water at 20 °C and 2.3 kPa, to condense the steam flowing from PC, thus controlling the PC and VV maximum pressure. Relief valves, opening when the PC pressure exceeds 0.15 MPa, initially close the relief pipes.

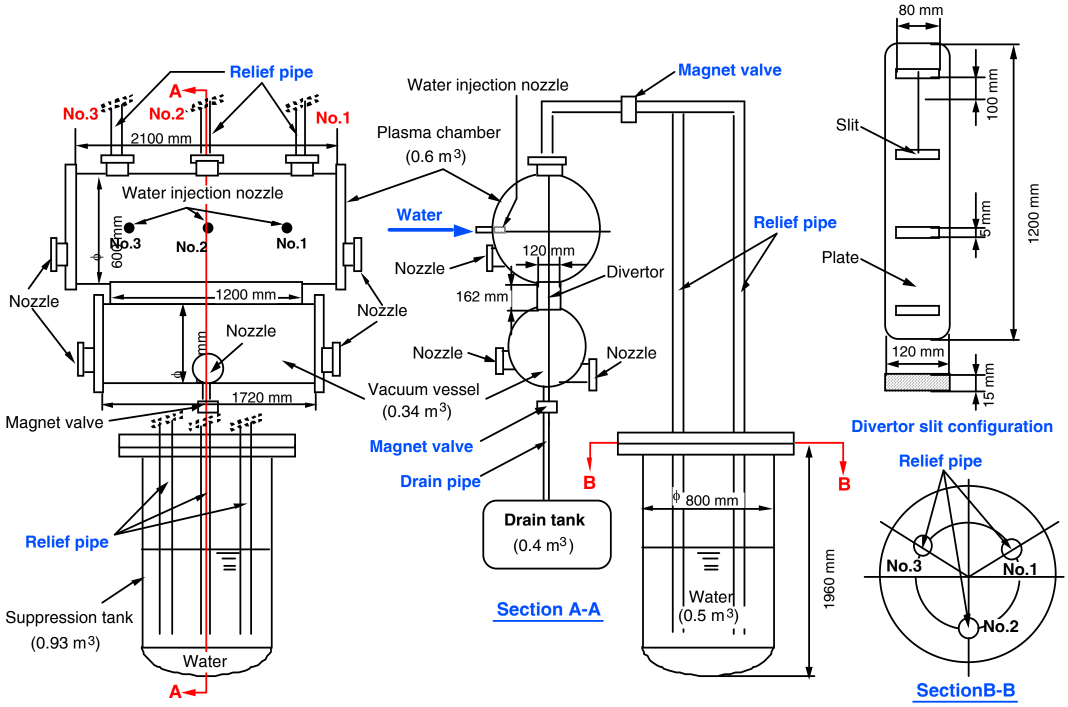

Fig. 1. Upgraded ICE facility.

3. The ICE P1 – P8 tests

The experimental transient starts when high pressure water from the boiler is injected into the PC at the boundary conditions reported in Table 1. Here a part of the water immediately flashes to steam while the residual water mass impinges the PC wall opposite the nozzles and it is dispersed circumferentially and longitudinally around the PC wall, adjacent to the impingement location, producing additional steam due to the hot wall surface temperature (205 ÷ 230 °C). This abrupt steam generation causes a fast increase in the PC and VV pressure. The formed steam is then discharged into the ST once the set-points of the magnetic valves closing the relief pipes are reached. In turn, the water not undergoing evaporation flows through the divertor slits into the VV bottom and discharges into the DT when the set-point of the magnetic valve closing the drain line is reached.

4. Employed ECART nodalisation

The ECART nodalisation consists of five control volumes, 4 representing the PC, the VV, the ST and the DT plus the three pipes connecting the boiler and the PC.

Atmospheric junctions connect the different volumes with the choked flow option activated. The pressure drops across these pipes have been tuned according to the facility geometry and the opening of the different magnetic valves is equal to the test real opening time.

Seven heat structures are present, with the jet impingement model activated only for the structure simulating the PC cylindrical body. Heat from the heating system (for PC, VV, and divertor) has been also considered. The boundary conditions (Table 1) have been set according to data available in literature [3].

Table 1. ICE test P1 - P8 boundary conditions.

No.	RP	No. Nozzles/ Diameter	PC Temp (°C)	VV Temp (°C)	Injection time (s)	Boiler Temp (°C)	Boiler Press (MPa)
P1	3	3 / 7.3 mm	228	227	45	152	2
P2	3	3 / 7.3 mm	210	120	45	151	2
P3	3	3 / 7.3 mm	205	110	45	125	3
P4	3	3 / 7.3 mm	205	105	45	126	2
P5	1	3 / 7.3 mm	210	116	45	125	2
P6	1	1 / 2 mm	226	210	600	225	4
P7	1	1 / 2 mm	215	121	600	125	2
P8	1	3 / 2 mm	211	125	200	125	2

5. ICE Tests Results

P1 and P7 tests are the most representative ones of the eight tests performed in the upgraded ICE facility, being P1 a high and cold mass flow rate test in which PC and VV are at high temperatures, while P7 a long and low mass flow rate test with hot PC and VV at a lower temperature. The remaining ICE tests present intermediate boundary conditions, so only the results of these two P1 and P7 tests are discussed in the following.

The calculated pressure peaks in the PC (figure 2) and in the VV during the P1 test present a small delay of about 0.5 s respect to the experimental data but a very good agreement on the values of these peaks. These good results are due to the delay opening of 2.5 s for the DT and ST rupture disks imposed in the ECART simulation based on the P1 experimental conditions. As a consequence of this delay, the initial PC pressurization phase is longer and the peak reached in the simulation is in very good agreement with the experimental one. From this initial pressure peak to the end of the water injection period (at 45. s) the ECART pressure curves follow accurately the experimental one, while a slightly underestimation is present in the P1 long-term phase, due to a too high mass flow-rate calculated towards the ST.

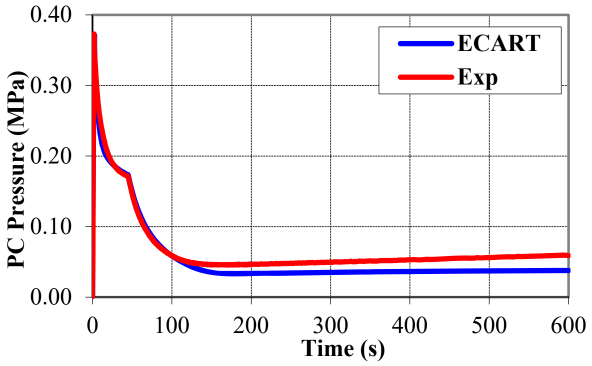

Fig. 2. PC Pressure (P1 test).

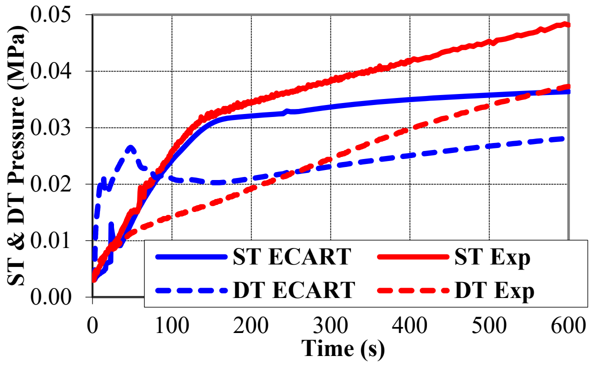

Fig. 3. ST & DT Pressure (P1 test).

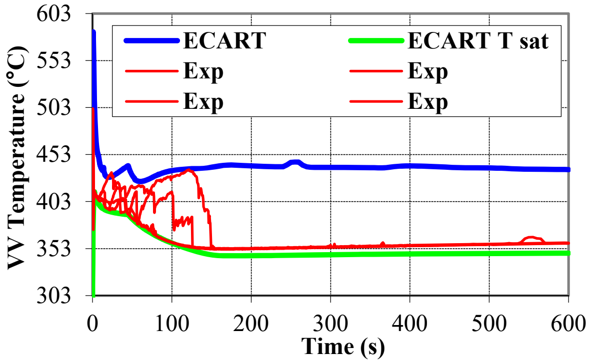

Fig. 4. VV Temperature (P1 test).

In fact, the calculated ST pressure curve (figure 3) is in very good agreement with the experimental signal during the initial injection phase and the following period (about 150. s) but in the long term this agreement worsens. The prediction of condensation inside the ST pool is accurate enough for the simulation of the injection phase, but the characterization of the last phase of the transient is questionable, probably due to the impossibility to reproduce the vent pipes geometry inside the ST and the unknown real initial ST water level.

The simulated PC atmosphere temperature follows correctly the temperature decrease due to the cold water inlet, apart some numerical oscillations. On the contrary, for the temperature of the VV atmosphere (figure 4) different phases in the ECART simulation are present with a different agreement with the experimental data:

a) strong temperature peak for ECART due to a compression effect in the first seconds of the VV transient, not present in the experimental data that immediately (in about 1 s) shift towards the saturation temperature value;

b) presence of a slow atmosphere temperature increase in the experimental signals during the first 150 s of the test, phenomenon followed quite well by ECART;

c) probably wetting by liquid drops and/or rivulets of thermocouples in the long term phase (after about 150. s), with no difference between the experimental signals and the calculated results for the saturation temperature (i.e. the water temperature).

The calculated pressure in the DT (figure 3) has a peculiar trend, always present also in the other simulations of these ICE tests, that approximates the experimental results with an initial compression phase, not measured in the experiments. In the long-term phase the pressure values are on the contrary similar between the code prediction and the experiment, also if the pressurization rate is slower for the code.

In the P7 test the timing of the peak of the calculated pressures in PC (figure 5) and in VV are delayed (5 s) if compared with the results obtained in the other tests and also the time trend of the two curves maintain higher values for about 200. s if compared with the experimental data. On the contrary, the long-term behavior is now quite satisfactory. The time delay in the pressurization history is due to the lack of the pressurization effect for the steam forming in the interactions with the VV structures that in this test P7 are quite cold.

The ST calculated pressure (figure 6) is in quite good agreement only in the injection phase (600 s). After this time, in the test there is a practically constant pressure inside the ST, not predicted by ECART, that contemporarily predicts also a relevant flow-rate entering into the ST after the injection stopping, probably for a doubtful nodalization of the suppression system lay-out.

Calculated DT pressure (figure 6) and atmospheric temperature approximate correctly the P7 experimental data, excluding again the initial compression effect predicted by ECART.

The temperature in PC (figure 7) shows good agreement during the injection phase but the final large superheating (more than 50 °C) is not simulated by ECART, due to the predicted prolonged presence of water in the atmosphere of the PC volume. This mismatch is due to an improper subdivision of the energy between atmosphere and PC walls by the ECART turbulent convection heat exchange models. The lower wetting of the PC surfaces in this P7 test (performed with only one small injection nozzle) is not sufficient to mask this problem as in the other ICE tests (performed with 3 nozzles). This is true also for the PC and VV wall temperatures.

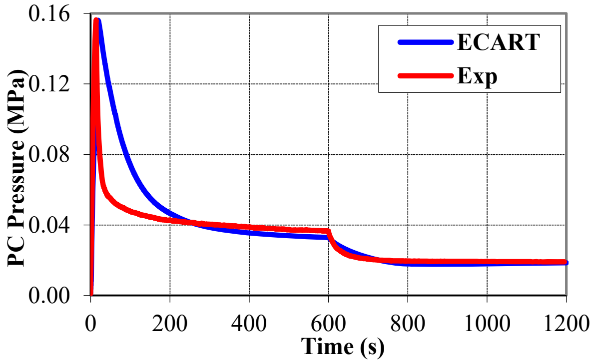

Fig. 5. PC Pressure (P7 test).

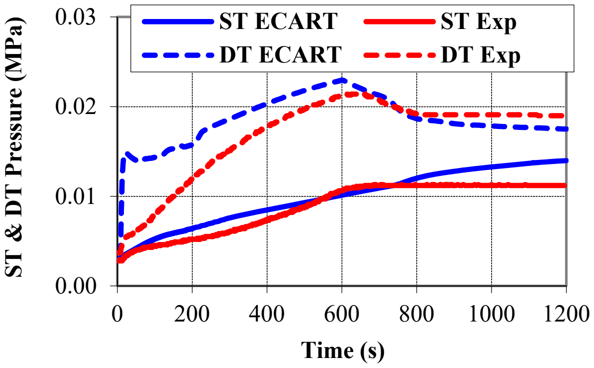

Fig. 6. ST & DT Pressure (P7 test).

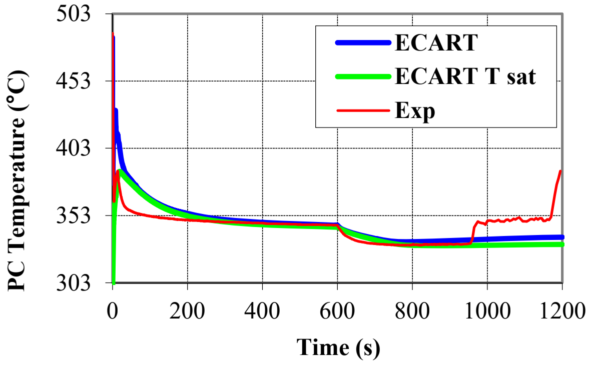

Fig. 7. PC Temperature (P7 test).

5. Conclusions

The analysis of the P1 – P8 ICE tests provided useful information on the capability of the ECART code in predicting thermal-hydraulics transients expected in future fusion reactors. The obtained differences between the experimental and calculated results are quite satisfactory for the most important thermal-hydraulics parameters (as the peak of PC pressure, time of this peak, long term pressure behavior and maximum temperatures) because the differences between the experimental and calculated values are lower than 20% for the most part of them.

The main problem has been highlighted in the prediction of the long-term depressurization phase, after the end of the water injection into the PC. This is a phase where pressure trends are strongly influenced by the predicted mass flow from the PC to the ST. An unsatisfactory characterization of the ST vent geometry and doubtful tank initial conditions (i.e., water level and sump temperature) led to some discrepancies in the code results. A questionable agreement has been also highlighted for the PC and VV wall and atmosphere temperatures. This poor agreement is mainly shown for the high turbulence tests, due to the needs of the ECART turbulent convection models, requiring a velocity only roughly estimated by a lumped parameter code (but this velocity could be imposed in the input deck), especially in small volumes as the ICE ones. Moreover, local phenomena as liquid drops or rivulets play an important role for the PC and VV wall temperatures, local phenomena that cannot be simulated by ECART.

Acknowledgments

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