Experimental analysis of steam condensation patterns within a pressure suppression system operating at sub-atmospheric pressure conditions

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Abstract
For some specific applications, the pressure suppression systems should be maintained at sub-atmospheric pressure, such as in fusion plants systems. This operation conditions differ considerably from those experienced in the suppression pools of BWR operating at atmospheric pressure. The steam condensation in water at sub-atmospheric conditions is not sufficiently known, if not at all; therefore its effectiveness has to be investigated experimentally. In fact the steam condensation at sub-atmospheric pressure requires a subcooling capacity 2.5 times higher than that at atmospheric pressure.

In consideration of that, a low scale experimental facility was designed and built at the University of Pisa. More than 350 steam condensation tests were performed in broad influencing parameters range (e. g. pressure within the condensation tank, water temperature and steam mass flux) to study of effectiveness of the steam condensation. In doing that, different sparger configurations (with single or multiple holes) were considered to check possible interference of condensing steam jets and bubble coalescence.

Results indicate a high efficiency of condensation for all the examined conditions. The 3D map of the condensation regimes demonstrate they are dependent only on the downstream exit pressure, the water temperature and the steam mass flux per hole.

1. Introduction
The ITER Vacuum Vessel (VV) operates in normal condition at 0.8±0.3MPa and in any case the maximum internal pressure shall be limited, e.g. in case of loss of coolant accident from the in-vessel components (coolant coming from the Tokamak Cooling Water System-TCWS) or LOVA (loss of vacuum accident) event, to 0.15 MPa absolute. In particular, to limit the VV internal pressure, in case of loss of coolant from the in-vessel components, VV has been directly connected to an additional sub-system: the Vacuum Vessel Pressure Suppression System (VVPSS).

Figure 1 shows the ITER Tokamak cooling system; VVPSS is the yellow colored system on the left side.
During an in-vessel coolant leak (Ingress of Coolant Event (ICE)) the VVPSS acts in concert with the VV drainage system: the former by condensing efficiently the hot steam in dedicated water suppression tanks allows to limit the maximum pressure to 0.2 MPa; the latter facilitates drainage of water from the VV. As a consequence of that, it appears that the steam direct contact condensation into the VVPSS suppression tanks water is the thermal-hydraulic phenomenon that guarantees the pressure safety limit are not exceeded.

In this study, the steam condensation in cold water at sub-atmospheric pressure is investigated: steam condensation regimes are determined along with the identification of main parameters influencing possibly the design of VVPSS. It is important to highlight that neither experimental nor analytical investigations of steam condensation at sub-atmospheric conditions, like those foreseen in ITER, have been yet reported in the available literature [1]÷[10].

In what follows a brief description of the VVPSS will be given. In section 3, we describe the experimental facility built at “B. Guerrini” Laboratory of the University of Pisa to study the steam condensation at sub-atmospheric condition along with the experimental work done. Critical discussion of the obtained experimental data is provided in section 4.

2. Description of VVPSS

The VVPSS is made of 4 Vapour Suppression Tanks (VSTs) of 100 m$^3$ each, with an inner diameter of 6.2 m and an overall height of about 4.7 m, mounted as two stacked assemblies (see Figure 2).

Each tank is designed to limit the final water temperature, after a loss of in-vacuum coolant event, to 95°C, to guarantee the structural integrity, withstanding all loads and load combinations that are within the design basis, the safe operation of the suppression system, and the confinement in the event of H$_2$ deflagration.

Figure 2 shows the arrangement of the VVPSS with the three Large LOCA Tanks (LLTs), and the Small LOCA Tank (SLT) that, despite the similar design, are filled with a different amount of water:
- 40 m$^3$ for the SLT;
- 60 m$^3$ for each of the LLT tanks 1, 2 and 3;

Moreover, the 3 LLTs are supposed to manage bigger LOCA events (cat. III and IV), while the SLT is supposed to manage smaller LOCA events (cat. II). VSTs are connected to the VV through two different relief lines, as shown in Figure 3, describing the VVPSS process flow diagram configuration.
By analyzing the VVPSS process flow diagram configuration, it appears that the SLT is connected by means of a DN300 relief line to one pipeline. A fully redundant set of double vacuum isolation bleed valves DN250 is provided to allow the trapped volume evacuation and the leak checking of the valves, as in the current VVPSS.

As to the LLTs, they are instead connected in parallel to a DN500 relief line, along which are installed two sets of rupture disks (full redundancy). When accident occurs, rupture disks opening will ensure the excess of steam is released to the DTR and condensed inside the VSTs.

2.1 Experimental test facility

The experimental facility of the DICI-University of Pisa, even if a scaled model if compared to the ITER VVPSS, has been designed in order to provide a good representation of the operational conditions of the VVPSS in terms of initial pressure in the tank free space (close to vacuum conditions), initial water temperature, water head level inside the tank, sparger holes dimension and steam mass flow rate per hole (minimum and maximum steam mass flow rate per hole of the VVPSS has been covered during experimental tests).

The facility consists of eight main sub-systems, which are:

- The Superheated Steam Supply System (SSSS);
- The Flow Rate Control System (FRCS);
- The Condensation Tank System (CTS);
- The Auxiliary Tank (AT);
- The Vacuum System (VS);
- The Cooler System;
- The Degassed Water Supply System;
- The Data Acquisition and Control System;
- The Visualization and video recording system (VVRS).

The SSSS is constituted by an electrical steam generator of 130 kW provided in series by a heater (6 kW), able to deliver a maximum steam mass flow rate of 45 g/s at a pressure of 0.16 MPa and 150° C superheated steam temperature. During the operation, the steam generator automatically adjusts the power required to produce the requested steam mass flow.

The CTS is the main sub-system composed by the condensation tank (CT) and the sparger connected to it. This system, shown in Figure 3, has been designed in order to allow the experimental tests on DCC phenomena and monitor all the most affecting parameters.

The CT is a stainless steel cylindrical vacuum tight vessel (with thermal insulation) of 4.55 m\(^3\) with 1.40 m ID, 3.2 m height. Moreover it is provided with a pressure safety valve set at 0.149 MPa (abs) and a manhole located at the bottom (same level of the sparger hole exit) to allow its inside inspection and maintenance.

The water inside the tank can be heated-up directly with the injection of the superheated steam from the electrical generator and cooled down through the Chiller (operated at atmospheric pressure) or indirectly flowing cold water in the coil piping located all around the internal wall of the Vessel.

In order to monitor the most affecting parameters, the CT has been deeply instrumented.

Figure 4 - CTS with all the measurement sensor before insulation (left) and after walls insulation
The CT volume may be thought as subdivided in eight control layers (L2÷L9), whose data are provided in Table 1.

To measure temperature and pressure throughout the water volume the CT was instrumented with 28 temperature sensors (TE) (± 0.1 °C) and 8 pressure transducers (PE) (± 0.1 kPa). The water head level is measured (± 1 mm) by means of a differential pressure sensor level.

### Table 1: Layer dimensions and sensors’ position

| Layer ID | Height (m) | Free Volume (m³) | Located Sensors Temperature | Height Position (m) | W.H. H1.0 | W.H. H1.3 | W.H. H1.6 | W.H. H2.0 |
|----------|------------|-----------------|-----------------------------|---------------------|------------|------------|------------|------------|
| L2       | 0.425      | 0.5353          | TE102                       | PE102               | - 0.35     |            |            |            |
| L3       | 0.400      | 0.6863          | TE103, TE113, TE123, TE133  | PE103               | 0.00       |            |            |            |
| L4       | 0.400      | 0.6120          | TE104, TE114, TE124, TE134  | PE104               | + 0.40     |            |            |            |
| L5       | 0.400      | 0.6120          | TE105, TE115, TE125, TE135  | PE105               | + 0.80     |            |            |            |
| L6       | 0.350      | 0.5352          | TE106, TE116, TE126, TE136  | PE106               | + 1.20     |            |            |            |
| L7       | 0.350      | 0.5352          | TE107, TE117, TE127, TE137  | PE107               | + 1.50     |            |            |            |
| L8       | 0.350      | 0.5380          | TE108, TE118, TE128, TE138  | PE108               | + 1.90     |            |            |            |
| L9       | 0.425      | 0.4790          | TE109                       | PE109               | + 2.15     |            |            |            |
| Total    | 3.100      | 4.5330          |                             |                      |            |            |            |            |

The steam flows along an inner 2” pipe (electrically heated and thermally insulated) having a bottom cap drilled with holes of 10 mm diameter. The insulated outside surface is equipped with an electric heater system such to avoid steam condensation within the tube.

Figure 5 shows the bottom ends of sparger system.

![Figure 5](image_url)
sparger exit: the front camera is at about 1.00 m in front of the sparger exit; the left and right cameras are at 0.72 m left and 0.72 m right from the sparger exit.

The upper camera is fixed on the top of the condensation tank (and aligned along the axis) at about 2.40 m above the sparger exit. The data acquisition and control system program is coded upon LabVIEW© platform.

2.2 Description of test matrix

The test matrix was properly designed and organized in order to investigate extensively a wide range of technical parameters affecting the condensation of steam in water at sub-atmospheric pressure. In developing this matrix the following variables were investigated:

- Three sparger’s configurations: 1, 3 and 9 holes (indicated with notation 1H, 3H and 9H respectively) of 10 mm diameter each. The latter sparger pattern was designed to check the jets interaction effects.

- Two thermodynamic states of the steam: superheated and saturated.

- Three steam mass flow rates for each sparger configuration:
  - 1H: 1.5, 2.5 and 5 g/s (55 tests);
  - 3H: 4.5, 6.5 and 15 g/s (25 tests);
  - 9H: 13.5, 22.5 g/s and 45 g/s (25 tests).

- Five initial water temperature ($T_w$) values: 10, 20, 30, 40 and 50°C.

- Water head levels available in the CT.

In particular, the attention was focused on the possible influence of the sparger configuration, basically associated to the number of holes available for each sparger, on the condensation efficiency.

Experimental tests have been performed for each sparger configuration as follows:

- High temperature tests as first in order to handle water with low air solubility rates;
- Low temperature tests as second ones.

Finally it is to remark that the condensation tests sequence has been such to move progressively from the sparger configuration, with one hole to that with the nine holes.

3. Results discussion

Results presented and discussed therein following are mainly oriented to demonstrate the efficiency of the steam condensation at sub-atmospheric condition and/at condensation regime (definition and construction of steam condensation map) in order to demonstrate the capability of VVPSS to mitigate the accident scenario, e.g. ICE IV, and fulfill design criteria.

Figure 6 shows the time-dependent behaviour of the axial increment of water temperature in case of 1H, 3H and 9H sparger configurations, and for initial water temperature of 30°C.
Figure 6 - Axial temperature profile (1 min time step): each colored curve represent temperature trend acquired thorough the 15 min. test duration.
Because of direct contact condensation (DCC- heat energy transferred from steam to water at vapour-water interface), it is possible to determine the steam condensation rate and the condensation efficiency, at the prevailing conditions, on the basis of the accurate measurement of water average temperature increase ($\Delta T_W$) before and after the event of steam discharge.

The efficiency of the steam condensation was in all test conditions greater than 99.7 %. This value has been determined as follows:

$$PSF(\%) = 100 \cdot \left( 1 - \frac{\Delta P_{net}}{P_{st-eq}} \right)$$ (1)

where $P_{st-eq}$ is the pressure-equivalent of the discharged steam (calculated based on the perfect gas law) while $\Delta P_{net}$ is the net pressure change in the vacuum space.

For any test, the increase of the water temperature (longitudinal and radial profiles), of the pressure in the vacuum space above the water head and the jet shape allow to characterise the condensation regimes and the heat transfer processes is taking place into the water mass.

It was observed that for water temperature ranges from 10 to 50°C and steam mass flux form 12 to 64 kg/(m$^2$ s), four different steam condensation regimes have been identified (see Figure 7). In this condensation map, it is possible to recognize the following regimes:

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

Figure 7- The condensation regime map at sub-atmospheric pressure. The test points are shown with different symbols for each sparger patterns. The pressure in free space volume was maintained slightly above saturation pressure of the water at the prevailing temperature to avoid boiling at water head interface.
In identifying the condensation regimes (CR), an important contribution is given by the image analysis of the thermal mixing (steam jet recorded by the video cameras), induced by the steam discharge in the water tank. Figure 8 shows some photographs of the typical shape of the condensing steam plume observed through the video cameras installed within the CT.

![Figure 8 - Photos of the characteristic shape of the steam jets at exit hole for each identified condensation regime [13].](image)

At sub-atmospheric pressure the CR resulted mainly governed by the water temperature \( T_w \) and steam mass flux to downstream pressure ratio \( G_s/P_W \): the condensation map, as shown in Figure 9, comprises six main condensation regimes (together with regions’ boundaries), experimentally identified throughout the investigated parameters ranges. They are:
- **Chugging (C)**: when the vapour-water interface locates alternatively inside and outside the sparger
- **Transitional Chugging (TC)**: when the vapour-water interface locates outside the sparger in tank water, and the vapour core is characterized by short varying dimensions.
- **Bubbling Condensation Oscillation (BCO)**: when the steam condenses in form of bubbles with varying diameters, oscillating in dimensions and extension directions.
- **Condensation Oscillation (CO)**: characterized by a condensing steam jet variable (unstable) in the longitudinal extension.
- **Stable Condensation (SC)**: reached when a stationary condensing steam jet plume is established and is characterized by its stability. The jet plume does not change neither in length nor in radial extension.
- **Interfacial Oscillation Condensation (IOC)**: characterized by intermittent destruction (disappearance) of the separation interface between the steam core and water. It is characterized by a random changing plume shape.
Figure 9 - Experimental CR map: each condensation region is identified with a different colour and form, proper nomenclature. GP points identify the intersections of straights associated to each CR domain. Stable condensation appears at high Gs/Pw ratio for Tw from 30°C to 50°C.

The analysis of the steam condensation regime maps as a function of the downstream pressure shows that when Pw increases, the observed regions of the six condensation regime extend from the low Gs towards that with high Gs values [11]. As shown in Figure 9, the stable condensation appears at high Gs/Pw ratio for Tw from 30°C to 50°C, the reverse for unstable regimes.

Finally it has to remark that the identified condensation regimes are classified by analogy with those provided by Kuo-Shing Liang in [12] and by Chul-Hwa Song et al. [1]: consistency (and a good agreement was observed) among the compared experimental results was made by comparing the steam condensation data obtained at atmospheric pressure condition.

4. Conclusion

Results of the experimental campaign highlights:

- The water temperature increase rate for the same mass flow rate depends on the initial water temperature and the total mass of water in the tank.

- The total water temperature increase ΔTw depends on the water mass in the condensation tank, the total mass of steam discharged, and the initial water temperature. In particular, it is independent from the water head level, the steam mass flow rate and the number of sparger holes (no evidence of hole steam jet coalescence).

- TW and GS/PW are the two governing parameters of the steam condensation which determine completely the condensation regime in any given VVPSS operation state, as far as we deal with pure steam.

- No steam jet interference has been observed. The steam bubble coalescence for the sparger configuration examined (1, 3 and 9 holes) is thus very negligible.

- The condensation of steam through Direct Contact Condensation within the volume of cold water of the suppression tank is enhanced.
Finally the ITER VVPSS seems to be very effective in limiting the maximum pressure in the VV to 0.2 MPa during in-vessel coolant leak events and in maintaining the VV long-term pressure below atmospheric pressure during cat. IV event.

DISCLAIMER
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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