Direct condensation of steam in a water tank at sub-atmospheric pressures

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Abstract. In the nuclear fusion reactor, ITER, the Loss of Coolant Accident (LOCA) in the Vacuum Vessel has to be managed with pressure suppression systems working at sub-atmospheric pressure. The operating conditions differ considerably from those experienced in the fission nuclear power plants such as BWR. The direct condensation at sub-atmospheric conditions is not sufficiently known, therefore, the effectiveness of systems operating at these particular conditions have to be investigated experimentally.

A research program is being carried out at the University of Pisa, funded by ITER, in order to study the steam direct condensation for nuclear fusion reactor conditions. For this purpose, an experimental test facility was designed and built and an extended experimental program was performed. Video cameras were used to visualize the steam condensation at different mass flow rates.

This paper deals with the elaboration of images of the steam jet flowing from a hole in the water. The steam condensation regimes depend on three governing parameters: downstream exit pressure, water temperature and steam mass flow rate per hole. Moreover, the condensation regimes are characterized by different shapes of steam jet.

The image analysis permitted to determine the heat transfer coefficient in the stable condensation regime at sub-atmospheric conditions. The results obtained are compared with those correspondent at steam condensation at atmospheric pressure, emphasizing the great importance of the downstream exit pressure and the subcooling on the steam condensation.

1. Introduction

The ITER Vacuum Vessel Pressure Suppression System (VVPSS) is designed to protect the Vacuum Vessel (VV) from over pressurization caused by in-vessel coolant leakage. In particular, a Loss Of Coolant Accident (called also Inlet Coolant Event, ICE) is assumed to occur during the operation of the reactor.

The basic concept is based on the containment design of BWRs even if the Vapor Suppression Tanks (VSTs) operate at sub-atmospheric pressure (max. allowed pressure inside VV is 0.15 MPa). VVPSS is made of 4 VSTs each of which has a height of 4.7 m and diameter of 6.3 m and an overall inner volume of 100 m³, partially filled with water in order to condense directly the steam. Figure 1 illustrates the four tanks located at the level -2 of the reactor building.
In nuclear fusion reactor, the LOCA in the Vacuum Vessel has to be managed with pressure suppression systems working at sub-atmospheric pressure. The steam condensation in water at sub-atmospheric conditions is not sufficiently known. Therefore, the effectiveness of such systems have to be investigated experimentally. At the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, a research program, funded by ITER Organization, is being carried out in order to investigate and analyse the steam condensation regime in such operating sub-atmospheric conditions. To the aim, an experimental test facility was designed and built and an extended experimental program was performed. Video cameras were used to visualize the steam condensation at different mass flow rates, water temperatures and pressures.

An accidental scenario in ITER foresees superheated steam at about 130°C flowing in water contained in closed tanks at initial pressure of about 4 kPa and initial temperature of 30°C. It is evident that if this superheated steam (at about 130°C) condenses in a tank at atmospheric pressure it needs that it is cooled down at 100°C to condense (the subcooling is $\Delta T_{\text{sub}} \approx 30^\circ\text{C}$). However, at sub-atmospheric pressure in the tank, e.g. 17 kPa (considering the steam entering under a 1.3 m water head) and 30°C, the saturation temperature is about 55°C. The same superheated steam has to be cooled down at 55°C in order to condense. In fact in this case the subcooling is 2.5 times higher ($\Delta T_{\text{sub}} \approx 75^\circ\text{C}$). Therefore, it is necessary to determine how the steam condensation occurs when it flows in the water [1÷5].

The analysis of the images of the steam jet formed during the direct contact condensation from a hole in water permitted to determine, along with the acquired experimental measurements, the steam condensation regimes which depend on three governing parameters: downstream exit pressure, water temperature and steam mass flow rate per hole. Moreover, it was observed that the condensation regimes are characterized by different shapes of steam jet.

The image elaborations of 8 tests allowed to determine average heat transfer coefficients and steam jet lengths for stable condensation regime at different condensation conditions. The experimental results compared with the correlations valid for the condensation at atmospheric pressure, emphasized the great importance of the condensation driving potential, proportional to the subcooling.

![Figure 1. Location of the VST in the level -2 of the ITER plant.](image)

2. Condensation regimes at sub-atmospheric pressures

Experimental tests permitted to identify six main condensation regimes [1] [2] (based on the recorded video) which are:

- Chugging (C)
- Transitional Chugging (TC)
- Bubbling Condensation Oscillation (BCO)
Figure 2 and 3 show the shape of the steam jet obtained at different temperatures and mass flow rates per hole, respectively. Specifically, figure 2 displays the steam jet shape at 20°C (figures 2.a and 2.b) and 50°C (figures 2.c and 2.d) for the same mass flow rate per hole (i.e. 5 g/s), considering sparger at one and three holes: at 20°C the condensation regime is Stable (SC), while at 50°C the regime is Condensation Oscillation.

Figure 3 shows the influence of flow rate on the condensation regimes at constant water temperature (T_w=50°C). A flow rate of about 1 g/s per hole (figures 3.a and 3.b) determines Chugging or Transitional Chugging; a flow rate of about 4 g/s (figure 3.c) per hole results in Condensation Oscillation (CO). The elaboration of recorded videos, joint with the measurement of the water average temperature(T_w), downstream pressure (P_w) and mass flow rate (Q) have permitted to obtain a map of condensation regimes (CR), as shown in figure 4, where G (kg/m^2s) is the steam mass flow rate per unit of hole area.
3. Heat transfer coefficients of the steam direct condensation at sub atmospheric pressures

The average heat transfer coefficient of the steam condensation, assuming a uniform heat flux at the interface area, is defined by using the thermal balance equation:

\[ h_{ave} = \frac{G A_e (H_s - H_f)}{A_i (T_s - T_w)} \]  

- \( h_{ave} \) is the average heat transfer coefficient, W/(m\(^2\)K);
- \( G \) is steam mass flux, kg/(m\(^2\)s);
- \( A_e \) and \( A_i \) are the area of the sparger hole and of the jet surface, respectively;
- \( T_s \) and \( T_w \) are the steam and water temperature in °C, respectively; and
- \( H_s \) and \( H_f \) are the steam and water enthalpy in J/kg, respectively.

\( h_{ave} \) is determined once the surface of the steam jet at the steam-water interface is known, being the other physical variables measured during tests and the area of the sparger hole fixed. \( A_i \) can be determined elaborating the videos recorded by four cameras (figure 5) during the condensation tests. Three of these cameras are located at the level of the sparger hole. Two of these look laterally the steam jet while the third is located in front of the jet. The fourth camera looks the free surface of the water. It is located on the upper part of the vacuum space, in correspondence of the vessel axis. The videos recorded by lateral cameras are idoneous to determine the jet surface, assuming an axial symmetric shape. An open source software of image elaboration (ImageJ-National Institute Health-USA) has been used to determine the profile of steam jet. The profile has been elaborated, determining the symmetry axis and the area of surface obtained rotating both half profiles (upper and lower one) around the axis. The two area values have been averaged giving an effective steam jet surface area.
The sampling frequency of videos is 120 Hz while the physical variables (temperature, pressure and flow rate) are sampled at 1 Hz. Steady state tests lasted till the average temperature of the water increase of about 2 °C (for several tests the duration was about 15 min). In these tests two fragments of video were recorded: the first fragment for two minutes from the start of test and the second fragment records the last two minutes of the test.

Different instants of the time in the two fragment of the video have been considered, for tests in stable condensation regimes. Eleven frames of the 120 corresponding at one second have been considered and elaborated by means of the image elaboration software, considering the median of the 11 image stack. In this manner one value of steam jet surface per 1 second has been determined and correlated to the own physical variables.

Table 1 illustrates the main data of the eight tests considered. In the column, the variable are the water pool temperature ($T_w$), the downstream pressure at injection hole level ($P_w$), the injection hole depth (H), the steam mass flow rate injected (Q), the steam pressure and temperature upstream the hole (inside the sparger), $P_s$ and $T_s$ respectively. In order to verify the variability of the jet profile in 1 second, the eleven frames have been singularly elaborated determining the jet steam profile, the surface area and the heat transfer coefficients. The elaboration of the test 3123, of eleven frames between 10 and 11 s, with steam jet profiles is shown in figure 6.

Table 1. Main data of the tests in stable condensation regime.

| Test n. | $T_w$ (°C) | $P_w$ (kPa) | H (m) | Q (g/s) | $P_s$(kPa) | $T_s$ (°C) |
|---------|------------|-------------|-------|---------|------------|------------|
| 3123    | 31.27      | 30.88       | 1     | 4.99    | 49.7       | 135        |
| 3133    | 31.288     | 39.97       | 1     | 4.93    | 57.01      | 135        |
| 3143    | 30.65      | 50.57       | 1     | 4.98    | 65.50      | 133.21     |
| 3223    | 29.95      | 36.36       | 1.6   | 5.02    | 54.49      | 132.6      |
| 3233    | 32.29      | 46.4        | 1.6   | 4.99    | 62.39      | 135        |
| 4123    | 40.71      | 30.63       | 1     | 4.99    | 51.2       | 126.75     |
| 4223    | 39.44      | 36.2        | 1.6   | 4.99    | 55.39      | 125.92     |
| 5123    | 49.66      | 30.18       | 1     | 4.98    | 52.73      | 135        |

The average length of the steam jet and its standard deviation are 24.7 mm and 1.45 mm, respectively. The jet length oscillates at a frequency of about 5 Hz. Obviously the same oscillation is verified for the value of the jet area and HTC (figure 7). The average values and standard deviations of jet area and HTC, during 1 s of transient are:

Jet area: 898 mm$^2$ – $\sigma$=150.9 mm$^2$

HTC: 273 kW/m$^2$k - $\sigma$=51.9 kW/m$^2$k

Figure 6. Profiles of steam jet.
Figure 8 illustrates the 3D reconstruction of the steam jet surfaces corresponding to 1 s. As it can be clearly seen, the shapes of steam jet repeat periodically. The elaborated tests reported in Table 1 correspond to regimes of superheated steam stable condensation. The tests have been performed at steady state conditions.

The steam mass flow rate is equal in all the tests (~5 g/s). The first 5 tests correspond at same value of water pool temperature and differ for the downstream pressure, which ranges between 30-50 kPa. The other three tests correspond to a greater pool temperature (40 and 50°C respectively). In the stable condensation, the steam jet is always present and its shape has small variation.

For each test, several instants of time have been considered, elaborating the jet profile, to determine the area of the correspondent 3D surface and the HTC (by equation 1).

The results are summarized in Table 2, where the average values obtained during the tests and the standard deviation are reported. The main parameter of the steam direct condensation is the condensation driving potential B, defined by the equation:

\[ B = \frac{C_p \Delta T_{sub}}{H_{fg}} \]  

(2)

C_p is the isobaric specific heat, \( \Delta T_{sub} \) is the subcooling and \( H_{fg} \) the latent heat of vaporization.

Figure 9 illustrates the HTC and the steam jet length – hole diameter ratio versus the parameter B. The following empirical relations have been determined by means of experimental results of tests showing mass flux (G) and critical mass flux (G_0) almost constant:

- for the heat transfer coefficient:
  \[ h_{ave} = 18284B^{1.8703} \]
  (3)

- for the steam jet length –hole diameter ratio:
  \[ \frac{L}{D} = 0.0844B^{-1.337} \]
  (4)

**Figure 7.** Steam jet length, surface area and HTC versus time in a time interval of 1 s (test n.3123).

**Figure 8.** 3D reconstruction of the steam jet surfaces corresponding to 1 s (test n.3123).
4. Discussion of the experimental results

Theoretical and empirical correlations of the average HTC and L/D ratio were determined. Kim et al. [6] proposed (for horizontal and vertical nozzles with diameter in the range 5-20 mm; steam mass flux, $G$, in the range 250-1188 kg/m$^2$s and pool water temperature in the range 35-80 °C) the following empirical equation:

$$ h_{ave} = 1.4453 C_p G_m B^{0.03587} \left(\frac{G}{G_m}\right)^{0.13315} \quad (5) $$

Yeon et al. [7] proposed a similar correlation with different coefficients (for horizontal nozzles having diameter in the range 1.35-7.65 mm, steam mass flux up to 1500 kg/m$^2$s and pool water temperature in the range 13-87 °C):

$$ h_{ave} = 1.3583 C_p G_m B^{0.0405} \left(\frac{G}{G_m}\right)^{0.3714} \quad (6) $$

where $C_p$ is the isobaric heat capacity and $G_m$ is the critical mass flow per unit of area (Kg/s m$^2$) rate given by:

$$ G_m = C_D \left(\frac{P_s \rho_s}{\gamma} \right)^{\frac{1}{\gamma+1}} \quad (7) $$

being $C_D$ the efflux coefficient which ranges between 0.8-1; $P_s$ and $\rho_s$ are the pressure and density of steam respectively; $\gamma=1.4$, the ratio of isochoric and isobaric heat capacity.

**Table 2.** Average steam jet length (L), surface area (JA) and HTC in SC

| Test n. | L (mm) | $\sigma_L$ (mm) | JA (mm$^2$) | $\sigma_{JA}$ (mm$^2$) | HTC(kW/m$^2$K) | $\sigma_{HTC}$ (kW/m$^2$K) |
|---------|--------|----------------|-------------|-----------------------|----------------|-------------------|
| 3123    | 31     | 3.28           | 943         | 104                   | 136            | 15.54             |
| 3133    | 28     | 5.04           | 887.7       | 178.1                 | 144.96         | 27.13             |
| 3143    | 18.88  | 0.16           | 622         | 7.8                   | 205            | 2.58              |
| 3223    | 21.49  | 0.84           | 595.3       | 6.32                  | 215.6          | 6.32              |
| 3233    | 19.56  | 0.26           | 647         | 63.2                  | 197.2          | 20.2              |
| 4123    | 41.87  | 1.47           | 1886.7      | 112.3                 | 79             | 3.88              |
| 4223    | 31.1   | 0.7            | 1199        | 66                    | 124            | 8.82              |
| 5123    | 70.99  | 3.87           | 4422        | 282                   | 33.83          | 2.24              |

In the tests performed at sub-atmospheric pressure the value of $G$ which determines stable condensation is about 10 times smaller than that correspondent at atmospheric pressure [1][2]. These tests have been performed at about 5 g/s which corresponds to a value of $G=63.7$ kg/m$^2$s. This value is small with respect that used for determining the correlations (5) and (6). These correlations applied at the conditions of our tests give a $h_{ave}$ value greater than the experimental one of a factor 2.5. Moreover, the correlations (5) and (6) give a negligible dependence on the condensation driving potential $B$ respect that determined in the tests (see equation (3)). The two correlations (5) and (6) have been modified using the exponent of $B$, given by the equation (3), and a different constant:

$$ h_{ave} = 52.3248 C_p G_m B^{1.8703} \left(\frac{G}{G_m}\right)^{0.13315} \quad (8) $$

$$ h_{ave} = 56.5493 C_p G_m B^{1.8703} \left(\frac{G}{G_m}\right)^{0.3714} \quad (9) $$

Analogously, the correlations for the evaluation of the jet length determined for direct condensation at atmospheric pressure do not represent the actual dependence on the parameter $B$, even if they give values quite similar at those obtained by our tests. Chul et al. [8] proposed the following correlation:

$$ L/D = 0.503 \times B^{-0.70127} \left(\frac{G}{G_m}\right)^{0.47688} \quad (10) $$

Kim et al. [7] proposed the correlation:
\[ L/D = 0.5923 \times B^{-0.66} \left( \frac{G_0}{G_{m}} \right)^{0.3444} \]  

(11)

L is the steam jet length, D is the nozzle internal diameter and \( G_0 \) is the steam mass flux in kg/(m\(^2\) s) at the nozzle exit condition.

Considering the dependence on B, defined by the equation (4) and modifying the constant in appropriate manner equations (10) and (11) become:

\[ L/D = 0.0992 \times B^{-1.377} \left( \frac{G}{G_{m}} \right)^{0.47688} \]  

(12)

\[ L/D = 0.0853 \times B^{-1.377} \left( \frac{G_0}{G_{m}} \right)^{0.3444} \]  

(13)

Figure 9. Heat Transfer coefficient (a) and L/D (b) versus the condensation driving potential B.

It is considered that constant mass flux experimental data (63.7 kg/m\(^2\) s), on which the modified correlations are based, do not affect significantly the correlations validity, because the driving parameter of sub-atmospheric condensation is the parameter B (mainly related to the water subcooling). In addition, the validation of modified correlations for various mass flux values is planned to be carried out and published in subsequent research activities.

Figure 10 shows the comparison between the results obtained by the modified correlations for HTC, eq. (8) and (9), and L/D eq. (12) and (13) with the experimental results, in (a) and (b) respectively. Lines inclined of 45° represent the equality between the theoretical and experimental data: the good agreement of these data shows also the strong dependence of the steam condensation on the driving potential B.

Figure 10. Comparison between the experimental values of HTC (a) and L/D (b) and the values predicted by modified empirical correlations (equations (8), (9) and (12), (13), respectively).
5. Conclusions
This paper illustrates the elaboration of the images of the steam jet which condenses in a water pool at sub-atmospheric pressures. The analysis has permitted to determine the steam condensation regimes which depend on three governing parameters: downstream exit pressure, water temperature and steam mass flow rate per hole.

Eight tests carried out in stable condensation regime were analysed evaluating the average heat transfer coefficients and steam jet length. Their correlations were determined and compared with those valid in direct condensation at atmospheric pressure. These correlations do not fit the greater importance that the condensation driving potential has in the condensation at sub-atmospheric pressures.

The tests performed are useful to qualify the VVPSS of nuclear fusion reactors.

References
[1] Mazed D et al. 2018 Experimental investigation of steam condensation in water tank at sub-atmospheric pressure, *Nuclear Engineering and Design* 335 (2018), 241-254.
[2] Mazed D et al. 2016 Experimental study of steam pressure suppression by condensation in a water tank at sub-atmospheric pressure, *Proceedings ICONE24*, June 26-30, Charlotte (USA).
[3] Lo Frano R et al. 2017 Methodology to investigate vibration phenomena caused by the steam condensation at sub-atmospheric condition, *Proceedings ICONE25*, Vol. 5, 2-6 July, Shanghai (China).
[4] Lo Frano R et al. 2017 Experimental investigation of functional performance of a vacuum vessel pressure suppression system of ITER, *Fusion Engineering and Design* 122 (2017) 42-46.
[5] Lo Frano R et al. 2016 Fluid dynamics analysis of loss of vacuum accident of ITER cryostat, *Fusion Engineering and Design* 109–111 (2016) 1302–1307.
[6] Kim H Y et al. 2001 Experimental study on stable steam condensation in a quenching tank, *International Journal of Energy Research* Vol. 25, pp. 239-252.
[7] Kim Y S et al. 1997 An experimental investigation of Direct Condensation of Steam Jet in Subcooled Water, *Journal of the Korean Nuclear Society* Vol. 29, Number 1, pp. 45-57.
[8] Chul et al. Characterization of Direct Contact Condensation of Steam Jets discharging into subcooled water, Korea Atomic Energy Research Institute.