Preliminary Considerations from the 2nd Phase of Experiments at the SIET/SWAM Facility

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Abstract

Severe accident codes study the thermo-hydraulics of the suppression chamber with a limited numbers of nodes, generally solving mass and energy equations and assuming perfect mixing conditions. In a long station black out the effect of the sparger's design might create local phenomena (e.g. stratification, hot-spots) which are hardly predicted by the current practices, resulting in mispredictions of the containment pressure evolution. In order to understand the effect of the sparger geometry, steam mass flux, water sub-cooling and air concentration the SWAM facility (Steam Water Air Mixing) at the SIET laboratory was employed performing around twenty different experiments, in conditions close to what is expected during the Fukushima Daiichi accident. The test facility (poll and pipes) is built with polycarbonate (transparent material) to ease the acquisition of the standard and high-speed cameras. Vertically distributed thermocouples and high-frequency pressure measurements are employed to obtain quantitative values for phenomena investigation and future CFD validations. It was shown that experiments with pure steam and relatively large diameter holes induce chugging that enhances mixing in the pool. Once chugging ceases, because of the reduced sub-cooling, a hot water layer is created in the upper part of the pool. The presence of air in the pipe induces large stratification from the condition of large subcooling because of the limited mixing introduced in the region below the pipe mouth.

Keywords
Steam condensation, air, Fukushima Daiichi, stratification/hot-layer, SWAM

1. Introduction

Direct Contact Condensation (DCC) is a method to condense steam employed in the Suppression Chamber (S/C) of Boiling Water Reactors (BWRs) because of the simplified geometry, and the large efficiency in suppressing the Primary Containment Vessel (PCV) pressure can realize relatively small PCV like Mark-I and II invulnerable to a design basis Loss of Coolant Accident.

Historical studies [1-8] applied to spargers with a single discharge hole at the bottom, found that the regime of condensation depends on the hole diameter, pool water subcooling and steam mass flux. The above studies focused on the characterization of the condensation regime based on the above parameters resulting into mainly three macroscopic regimes, that is to say chugging, bubbling and jetting. In addition, during an actual accident, the method of condensation will affect the temperature distribution in the pool and pressure evolution in the PCV. Also in the actual plant conditions can be far from what actually adopted during the experiments. In particular the steam volume fraction might be considerably lower than one (as expected in the uncontrolled operation of the RCIC in Unit 2), the sparger geometry might be more complex with a multi-holes configuration [9] and non-condensable gases could be contained in the flow.

For the explanation of the above issues the SWAM facility, at the SIET laboratories, has been employed. 20 experiments were performed varying the pipe, steam and air mass flow rates to investigate the above conditions measuring pool water temperature, steam temperature and water temperature in the pipe and recording with two high-speed cameras and a usual speed camera.

2. SIET facility

The flow diagram and geometry of the experimental facility are reported in Figure 1. The actual facility is shown in Figure 2. The preheater and steam generator provide saturated steam flow from a demineralized source of water to be injected in the pool. The available mass flow rate spans from 25 g/s to 200 g/s. Air flow line intersects the steam line upstream the flow meter with a maximum volumetric flow rate of around 17.0 l/h. The water pool internal dimensions are 0.65x0.65x3.0 m and the walls are fabricated of transparent polycarbonate, 15 mm thickness, jointed by a resistant glue. The mechanical resistance of the walls is increased by additional horizontal steel reinforcements, 65x6 mm section, placed around the pool at a distance of about 250 mm each from the other.

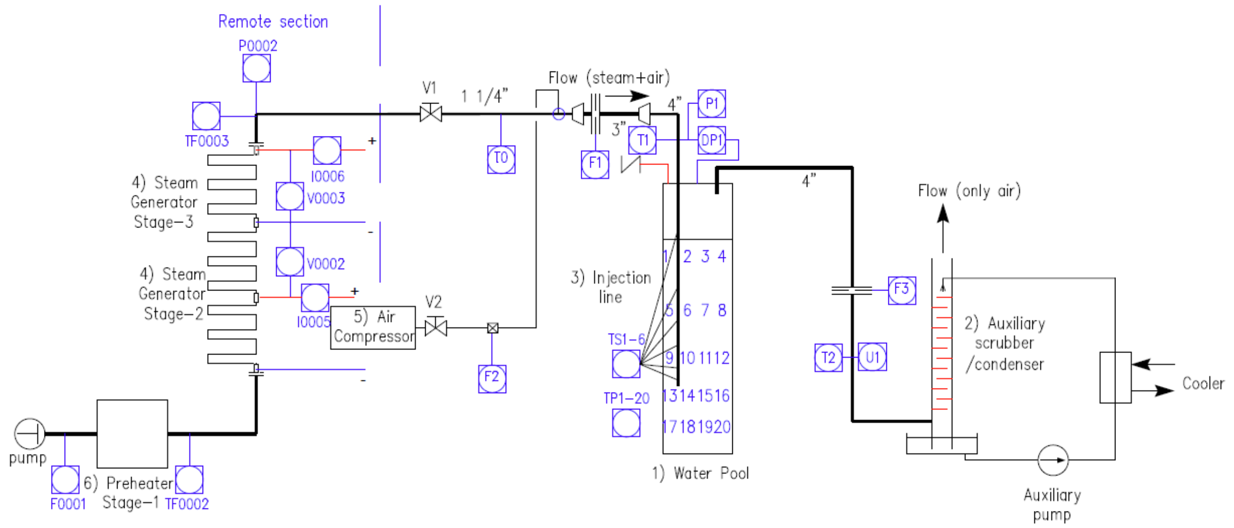

Figure 1 Facility diagram of the SWAM facility.

The facility is also equipped with a scrubber for experiments of FP decontamination factor which is not discussed in this paper. Dimensions of the scrubber are reported for completeness. The internal dimensions of the scrubber/condenser are 0.27x0.3x2.0 m. The walls are of transparent polycarbonate with a thickness of 15 mm. Horizontal plates in polycarbonate are located inside the scrubber column in order to create a waterfall for gas and water mixing. The scrubber lower part is located within a transparent polycarbonate squared pool of 15 mm wall thickness. The dimensions of the squared pool are 0.65x0.65x0.4 m. Chemical tracers for decontamination factor investigation can be injected upstream of the steam flow rate as a suspension in different concentrations by means of a variable piston stroke pump having a nominal flow rate of 18.0 l/min. In this paper the experiments regarding FP scrubbing will not be presented.

2.1 Employed spargers

Three spargers are employed in order to simulate different locations of steam discharge within the S/C. Spargers #1 is a simple pipe open at the bottom as presented in Figure 2 c). This pipe was employed to investigate phenomena of chugging condensation with pure steam and with the contribution of non-condensable gases. This pipe has an internal diameter of 0.1 m. Sparger #2 and #3 represent two scale-down models of the multi-hole sparger employed in Unit 3 RCIC design. The sparger has an internal diameter of 0.283 m and two regions of holes of 10 mm and 25 mm. The scaling is defined based on the nominal steam mass flow rate condition of RCIC of around 2.5 kg/s. Since the mass flow rate for the experiments is roughly 12 and 24 times smaller, the number of holes in the two hole regions have been reduced coherently and only a circular sector of holes is present. Vertical and lateral dimensions among holes are maintained in full scale with the original design. Details are presented in Figure 2 a and b).

2.2 Measurements

The measurements consider the following parameters: water and steam mass flow rate, air mass flow rate, steam temperature, steam pressure, differential pressure across the steam pool inlet, pool water temperature at #20 locations located on a single pipe as presented in indicated in Figure 2 c) and d).

The water level was maintained 2 meters above the pipe bottom. An attempt was also done to locate thermocouples within the pipe to study the frequency of the chug. High-speed cameras and normal-speed camera were used to record bubble collapses and overall phenomena respectively

3.3. Test Matrix

Table 1 Test matrix of the experiment presented in the paper.

	Steam mass flow rate [g/s]	Steam quality [-]	Air mass flow rate [g/s]	Sparger #
Test-1	50	1	0.0	1
Test-2	200	0.25	0.0	1
Test-3	100	1	0.0	1
Test-4	100	1	1.8	1
Test-5	200	1	0.0	2
Test-6	100	1	0.0	3

Six of the experiments performed are organized and explained in the paper. The experiment are organized to compare the effect of steam quality (Test-1 vs. Test-2), air mass flow rate (Test-3 vs. Test-4) and scaling effect of unit 3 sparger (Test-5 vs. Test-6).

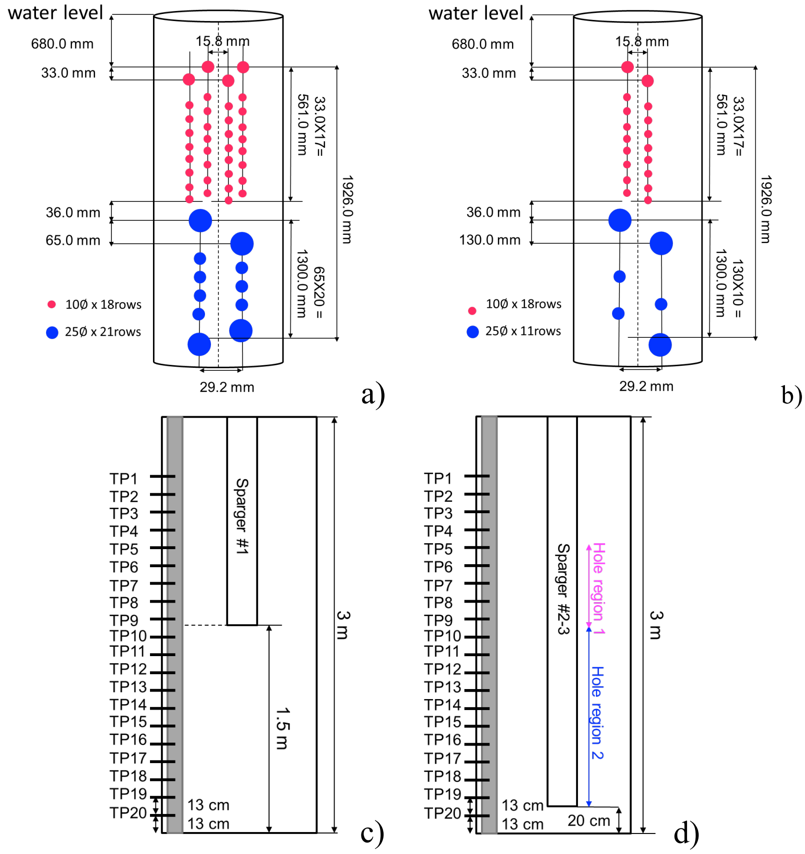

Figure 2 Details of a) sparger #2 and b) sparger #3 and position of the pipe in the pool and thermocouples.

3. Results

3.1. Effect of steam quality

Two experiments were performed with mass flow rate 50 g/s and steam quality 1 and 200 g/s steam with quality 0.25 respectively, in order to maintain the same total steam mass flow rate. The water pool temperature results are presented in Figure 3. The temperature history is characterized by a linear transient where the temperature distribution in the vertical direction is extremely homogeneous. This behavior is created by the onset of chugging phenomenon at the pipe outlet. Chugging is characterized by bubble implosion at the outlet of the pipe and depressurization of the steam flow which draws the water backward into the pipe. At the subsequent cycle the water is newly discharged at relatively high velocity in water pool creating a very uniform temperature distribution. We could state that the presence of low quality steam does not affect the creation of chugging. Once eventually the chugging phenomenon ceases the steam condenses close to the pipe without any discharging of high velocity jet and therefore little mixing is created. The temperature of the pool splits and stratification arises. Comparing the singular point among the two tests the stratification is crated essentially at the same value of the pool temperature, around 70 °C, as presented in Figure 3 c) and d).

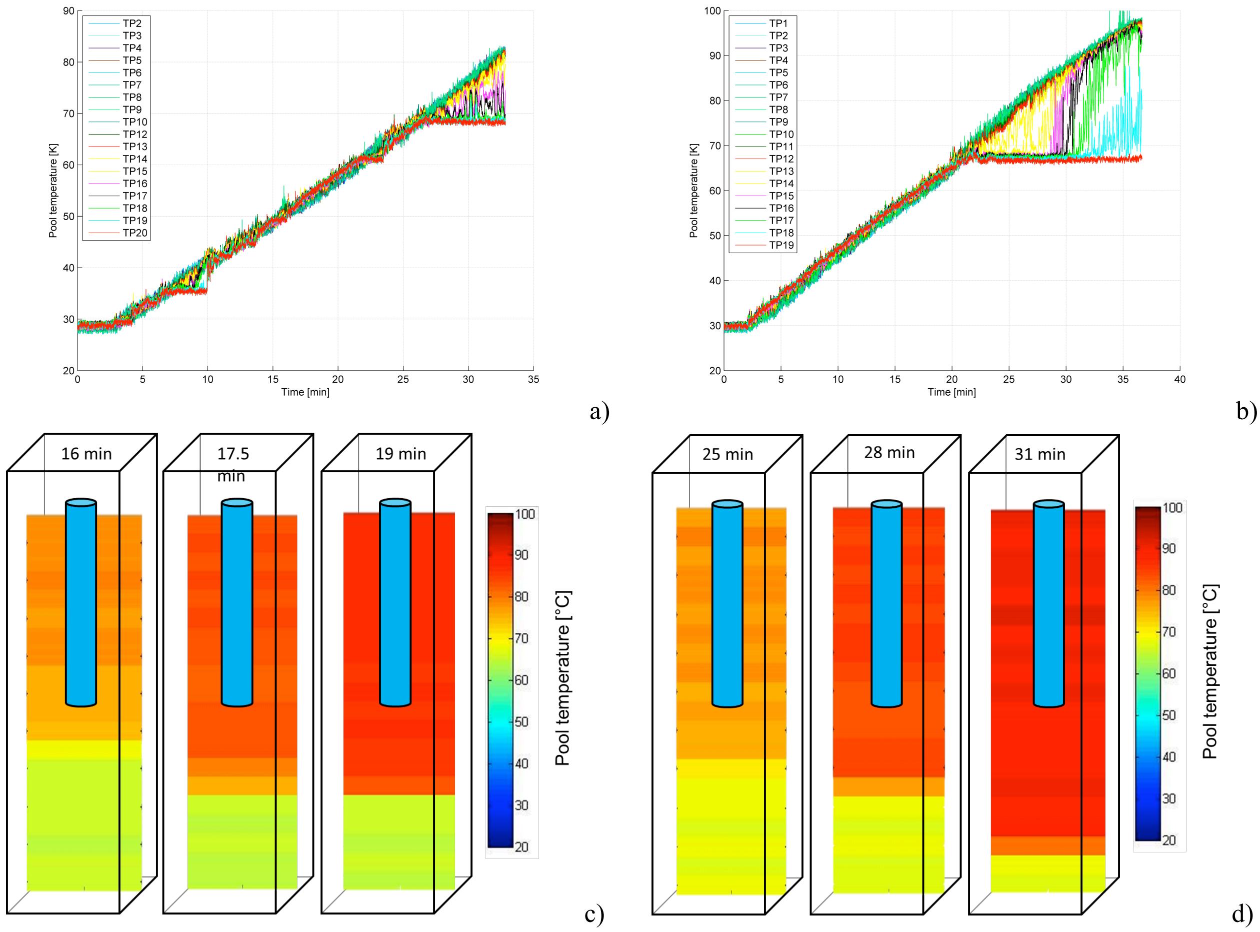

Figure 3 Pool water temperature in Test-1 (a and b) and Test-2 (c and d).

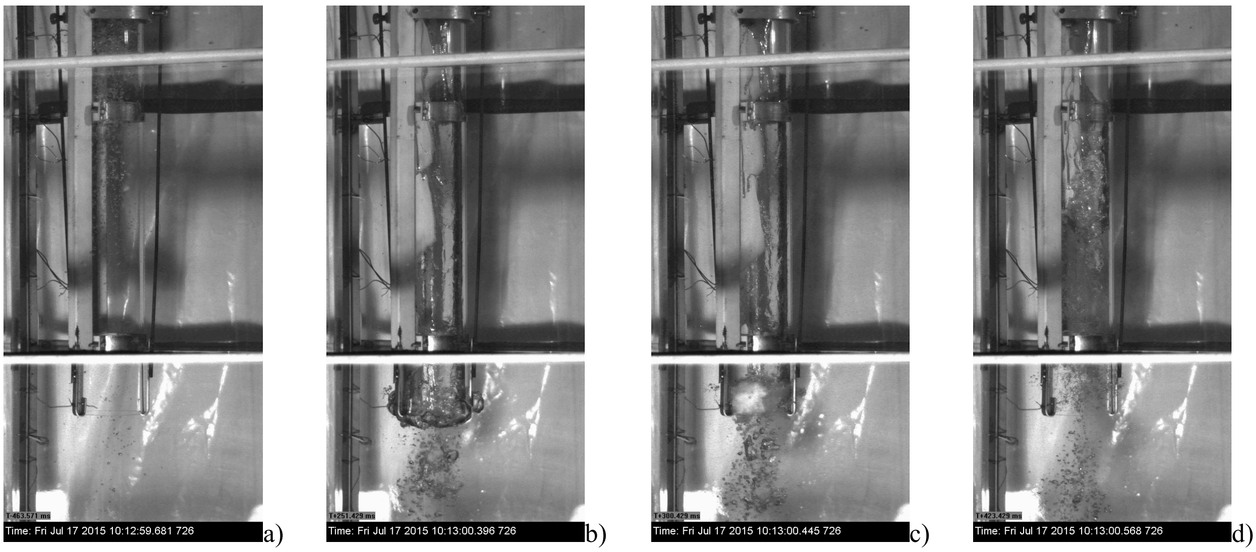

Figure 4 Frames of steam flow obtained by high-speed camera of Test-1. a) steam is flowing downward, b) bubble at the outlet, c) bubble implosion and d) steam moving upward.

7.2. Effect of non-condensable

Test-3 and Test-4 are performed with the same steam mass flow rate (100 g/s) while the latter contains also air. In case of a relatively small amount of air concentration, the chugging behavior is eliminated and the bubble remains condensing at the outlet (Figure 6), without the water being displaced at every cycle. This behavior introduces reduced mixing in the vertical direction of the pool and stratification arises early in the test, as presented in Figure 5. This result has a clear implication during steam being discharged through the vent pipes after core degradation has started because it could affect the scrubbing efficiency of the water. The breaking of the stratification, as presented Figure 5 c) and d), is related to the relatively small cross section which might add agitation of the pool water and due to the discharge of water from the bottom that was performed several times in order to maintain a constant water level without overflowing the facility.

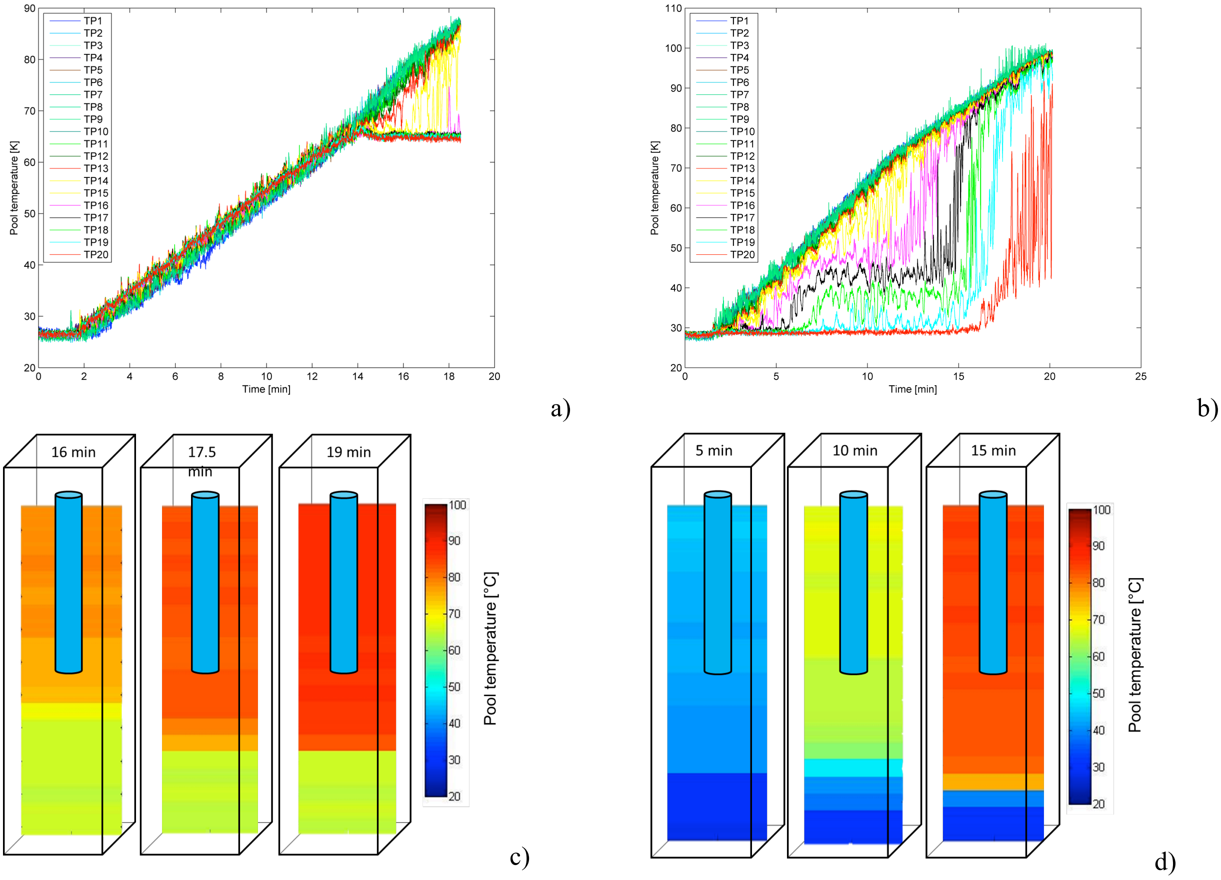

Figure 5 Pool water temperature in Test-3 (a and b) and Test-4 (c and d).

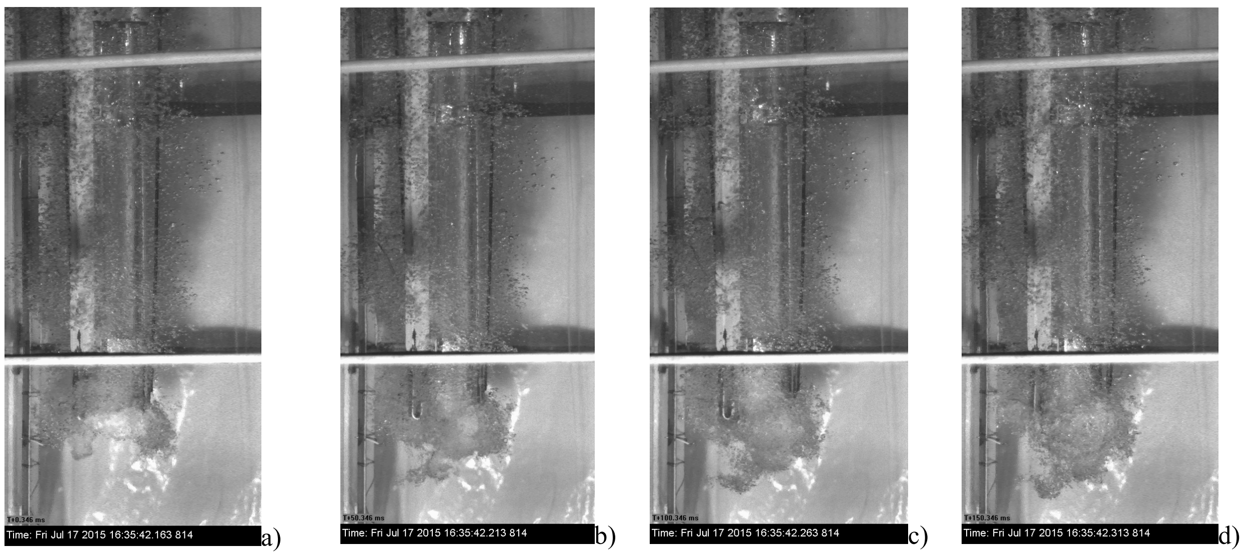

Figure 6 Frames of steam flow obtained by high-speed camera of Test-4. From a) to d) the bubble remains at the pipe outlet.

7.3. Effect of multi-hole sparger scaling

The spargers #2 and 3## have been scaled down following 1/12 and 1/24 ratio respect to the number of holes in the real sparger employed in the Fukushima Daiichi Unit 3. The purpose of the experiment was to consider the scaling effect adopting exactly the same mass flux and holes diameter. The results presented are extremely interesting because, even though the three dependencies identified in historical experiments are maintained the same for the experiments, the temperature distributions present a large difference as presented in Figure 7.

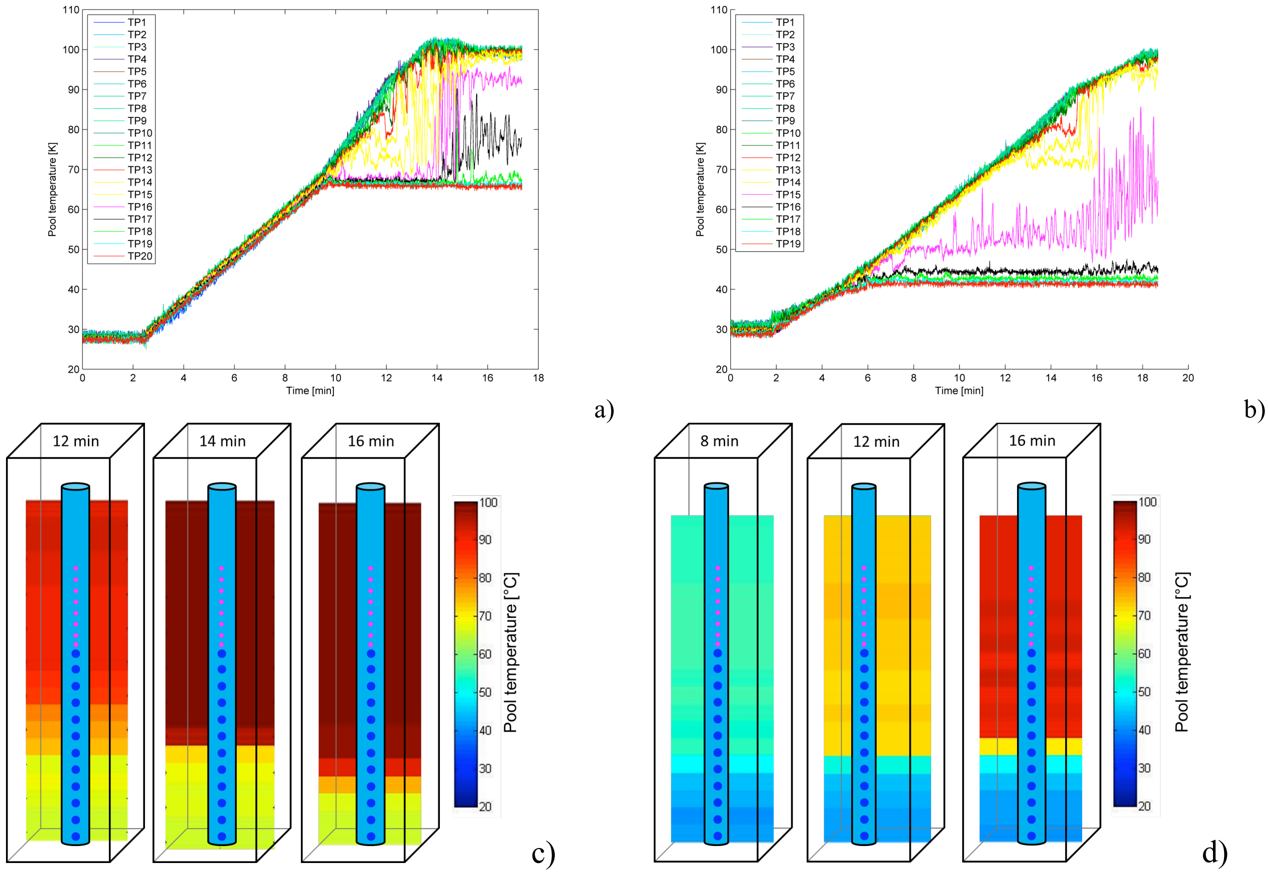

Figure 7 Pool water temperature in Test-3 (a and b) and Test-4 (c and d).

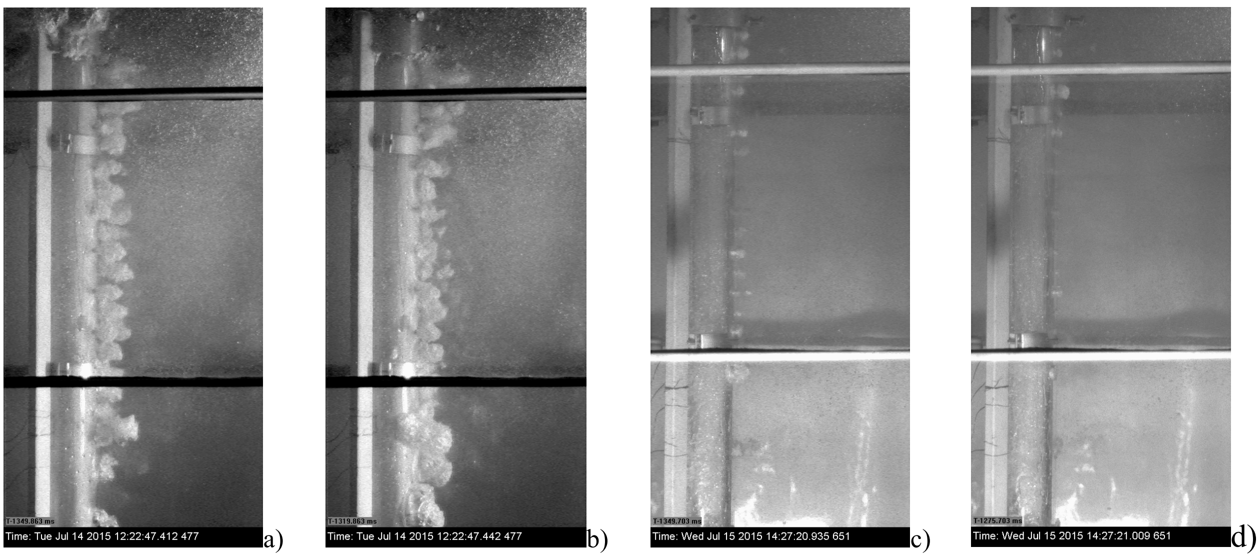

Figure 8 Frames of steam flow obtained by high-speed camera of Test-1. From a) to d) the bubble remains at the pipe outlet.

Both transients show homogeneous temperature in the pool while large chugging exists. However, the temperature value where the chugging stops and stratification is created is considerable different if compared Figure 7 a) and b). The stratification created in the Test-6 is larger because chugging ceases earlier, at around 45 °C. Another difference is the immediate change in condensation regime that was experienced in Test-5, while Test-6 presented a more gradual variation from chugging to bubbling. A possible reason to explain the difference is the different steam velocity in the pipe which is double for Test-5, because the pipe cross section has not changed. Even though this is the only macroscopic difference that could explain the results, up to now there is not mathematical evidence of the actual effect of the large velocity of the steam in the pipe.

4. Conclusions

A new experimental campaign has been performed at the SIET labs in the SWAM facility, to investigate some of the remaining issues related to steam condensing in the S/C with expected conditions during the Fukushima Daiichi accident. In the paper we have presented 6 of the 20 experiments introducing some preliminary considerations regarding the effect of low steam quality, non-condensable effect and scaling of the multi-hole sparger, in particular explaining the effect on the temperature evolution of the pool. It has been found that the steam quality does not affect the overall condensation methods (chugging is created at large subcooling) and stratification is developed from the same absolute temperature values of the pool. It has been found that the presence of air eliminates chugging and adds stratification in the upper part of the pool from the very beginning of the transient. The results of the scaling of the sparger are also extremely interesting. Even though two spargers that guarantee the same mass flux and same holes diameter have been employed, the methods of chugging onset and the water temperature value when the phenomenon disappears and stratification develops are considerably different (i.e. around 45 °C vs. 68 °C). It was suggested that this discrepancy might be introduced by the inner velocity of the flow but further studies are needed in this direction.

5. References

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