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To cite this article: A Pesetti *et al* 2021 *J. Phys.: Conf. Ser.* **1868** 012018

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Direct steam condensation at sub-atmospheric pressure: experimental tests and similitude analysis

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Abstract. This paper deals with experimental and theoretical analyses of the steam direct condensation at sub-atmospheric pressure. These operation conditions occur in the Vacuum Vessel Pressure Suppression System (VVPSS) of ITER Nuclear Fusion Reactor. This safety system permits to manage the Ingress of Coolant Event (ICE cat. IV) accident condition, postulated to occur in the ITER Vacuum Vessel (VV) as a consequence of the rupture of the shielding blanket cooling piping or the rupture of the divertor cassette piping.

Experimental tests of steam direct condensation at sub-atmospheric pressures in a 1:22 scale facility were performed at the laboratory Guerrini of DICI-University of Pisa. Presently a full-scale facility is being building at DICI. This paper illustrates the similitude analysis elaborated to scale up the experimental results obtained in the reduced scale facility. The main variables which influence the steam direct condensation were analyzed and the relative scale laws determined. CFD numerical simulations of direct steam condensation in the actual geometry and in a vessel of equal volume permitted to verify some of the assumptions on which the scale laws are based. Scaling studies were first performed in order to calculate the transient of steam mass flow rate occurring during the ICE IV event in the scale apparatus, starting from the thermal hydraulic studies performed at ITER and successfully compared with the experimental results carried out in scaled apparatus. This confirmed the suitability of scale laws and in the same time the capability of the VVPSS to condense the injected steam at sub-atmospheric pressure, matching the safety goal to reduce the system pressurization.

1. Introduction

The ITER VVPSS is designed to protect the VV from overpressurization caused by in-vessel coolant leakage. In particular, an Inlet Coolant Event (ICE) is assumed to occur during the normal operation activities of the reactor. VVPSS is based on the containment design of the nuclear fission reactors BWR, even if the Vapor Suppression Tanks (VSTs) operate at sub-atmospheric pressure (maximum allowed pressure inside VV is 0.15 MPa). VVPSS consists of 4 VSTs with a height of 4.7 m and a diameter of 6.3 m and an overall volume of 100 m³ each, partially filled with water in order to directly condense the steam.

Each tank contains a single vertical sparger tube to discharge the steam and the non-condensable gases. The design configuration for the VSTs is shown in Figure 1. One tank, Small LOCA Tank (SLT), is used to manage small LOCAs and Loss of Vacuum Accidents (LOVAs). This tank contains 40 m³ of water. The other three tanks, Large LOCA Tanks (LLTs) are used to manage higher category events. Each of the three tanks contains 60 m³ of water for a total capacity of 180 m³.



No previous researches or applications of steam pressure suppression systems at sub-atmospheric pressure are available in the technical literature. Therefore, a research program with a “small-scale” experimental rig (4.5 m³ corresponding to about 1:22 reduced scale) was funded by ITER and carried out at DICI-University of Pisa [1]-[2]. About five hundred condensation tests were carried out in three separated test phases, allowing the definition of a condensation regimes map at sub-atmospheric conditions. Moreover, a similitude analysis was elaborated and the scaling laws were applied for simulating accidental scenarios which could occur in the Vacuum Vessel of ITER.

An experimental analysis of the small LOCA accidental scenario was carried out in the small-scale experimental rig and the results compared with those of a developed theoretical model. In addition, CFD analyses were carried out simulating [4][5] the condensation in the actual VST and in a large-scale (1:1.08 scale) Experimental Test Tank (ETT), during the first 500 s of the Large LOCA transient scenario, in order to assess the elaborated scaling laws.

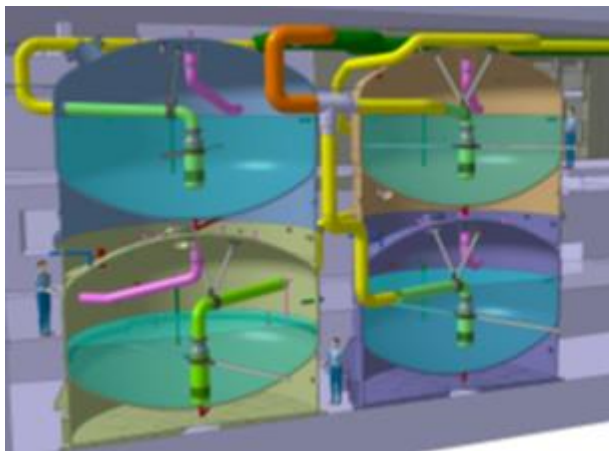


Figure 1. Configuration of VVPSS [7]



Figure 2. Reduced Scale experimental rig

2. Experimental test facility

Figure 2 shows the reduced scale experimental rig located at the Laboratory B. Guerrini of DICI-University of Pisa. The main component is the Reduced Condensation Tank (RCT) (4.5 m³, scale factor about 1:22). It is deeply instrumented with 28 temperature sensors and 8 pressure transducers. An internal vertical sparger with several holes discharges the steam inside the water. The steam mass flow rate, produced by an electric steam generator, is controlled by means of Vortex or Coriolis measurement devices. The sub-atmospheric pressure conditions (up to about 0.1 bar absolute) are achieved with a dedicated vacuum pump. Plant details are available in [1][2].

3. Similitude analysis

Based on the performed experimental activity, a suitable similitude analysis was elaborated to describe the steam condensation at sub-atmospheric pressure.

The geometric scale factor is defined as $S = V_{ACT}/V_{SCAL}$, where V_{ACT} is the VST actual volume and V_{SCAL} is the volume of the scaled facility condensation tank. The ratio of the volume occupied by the water to that of the vacuum space is equal for the full-scale tank as well as for reduced scale tank and it is equal to S .

From the experimental tests, it was deduced that the condensation regimes depend mainly on:

- the steam mass flux $G_S = q_S/A_H$ (kg/s m²), q_S (kg/s) is the steam mass flow rate per hole and A_H (m²) the hole area;
- the downstream pressure P_W (water pool pressure in front of the hole);
- the average water temperature, T_W .

The water temperature, T_W , depends on the water mass in the tank, M_W , and on the steam condensed mass M_S . The downstream pressure, P_W , depends on the saturation pressure correspondent to the water

temperature, T_w , and on the water head, H_w . On the basis of the abovementioned governing parameters, it is possible to obtain similar condensation regimes, in the full-scale as well as in the reduced scale system, if:

- the steam mass is scaled: M_s/S (being M_s the actual total steam mass of the transient, S the volume scale factor);
- the steam mass flow rate per hole, q_s , is equal;
- the condensation time (test duration) is amplified by factor: $K=(N_E/N_s)/S$ (being N_E the hole number of actual sparger and N_s the hole number of the scaled sparger), for evaluating different holes number;
- the water head, H_w is equal.

At scaled time, the average water temperature, T_w , and the pressure, P_w , are the same in the full-scale as well as in the reduced scale system. The experimental tests have permitted to identify the following six main condensation regimes (based on the video recorded during the tests):

- Chugging (C);
- Transitional Chugging (TC);
- Bubbling Condensation Oscillation (BCO);
- Condensation Oscillation (CO);
- Interfacial Oscillation Condensation (IOC);
- Stable Condensation (SC).

The different condensation regimes are identified by characteristic steam jet shapes exiting from the sparger holes. In the Stable Condensation, the steam jet has a conical shape and it is stable during all the transient. The Chugging regime is characterized by an alternate exit of steam and water from the holes, determining vibrations on the structures. The Bubbling regime is characterized by a steam bubble which forms in front of the hole and alternatively increases its dimensions and subsequently collapses. The other regimes show steam jet shapes which are transition between the most identifiable regimes, previously indicated. All these last regimes are characterized by unstable condensation producing mechanical loads on the structures. The previous described scale laws permit to have similar condensation regimes in the actual tank and in the scale experimental facility, reached at different times. The research activity, performed at DICI, permitted to elaborate a map of condensation regimes in which the three main parameters of the steam condensation (T_w , G_s and P_w) are represented. In particular, the research activity demonstrated that the condensation regimes could be mapped in the 2D plane (T_w , G_s/P_w). Figure 3 shows the map of condensation regimes [3]. The stable condensation at sub-atmospheric pressure is reached for a steam mass flow rate per unit of area, G_s , about ten times smaller than that corresponding to the atmospheric pressure case [3].

3.1. Analytical Simulations of the Accidental Scenarios

As experimentally demonstrated [1]-[3], the steam mass flow rate per one hole, q_s , is one of the main governing parameters. The physical behavior of the steam condensation mechanism (i.e. condensation regime, condensation heat transfer coefficient HTC at steam-water interface, and so on) is fully controlled by the average condensation heat transfer coefficient h_{AVE} , on one hand and by the condensation driving potential B (depending mainly upon the subcooling, $\Delta T_{SUB} = T_{SAT} - T_w$) on the other hand.

According to the literature [6], the average condensation heat transfer coefficient h_{AVE} can be approximated by the correlation in the form:

$$h_{AVE} = a C_P G_s B^b \left(\frac{P_s}{P_w} \right)^c \quad (1)$$

where, a , b , c are fitting constants, C_P is the specific heat of water, G_s is the steam mass flux, P_s and P_w are respectively the steam upstream pressure inside the sparger and water downstream pressure and B stands for the condensation driving potential, given by:

$$B = C_P \frac{\Delta T_{SUB}}{H_{FG}} \quad (2)$$

ΔT_{SUB} is the subcooling, and H_{FG} is the latent heat of vaporization.

The average condensation heat transfer coefficient h_{AVE} , is proportional to the steam mass flux G_S . The condensation regime operation is fully determined by the ratio of the steam mass flux to downstream pressure, G_S/P_W , given by:

$$\frac{G_S}{P_W} = \frac{q_S}{A_H P_W} \quad (3)$$

where, q_S is the steam mass flow rate per one hole, A_H is the hole cross section area and P_W is the pressure downstream the hole, related to water head, H_W , by:

$$P_W(z_H) = P_{FSV} + \rho_W(T_W)gH_W \quad (4)$$

where, $\rho_W(T_W)$ is the water density at temperature T_W , g is the gravitational acceleration, and P_{FSV} is the Free Space Volume (FSV) pressure, also related to the water temperature T_W through the steam saturation pressure P_{SAT} (kPa) correlation:

$$P_{FSV} = P_{SAT} = 0.97417[1 - 1.13943\theta(1 - 38.919\theta + 36.036\theta^2 - 88.345\theta^3)] \quad (5)$$

being $\theta = T_W/100$ and the correlation is valid in the range $10 \leq T_W \leq 110^\circ\text{C}$.

$$\rho_W(T_W) = 10^3 \left(1 - \frac{(T_W + 288.941)(T_W - 3.9863)^2}{5.089292 \cdot 10^5 (T_W + 68.12693)} \right) \quad (6)$$

$\rho_W(T_W)$ is given in kg/m^3 and the correlation is valid in the range $10 \leq T_W \leq 100^\circ\text{C}$.

Figure 4 illustrates the diagrams of total steam mass flow rate Q_S versus time that could be originated by postulated Large (blue) and Small (orange) LOCA accidental scenarios in the Vacuum Vessel of ITER and are called ICE cat.IV events [7]. The two depicted mass flow rate time trends represent the steam injected into the three LLTs (blue) and SLT (orange) of ITER VVPSS. Using the previous formulas, the similitude laws and the experimental data obtained in the experimental campaign on the reduced scale facility, the accidental events that could occur in the ITER Vacuum Vessel, requiring the intervention of steam pressure suppression system, were theoretically simulated. The small LOCA event (having a peak of about 7 kg/s of steam, 900 s of duration and about 3200 kg of total steam injected) is managed in a 100 m^3 tank which is called Small LOCA Tank (SLT). The Large LOCA is managed in three 100 m^3 tanks which are called Large LOCA Tanks (LLTs). Assuming that the steam mass flow rate related to the Small LOCA is all condensed in the SLT, the average water temperature, T_W , and the downstream pressure, P_W , were calculated. These results are shown in Figure 5 together with the diagram of the steam mass flow rate and the indication of the condensation regimes. All these results can be reported in the condensation regime map, as illustrated in Figure 6. Similar calculations have been performed for the Large LOCA, managed in the LLTs (see red trend in Figure 11).

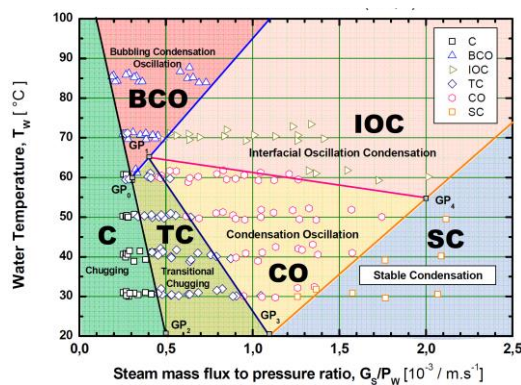


Figure 3. Map of condensation regimes [3]

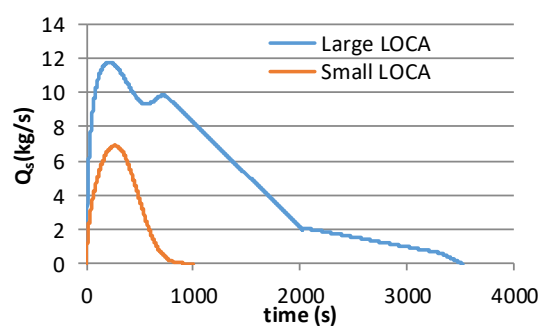


Figure 4. Steam mass flow rates versus time considered ICE cat. IV events in ITER Vacuum Vessel

3.2 CFD Analyses of Steam Direct Condensation

The steam direct condensation was simulated numerically by means of ANSYS FLUENT® considering the actual condensation tank (LLT 100 m^3) and the large scale ETT (92 m^3).

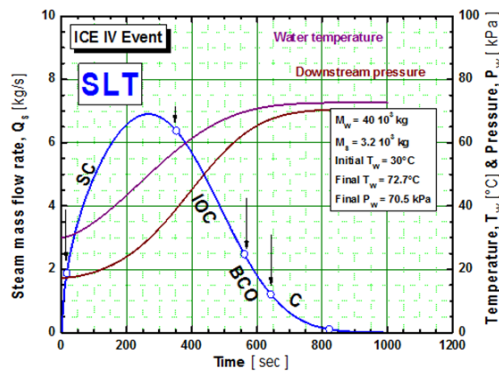


Figure 5. Diagram of T_w and P_w versus time in the SLT produced by steam of a Small LOCA

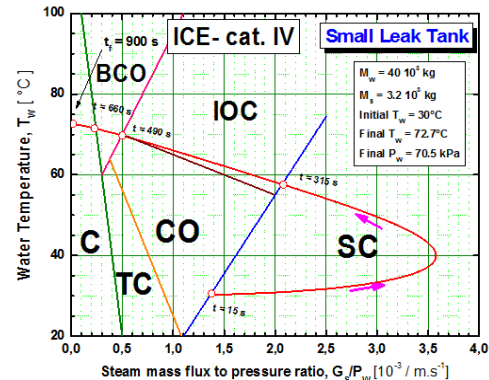


Figure 6. Condensation regimes during a Small LOCA managed in the SLT

ETT is the condensation tank planned to be adopted at DICU-University of Pisa in a wide series of experimental steady-state and transient tests, relevant to support the validation of the VVPSS safety functions suitability [3]. The FLUENT 2D axisymmetric models of two vessels LLT and ETT are depicted in Figure 7. The top dished head of both numerical models was not simulated in order to reduce calculation time and consequently a reduced cover gas volume was modelled. In order to simulate both water and low-pressure air domains the multiphase model Volume of Fluid (VOF) was adopted. The analyzed transients of 500 s consist on the steam condensation of 5 kg/s of superheated steam at 130°C injected horizontally into liquid water at 30°C through 1000 holes of 10 mm of diameter, disposed on 20 circumferential levels with 50 holes each.

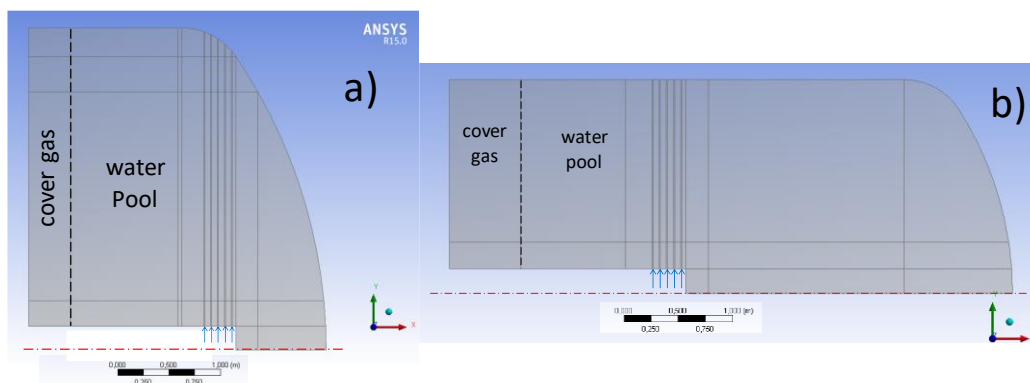


Figure 7. FLUENT models of LLT (a) and ETT (b)

The released latent heat of condensation was simulated by means of energy source (W/m^3) located in a small region adjacent to the injection holes. The buoyancy phenomena in the liquid phase were taken into account implementing a liquid density function of temperature between 0 and 98°C.

Figures 8-10 show the contour plots of temperature in Kelvin degrees for ETT (left) and LLT (right), being the two models glued together at different transient instants. The comparison between ETT and LLT was done on the base of the similitude laws which establish a time amplification given by $K=(N_E/N_S)/S$. In the simulated case $N_E=N_S=1000$ and $S=M_{WE}/M_{WS}=1.1276$ and $K=0.88$, being M_{WE} and M_{WS} the mass of water in LLT and ETT models, respectively. This law assures that, at correspondent times, the energy supplied to a unit of water mass, on average, is equal in the two systems (full scale and reduced scale). The CFD analyses do not simulate correctly the actual turbulent zone near the jet plume. Experimental tests showed, in stable condensation, convective motions in front of the holes. This turbulence determines a two-ways heat transfer: towards the free water surface and also towards the bottom. The CFD simulations provided a heat transfer which evolves in this manner:

- It goes towards the top near the surface of the sparger,
- It moves parallel to the free water surface;

- It expands towards the bottom.

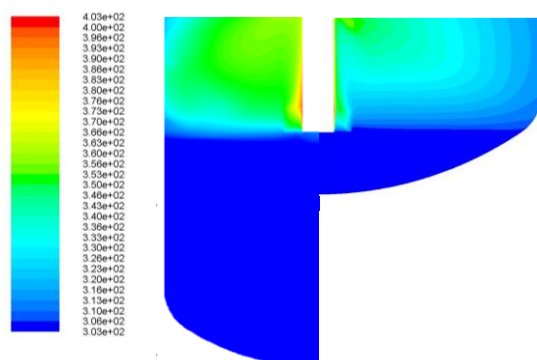


Figure 8. Contour plot of temperature [K] at 260 s for ETT and at 300 s for LLT

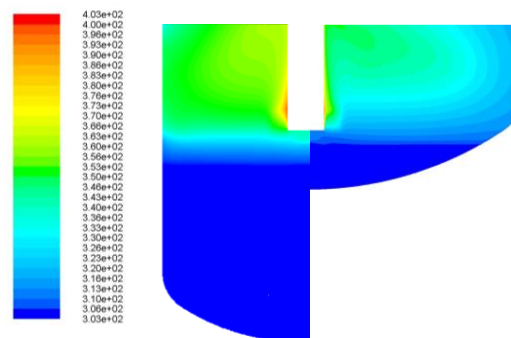


Figure 9. Contour plot of temperature [K] at 350 s for ETT and at 400 s for LLT

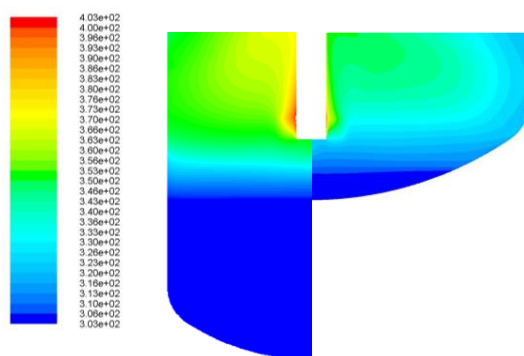


Figure 10. Contour plot of temperature [K] at 440 s for ETT and at 500 s for LLT

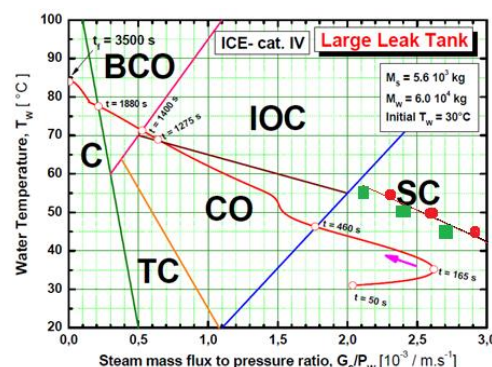


Figure 11. Condensation regimes correspondent to CFD simulations (LLT green squares, ETT red circles)

This heat transfer model is more adherent to the chugging or bubbling regimes. A greater temperature stratification is produced by the absence of turbulence in front of the holes. This fact influences greater the ETT than the LLT, because the former has a greater part of water under the sparger.

Another consequence of this temperature non-uniformity is that the pressure in the vacuum space could depend to a certain extent on the temperature of free water surface (T_H) which is greater than the average value; the condensation regime is moved towards no stable zones

From the temperature distributions illustrated in the Figures 8-10, the variables (T_w , G_s/P_w) and the position of the three instants of the transient in the condensation regime map can be derived for the ETT as well as for the LLT.

Table 1 reports the data obtained by the CFD analyses corresponding to the analyzed three couples of transient instants shown in Figures 8-10. Figure 11 illustrates their position in the condensation regime map with red circles for the ETT and green squares for LLT. The straight line close to these CFD results (points) represents the calculated results of theoretical approach, previously illustrated, applied to the transient simulated by CFD. The CFD results fit very well the theoretical curve, being almost superimposed. Figure 11 shows also the results of theoretical approach applied to the ICE IV event in the LLT: red line showing the transient from 50 to about 3500 s.

The CFD analysis provided a good agreement of parameters P_w , G_s/P_w and T_w computed at scaled time instants. The ETT geometry (with a great part of water under the sparger) is most influenced by the CFD assumption to spread the condensation latent heat in a small volume near the sparger surface. It is confirmed by the average temperatures along a vertical line 200 mm distant from the sparger (T_v) and along the free water surface (T_H), they are greater in ETT than LLT (see table 1).

Table 1. Condensation Regimes parameters obtained by the CFD analyses for the ETT and LTT

Experimental Test Tank (ETT)						Large LOCA Tank (LLT)					
t	T _V (°C)	T _H (°C)	P _W (kPa)	G _S /P _W (10 ⁻³ s/m)	T _W (°C)	t	T _V (°C)	T _H (°C)	P _W (kPa)	G _S /P _W (10 ⁻³ s/m)	T _W (°C)
260	85.69	70.49	21.95	2.9	45.25	300	63.05	54.8	23.51	2.825	45.6
350	91.13	77.28	24.59	2.59	50.4	400	69.64	56.74	26.47	2.5	52
440	97.042	84.96	27.74	2.3	55.4	500	74.03	59.72	30.15	2.182	55

4. Experimental Assessment of the similitude laws

The established scale laws were applied for simulating theoretically and experimentally the Small LOCA scenario in the reduced scale facility of Pisa University. The Small LOCA scenario was managed in the Reduced Condensation Tank (RCT) with a 6 holes sparger and a total mass of water $M_W=1824$ kg. The obtained scaling parameters were $S=22$ and $K=7.58$, providing the scaled total discharged steam mass $M_S=145$ kg and the duration transient $\Delta t=6840$ s, respectively.

Figures 12-13 illustrate the comparison between the results of the theoretical approach (blue time trends) and those obtained during the experimental test (red). It is worthwhile to note that in the stable condensation regime, the downstream pressure has smaller values of the theoretical one. This fact produces a greater extension of the zone of the stable condensation, as the Figure 13 shows.

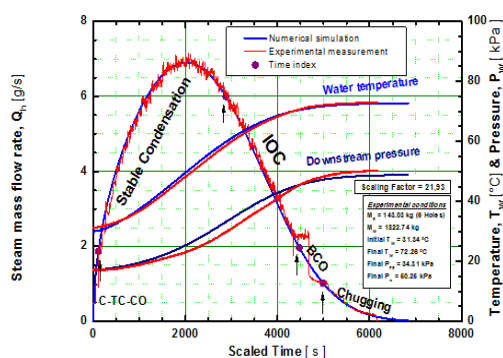


Figure 12. Comparison of T_W and P_W versus time obtained by the theoretical model and experimental tests

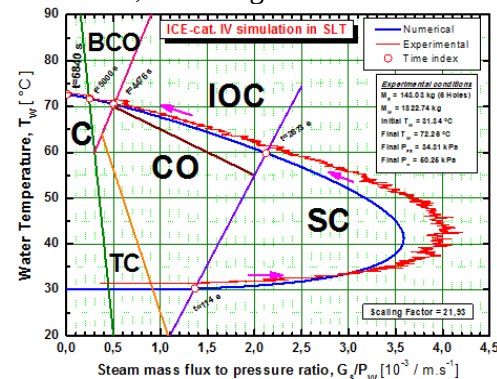


Figure 13. Small LOCA managing; comparison between theoretical model and experimental results

The justification of this behaviour is similar (and opposite) to that noted in the CFD simulations, the sparger is near of the tank bottom and the steam jet is prolonged along the entire diameter of tank. In this manner the water located under the sparger collaborates greatly at the steam condensation and the temperature at the water free surface is reduced as well as the vacuum space pressure. The condensation regimes were verified by means of the video recorded during the transient. Figure 14-a) shows the Stable Condensation (SC, $t=2225$ s). The bubbling oscillation condensation, shown in Figure 14-c) ($t=5910$ s), has steam adherent to the sparger surface and turbulence is no anymore present. The final values of the main variables (Table 2) obtained in the experimental test are in optimum agreement with the theoretical ones.

Table 2. Final main values obtained by the theoretical model and by the experimental test simulating the Small LOCA scenario in the reduced scale facility

Parameter	Theoretical results	Test results
Final T_W [°C]	72.7	72.78
Final P_W [kPa]	48.8	50.26
Final P_{FSV} [kPa]	34.93	34.31

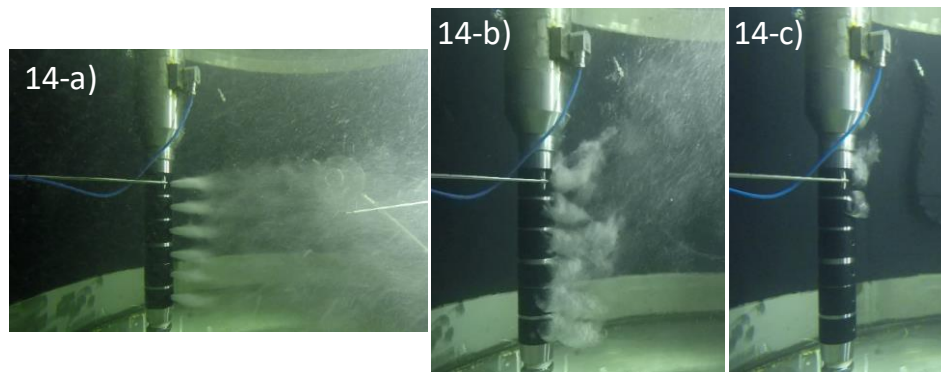


Figure 14. Condensation regimes: a) Stable condensation ($t=2225$ s); Interfacial Oscillation Condensation ($t=3985$ s); c) Bubbling Oscillation Condensation ($t=5910$ s)

5. Conclusions

The paper summarizes the defined scale laws suitable for direct steam condensation analysis at sub-atmospheric pressure conditions in reduced scale experimental rigs. The assessment and verification of this similitude analysis, based on Small and Large LOCA postulated accidents in ITER plant, were carried out performing both CFD numerical simulations and comparison of theoretical-experimental (Lab. Guerrini of DICI- University of Pisa) analysis.

The initial part of Large LOCA event (5 kg/s of steam injected for 500 s) was simulated adopting FLUENT® code in both actual VST (100 m³) and ETT (92 m³) (UNIPi large facility tank), comparing the results at three time instants, computed on the basis of the defined amplification factor $K=0.88$. The numerical results confirm the suitability of the defined scale laws, being the main pool parameters P_w , G_s/P_w and T_w of the two simulations almost equal. The discrepancies between pool temperature in the two numerical analysis ($T_{ETT} > T_{VST}$) are correlated to the different geometry of the two tanks.

The scale laws were also positively assessed on the basis of the whole Small Loca event in the “small scale” facility at UNIPi (1:22). In this case, taking as boundary conditions the steam mass flow rate injected in the SLT amplified by $K=7.58$, the time trend P_w and T_w and final P_{FSV} computed by a theoretical model were compared with corresponding values measured in the RCT during an experimental activity, showing a quite good agreement. Moreover, the video cameras acquisitions during the experimental test allowed to determine the condensation regimes at amplified time scale and their agreement with condensation regimes theoretically predicted in the actual SLT.

On the basis of the performed activities, the proposed scale laws were numerically, theoretically and experimentally verified and could be considered a precious instrument to investigate condensation phenomena occurring in sub-atmospheric conditions in geometrically scaled condensation tanks. An extensive experimental campaign is ongoing in the large ETT tank, for further validation.

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