Study of steam condensation at sub-atmospheric pressure: setting a basic research using MELCOR code

A Manfredini and M Mazzini
ACTA Srl Via di Torretta snc, 56122 – Pisa

E-mail: mazzini@ing.unipi.it

Abstract. One of the most serious accidents that can occur in the experimental nuclear fusion reactor ITER is the break of one of the headers of the refrigeration system of the first wall of the Tokamak. This results in water-steam mixture discharge in vacuum vessel (VV), with consequent pressurization of this container. To prevent the pressure in the VV exceeds 150 KPa absolute, a system discharges the steam inside a suppression pool, at an absolute pressure of 4.2 kPa. The computer codes used to analyze such incident (eg. RELAP 5 or MELCOR) are not validated experimentally for such conditions. Therefore, we planned a basic research, in order to have experimental data useful to validate the heat transfer correlations used in these codes. After a thorough literature search on this topic, ACTA, in collaboration with the staff of ITER, defined the experimental matrix and performed the design of the experimental apparatus. For the thermal-hydraulic design of the experiments, we executed a series of calculations by MELCOR. This code, however, was used in an unconventional mode, with the development of models suited respectively to low and high steam flow-rate tests. The article concludes with a discussion of the placement of experimental data within the map featuring the phenomenon characteristics, showing the importance of the new knowledge acquired, particularly in the case of chugging.

1. Introduction
One of the most serious accidents that can occur in the experimental nuclear fusion reactor ITER is the break of one of the headers of the first wall cooling system of the Tokamak. This results in water-steam mixture discharge in vacuum vessel (VV), with consequent pressurization of this container. To prevent the pressure in the VV exceeding 150 KPa absolute, a venting system discharges the steam inside a Suppression Pool (SP). The design foresaw initially the use of 24 spargers, each with about thousand holes of 10 mm diameter, venting the steam under a water head between 1 m and 2 m. (It has to be noted that at present the solution adopted by ITER Organization for VVPSS is different, but the range of steam flowrate per unit area of the sparger remains about the same).
Ultimately it is an accident similar to that of LB-LOCA in a BWR, with the important difference that the suppression pool in ITER is initially at a sub-atmospheric pressure of 4.2 KPa.
The computer codes used to analyze such accident (e.g. RELAP 5 or MELCOR) are not validated experimentally for such conditions. Therefore, during a meeting with the staff of ITER, the Director of the DIMNP of the University of Pisa and ACTA Srl, M. Mazzini proposed to run a basic experimental research on the phenomenology now mentioned, in order to have experimental data useful to validate the heat transfer correlations used in these codes.
The main objectives of the research program were:
- the clear understanding of VVPSS prototypical thermal-hydraulic (TH) conditions impact on direct contact condensation: bubble formation, bubble condensation, bubble size distribution, bubble rise velocity, potential for bubble coalescence, etc.
• to acquire data for thermal hydraulic code qualification.

As already stated, the phenomenological basis of VVPSS behavior cannot be considered completely covered by previous experience, due to the fact that the VVPSS thermal-hydraulic conditions are rather unique:

- initial pressure of SP free space: 4.2 kPa
- steam pressure at VVPSS inlet: 106-150 kPa
- SP initial water temperature: 280-300 K
- steam flow-rate into the suppression pool: 0.3-5 g/s per sparger hole (corresponding to a total flow-rate in the range 5-100 kg/s)
- water head above the exit hole: 1-2 m

The experimental steam flow-rate range was established taking into account the results of the MELCOR calculations of the reference accident (Fig. 1) and the possibility of a not uniform distribution of the steam among the 24 spargers.

After a thorough literature search on this topic, ACTA, in collaboration with the staff of ITER, defined the experimental matrix and performed the design of the experimental apparatus.

The experimental equipment is extremely simple: a container of adequate size, initially at a pressure of 4.2 KPa absolute, in which a pipe discharges steam at specified conditions of pressure and temperature, through one or more holes of 10 mm diameter. Of course, the equipment includes the required systems for steam flow generation, realization of vacuum, water temperature and level adjustment in the condensation tank, in addition to the instrumentation and control systems.

For the thermal-hydraulic of the experiments, a series of calculations was executed by the MELCOR code.

![Figure 1: Trends of steam flow-rate in VVPSS in case of DBA in ITER plant](image)

2. Bibliographic research

The bibliographic research aimed at the understanding the fundamental characteristics of a condensation jet and the resulting thermal mixing in a subcooled water pool.
To analyse the thermal mixing induced by a steam discharge into a pool, it is essential to understand the phenomena occurring in a condensing jet. Both the thermal aspects and the hydraulic ones must be studied.

When the steam jet penetrates into a water pool, it entrains liquid from the pool water and induces a turbulent jet, the velocity of which decays slowly along its axial distance. The pool water entrained into the vapour core forms a two-phase mixture jet region. Therefore it is important to consider the interfacial transfer of mass and energy.

When the pool temperature increases or the steam mass flux decreases, the circulation flow pattern induced by the horizontal turbulent jet diminishes and a buoyant plume appears distinctively near the sparger due to the increased effect of buoyancy and/or the decrease of condensation efficiency.

In general, the behaviour of a steam condensing jet immersed in a pool of water is characterized by three distinct regions:
1) The steam core or cavity of vapour,
2) The mixing region, with “vapour entrapment” and “liquid entrainment” phenomena,
3) The region of turbulent jet generated by the condensation of the jet.

These can be described by introducing some characteristic parameters that include the form of the steam jet, the jet expansion rate or the length of penetration, the distribution of temperature within the vapour cavity, the features of the turbulent jet, etc..

In particular, high condensation rates are achievable thanks to the high temperature difference between the two phases.

The condensation process can directly generate instability at the interface of condensation, which is inherently unstable in a macroscopic sense and may be more unstable in some conditions.

Actually, in practical applications in nuclear technologies at atmospheric pressure, the behaviour of a vapour jet in a condensation pool is generally governed by two factors: the steam mass flow rate for unit area at the exit hole and the temperature of the pool water Tp. The experimental observation shows also that, at atmospheric pressure, the shape of the vapour cavity is rather random and condensation instabilities of various type occur for mass flow-rates lower than 270 kg/s.m² in the entire temperature range tested. With a mass flow-rate higher than 300 kg/s.m², instead, the steam jet becomes stable. In this case, the shape of the cavity of the steam jet is conical or ellipsoidal, depending on the mass flow and the temperature of the pool. Also the temperature of pool water has an important effect on the thermal-hydraulic behaviour of the condensing steam. These two factors are used for the construction of stability maps, that effectively represent a reference for the results of many studies (References (1), (2), (3), (4), (5), (6)). In particular, Cho et al. proposed a map covering a wide range of mass flows of steam and temperature of the pool (Fig. 2). The condensation regimes are classified into the following types: chugging (C), transitional chugging (TC), condensation oscillation (CO), bubbling (BCO), stable condensation (SC) and interfacial condensation oscillation (IOC). The researchers recorded the highest noise and higher vibrations in unstable condensation regimes, such as chugging and condensation oscillation.

Typically, the single phase turbulent jet becomes a nearly flat, turbulent front and a mixing layer forms at the tip of the nozzle exit. In the region close to the nozzle, the turbulence penetrates inward toward the axis of the jet and forms a wedge-like region, with the potential core surrounded by a mixing layer. In the fully developed region, the turbulence penetrates to the axis and the potential core disappears. Down-stream of the potential core, the flow begins to develop into the Gaussian shape of a velocity profile, which reaches and maintains a self-preserving shape. This asymptotic self-similarity of the free turbulent jet flow is normalized reasonably well with its maximum values and characteristic width. The static pressure in the jet core region is below the surrounding fluid pressure and the fluid is entrained considerably as the jet travels forward, and then the mass flow of the jet increases downstream.
This introduces another point of view, which underlines that the dynamic pressure characteristics determine the stability of the jet of steam. The dynamic pressure shows a trend that is strictly dependent on the mass flow-rate of steam and the temperature of the pool water.

The pressure load increases gradually with the increase of the steam mass flow-rate in the CO scheme, but decreases rapidly in case of higher undercooling (Tp = 30°C or 40°C); lower pressure loads indicate that the steam jet is condensed with efficiency and stability. On the contrary, with a very low sub-cooling (Tp higher than 90°C), at atmospheric pressure, the condensation of steam is inefficient, and this causes a small change of the pressure loads. Experimental data show that the interference of the steam with water during the condensation process is stationary until the temperature is low and the steam mass flow-rate is high. At high temperature of the pool water, the rate of condensation at water-steam turbulent interface is reduced below that necessary to condense the steam.

Besides, one can observe that the effect of non-condensable gases, either on steam condensation or on the resulting dynamic pressure, is very pronounced.

The rate of condensation is limited by the effectiveness of the thermal diffusion process from the interface to the mass of the liquid; in turn, it depends on the intensity of turbulence on the liquid side and therefore on the distribution of water temperature in the pool. The local temperature distribution is an effect of the turbulent mixing due to the jet, of the pool water circulation and of stratification due to gravity.

Predicting the thermodynamic behaviour of the steam discharged in a pool requires, in general, three-dimensional analysis capabilities.

![Figure 2: Map of the various regimes of steam condensation as a function of pool temperature and steam specific mass flow-rate](image)

3. Planned experimental matrix
With respect to the experimental ranges indicated in the introduction, due to the limited funding available, the minimum test flow-rate has been established to 0.5 g/s (for characterizing the VVPSS behavior during the last part of VV depressurization transient - Fig. 1). This low value of steam flow-rate is applied only to experiments with the lower head of water above the sparger hole: 1.3 or 1.6 m (we did not consider tests with water head above the exit hole of 1 m). The value of 2.5 g/s corresponds to the mean flow-rate foreseen during the first 500 s of this transient, while the value of 5 g/s overcomes the maximum steam flow-rate, also considering possible not uniform distribution of steam among the various spargers.

The test matrix (Table 1) comprises 3 series of test sequences:
A. 1 Hole of 10 mm diameter
B. 3 Vertical Holes of 10 mm diameter and pitch equal to actual sparger
C. 9 Holes of 10 mm diameter and pitch equal to actual sparger.

The results of the first series of test sequences will constitute the data basis needed for the validation of the computer codes used for simulating VVPSS behavior. Besides, they will give important information on related phenomena (bubble formation, bubble condensation, bubble size distribution, bubble rise velocity, potential for bubble coalescence, etc.), as well as on possible dynamic loads originated by the steam condensation. Apart from the above-mentioned limitations about the hydraulic head, they cover the whole spectrum of foreseen TH conditions.

The following series B and C are aimed at investigating possible interaction between one hole and the neighboring holes, firstly in one dimension (series B) and finally in two dimensions (series C). In these series, the test TH conditions are limited to those more prototypical of VVPSS behavior. Actually, each experiment is a sequence of 4 or 5 tests (depending from the water temperature foreseen for the beginning of the sequence). Each test sequence will be executed with the following procedure.

The condensation tank will be filled with normal water at the temperature foreseen for the sequence (10 or 20 °C), up to the specified level (according with the values foreseen in the test matrix). Thereafter the vacuum system will establish the required pressure in the SP free volume, the test will be started injecting steam at the specified value of steam flow-rate in the condensation tank. After 15 minutes of stationary conditions, the test will be finished, isolating the condensation tank. The pool water temperature will be increased of 10 °C with respect to the previous test value, achieving the new test initial conditions. Immediately after, the new test will start with the same modalities. This last part of the procedure will be repeated two or three times, completing the test sequence.

4. Thermal-hydraulic design of tests

A sketch of the model, initially set up for the MELCOR code to simulate the VVPSS experimental apparatus, is rather conventional, as shown in Fig. 3. However, this model results in a prompt mixing of all the pool water, with very limited increases of the temperature anywhere. Thereafter, a preliminary effort was done, studying both experimentally and analytically, by the use of a CFD code, the discharge of air in a water pool. These runs showed that:
- at low flow-rate (0.3-1 g/s), small bubbles of air form at the hole exit, moving immediately upward along the vent pipe;
- at high flow-rate (2.5-5 g/s), a jet forms pushing away the water in front of the exit hole.

This confirms the conclusions drawn from the bibliographic research: it is very important to accurately simulate the two different steam condensation modalities, "forced jet" and "buoyant plume", which directly affect the mass transfer from the steam cavity to the surrounding fluid.

On the basis of these observations, a new nodalization was set-up for the condensation pool; Figures 4 and 5 show respectively its vertical and horizontal sections in correspondence to the steam injection volume (named CV105). In this second nodalization we split the condensation pool into 114 control volumes interconnected by appropriate junctions (a total of 342), such as to simulate the steam jet.
dispersion along the directions more relevant. In particular, as shown in Fig. 4, we split the pool volume in 6 slabs with the same number and layout of control.

Table 1. Initial conditions of the various series of basic experiments

| Series | Test no. | Sparger inlet | Condensation tank |
|--------|----------|---------------|-------------------|
|        |          | Pressure | Steam flow-rate | Water temp. | Water level |
| A) 1 Hole 10 mm | 1 | < 150 kPa, s.h. | 0.3 g/s | 10 °C | 1.3 m |
|        | 2 | < 150 kPa, s.h. | 2.5 g/s | 10 °C | 1.3 m |
|        | 3 | < 150 kPa, s.h. | 2.5 g/s | 20 °C | 1.3 m |
|        | 4 | < 150 kPa, s.h. | 5.0 g/s | 10 °C | 1.3 m |
|        | 5 | < 150 kPa, s.h. | 0.3 g/s | 10 °C | 1.6 m |
|        | 6 | < 150 kPa, s.h. | 2.5 g/s | 10 °C | 1.6 m |
|        | 7 | < 150 kPa, s.h. | 5.0 g/s | 10 °C | 1.6 m |
|        | 8 | < 150 kPa, s.h. | 2.5 g/s | 10 °C | 2.0 m |
|        | 9 | < 150 kPa, s.h. | 5.0 g/s | 10 °C | 2.0 m |
|        | 10 | < 150 kPa, sat. | 2.5 g/s | 10 °C | 1.3 m |
|        | 11 | < 150 kPa, sat. | 2.5 g/s | 10 °C | 1.6 m |
|        | 12 | < 150 kPa, sat. | 2.5 g/s | 10 °C | 2.0 m |
| B) 3 Holes 10 mm | 13 | < 150 kPa, s.h. | 0.3 g/s | 10 °C | 1.3 m |
|        | 14 | < 150 kPa, s.h. | 2.5 g/s | 10 °C | 1.3 m |
|        | 15 | < 150 kPa, s.h. | 5.0 g/s | 10 °C | 1.3 m |
|        | 16 | < 150 kPa, s.h. | 2.5 g/s | 10 °C | 2.0 m |
|        | 17 | < 150 kPa, s.h. | 5.0 g/s | 10 °C | 2.0 m |
| Series | Test no. | Sparger inlet | Condensation tank |
|--------|----------|---------------|-------------------|
|        |          | Pressure      | Steam flow-rate   | Water Temp. | Water level |
|        |          | 150 kPa, s.h. | 0.3 g/s           | 10 °C       | 1.3 m       |
|        |          | 150 kPa, s.h. | 2.5 g/s           | 10 °C       | 1.3 m       |
|        |          | 150 kPa, s.h. | 5.0 g/s           | 10 °C       | 1.3 m       |
|        |          | 150 kPa, s.h. | 2.5 g/s           | 10 °C       | 2.0 m       |
|        |          | 150 kPa, s.h. | 5.0 g/s           | 10 °C       | 2.0 m       |

Notice: the steam flow-rate is that of each sparger hole. The water level is that above the simulated sparger hole centerline.

Notice: the steam flow-rate is that of each sparger hole. The water level is that above the simulated sparger hole centerline.

Figure 3: First nodalisation of the condensation pool for MELCOR code.

Volumetric, but with different heights: the first slab goes from 0 m to 0.2 m; the second from 0.2 m to 0.4 m; the third from 0.4 m to 0.6 m; the fourth from 0.6 m to 1 m; the fifth one from 1 m to 2 m; the sixth from 2 m to 3.2 m. In this way the zone closest to the injection hole/s, simulated by smaller control volumes, is described in a greater detail. The same principle was applied to the control volumes subdivision in the horizontal plane, as shown in Fig. 5. The volumes immediately adjacent and nearest to the injection hole/s were shaped with a rectangular basis of 0.2 x 0.22 m$^2$ up to the opposite wall of the tank. A total of 15 of these small volumes are present for each plan. Excess space was modeled with much broader control volumes, taking also into account the cylindrical form of the tank. Applying to the junctions appropriate values of the local, direct $k_d$ and reverse $k_r$ pressure drop coefficients (i.e., $k$ values up to three orders of magnitude higher than those for the junctions on the
sides of the control volume that correspond to the jet direction), we can effectively simulate the jet formation, the natural circulation induced by steam condensation and the energy released from the latter.

Due to the intrinsic characteristics of MELCOR code, the steam condensation is complete in all the simulation, but the effects of the steam jet for the higher flow-rates seem simulated adequately.

| CV502 | CV505 | CV506 | CV507 | CV508 | CV509 |
|-------|-------|-------|-------|-------|-------|
| CV402 | CV405 | CV406 | CV407 | CV408 | CV409 |
| CV302 | CV305 | CV306 | CV307 | CV308 | CV309 |
| CV202 | CV205 | CV206 | CV207 | CV208 | CV209 |
| CV102 | CV105 | CV106 | CV107 | CV108 | CV109 |
| CV002 | CV005 | CV006 | CV007 | CV008 | CV009 |

Figure 4: Vertical section of the condensation pool in the second nodalization

Some calculation results are reported in Figure 6 for a high flow-rate test. The calculation is done with 600 s of stationary initial conditions; at this moment the test starts, with the injection of steam in the CV105 volume. The effects of the steam induced turbulence and of natural circulation correspond to a quick water temperature increase in the steam discharge volume (CV105) and in the two forward volumes (CV106 and CV107), while the rest of the pool has slower and modest increases of temperature.

Analogously, we tried to simulate the buoyant plume, which develops for small steam flow-rates, as shown in Fig. 7. A small peak in water temperature occurs initially in the discharge volume CV105, but the heating of all other volumes is very low.
5. Concluding Remarks

In the attempt of generalize the results of the research, we tried to derive from Figure 2 a more general map, considering instead of pool temperature the “nominal” degree of sub-cooling $\Delta T$. This quantity is calculated assuming as reference saturation temperature 100°C, because all the experiments of Fig. 2 were performed at ambient pressure. The new map is shown in Fig.8, where also the points corresponding to the tests foreseen in this research are indicated.

The experiments carried-out at the lower flow-rate are all concentrated in the chugging zone, while the others at intermediate or greater flow-rates lie mostly in the transitional chugging zone. Only a few tests, carried out with the condensing pool at a temperature of 50 °C (and therefore with the lower subcooling) should enter in the bubbling zone.

The experimental results will extend the map in a considerable way with respect to the previous situation toward the lower flow-rates. This is particularly interesting, because it corresponds to the occurrence of chugging and transitional chugging.

It has to be noted that the experimental team, together with the new representatives of ITER Organization, presented at ICONE 24 the results of the tests actually carried out (Ref. (7)). These showed a behaviour sometimes different from that presented in Fig. 2: at sub-atmospheric pressure,
the region of stable condensation is largely extended (a factor of about 5) toward the lower steam flow-rates, while the areas of chugging, transitional chugging and condensation oscillations are highly reduced. Good news, from the safety point of view.

Chugging can generate noticeable, negative pressure peaks, which shall be taken in due account in the design of the condensing apparatus: the VVPSS of the ITER plant. Obviously, MELCOR cannot reproduce these pressure spikes, due to its nature of lumped parameters thermal equilibrium code. The steam condensation should occur in all the tests. The mean temperature increase in the condensation pool in all test is limited to 1 or a few °C, due to the modest energy injection. The related experimental results will be particularly useful for the validation (or the modification) of the correlations used in the codes of thermal-hydraulic design of the VVPSS of the ITER plant.

The last observation concerns the possibility of simulating by MELCOR the natural circulation patterns, which develop in the condensing pool at low and high steam flow-rates, both in clock wise and in counter-clock wise sense. These effects can be reproduced also by a lumped parameter code, if properly used.

![Figure 8: Map of various regimes of steam condensation as a function of pool sub-cooling and steam specific mass flow-rate](image)

6. Acknowledgements
The authors acknowledge ITER Direction, and particularly Ing. Sergio Orlandi, for making possible this publication and for the useful suggestions for its final drawing. Thanks are due also to Mr. Mike Meekins, at the time ITER responsible of the VVPSS research for his contribution to the set-up of the experimental matrix. Finally, we thank very much Mr. Marco Galassi, who executed the MELCOR calculations inside his degree thesis in nuclear engineering, contributing also to the issue of this article.

7. Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. The results should be considered preliminary until they are accepted by the ITER licensing agency.
References

[1] Fukuda S 1982 J. Nucl. Sci. Tech. 24 pp 466–474
[2] Narai H and Aya I 1986 J. Nucl. Eng. Des. 95 pp 35–45
[3] Chun M H, Kim Y S and Park J W 1996 Int. Con. Heat Mass Transfer 23 pp 947–958
[4] Petrovic A, Calay R K and De With G Int. J. Heat Mass Transfer 50 pp 1762–1770
[5] Wu X Z, Yan J J, Shao S F, Cao Y and Liu J P 2007 Int. J. Multiphase Flow, 33(12)  pp 1296–1307
[6] Wu X Z, Yan J J, Li W J, Pan D D and Liu G Y 2010 Exp. Therm. Fluid Sci. 34 pp 10–19
[7] Mazed D, Lo Frano R, Aquaro D, Del Serra D, Sekachev I and Orlandi F 2016 Proc. of the 24th Int. Conf. on Nuclear Engineering ICONE, Vol 2