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Experimental investigation of steam condensation in water tank at sub-atmospheric pressure

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ABSTRACT

The International Thermonuclear Experimental Reactor (ITER) Vacuum Vessel Pressure Suppression System (VVPSS) limits the Vacuum Vessel (VV) internal pressure, in case of loss of coolant (LOCA) or other pressurizing accidents from the in-vessel components, to 150 kPa (abs). This is key safety function because a large internal pressure could lead to a breach of the primary confinement barrier. Safety is ensured by discharging the steam evolved during the accident event to the VVPSS suppression tanks where it is condensed. Steam condensation occurs at sub-atmospheric pressure condition. Moreover, being this latter not standard for traditional nuclear systems, this investigation is quite new (not studied in detail before) and deals with an experimental investigation of the direct contact condensation at VVPSS prototypical thermal-hydraulic conditions.

To the purpose, a small-scale experimental rig was properly designed and built at Lab. B. Guerrini of DICI-University of Pisa as well as different temperature, pressure and steam mass (flow rate per hole) conditions and sparger patterns have been investigated. The experimental test matrix is also presented in this study.

The obtained results show high efficiency of condensation for all examined conditions. The main condensation regimes at sub-atmospheric pressure conditions were identified. In addition, a comparison was done between the condensation regimes experimentally determined and those available in the literature, which were obtained at atmospheric pressure. Finally, results demonstrated to be representative of the real configuration at ITER reactor.

1. Introduction

The steam condensation plays an important role in a variety of high efficient engineering systems such as heat pipes, nuclear power plants (fission technology), seawater desalination units etc.

During the condensation, it is generally assumed that the only rate controlling process is the heat transfer across the condensate layer.

The direct contact condensation (DCC) of steam injected into a pool of subcooled water is a well-known (Al-Shammari, 2004; Huang, 2015; Hong, 2012) and widely studied at atmospheric condition, involving pure steam or steam with non-condensable gases.

At "sonic" condition, a stable cone of steam forms at the outlet, so that it is possible to measure its length and, consequently, the surface of separation between steam and liquid through which the heat transfer takes place. Varying the specific mass flowrate and the subcooling, a transition between stable and instable behaviour may take place, and the transfer of vapour to the water surface may become controlled by diffusion than convection.

With reference to the nuclear application, a lot of experience has been gained studying the pressure suppression pool in BWR, although studies on steam condensation referred also to the drain tank and the in-containment refuelling water storage tank (IRWST) in advanced PWRs.

By reviewing the state of art concerning mainly the steam condensation at atmospheric pressure, it emerged that the attention of researchers was focused on the following aspects:

"Dimension" of steam plume into the water (shape and length);
Investigation of DCC and heat transfer coefficient;
Identification of condensation regime map (with condensation regime operation prevailing for a set of established parameters);
Characteristics of pressure waves generated during DCC (vibrations investigation).

In particular, although several theoretical and experimental studies were conducted on DCC, such as the experimental works at low steam

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mass flux conditions of Aya and Nariai (1991), or at intermediate range of steam mass flux of Young et al. (1974) and of Fukuda (1982), details of the DCC phenomena are not well understood. Moreover, Cumo et al. (1978) and Chun et al. (1996) provide correlation for a wide range of steam mass flux conditions while Del Tin et al. (1983), Stanford and Webster (1972) and Kerney et al. (1972), etc. proposed empirical correlation of the steam jet length for relatively low and high steam mass flux conditions respectively, even if these latter are not in agreement with each other.

Tsai and Kazimi (1976) and Chen and Faith (1982) studied the steam jet penetration by proposing simple models to describe the jet penetration distance. Unfortunately, a limit of their models is represented by the dependence of the prediction of steam jet length on the made assumptions. Song et al. (1998) as well Kim et al. (1997) observed that the steam jet may assume different shapes (conical, ellipsoidal and divergent) depending on the steam mass flux, the sub-cooling (water temperature) and the nozzle diameter. Similar considerations were provided earlier by Cumo et al. (1978). Further outcomes on DCC are provided in Kim et al. (1997), in which it is indicated how for large water sub-cooling and low steam mass velocity, the steam jet looks like a conical shape, while for intermediate and large water sub-cooling the plume shape tends to be ellipsoidal.

Zhu et al. (2013) investigated DCC of stable steam jet in water flow in a vertical pipe (for pool temperature range 20–70 °C and for single nozzle of 8 mm diameter), while Huang et al. (2015) provided a broad review of vapour condensation mechanisms.

As a conclusion, it has to be remarked that quite all the studies available in literature refer to DCC at atmospheric; this makes the study we will present in what follows new and difficult to compare with the others.

This paper focuses on investigating experimentally the DCC of steam at the Vacuum Vessel Pressure Suppression System (VVPSS) prototypical thermal-hydraulic conditions (i.e. sub-atmospheric condition) and deriving prediction to be used to support its configuration design. It is also worthy to note that the VVPSS thermal-hydraulic conditions, characterized by slightly superheated steam condensed, at very low (near vacuum) pressure, in water at close saturation condition, are not standard for traditional fission nuclear power systems. This peculiarity makes the proposed assessment new in the nuclear field: in fact, neither experimental nor analytical investigations of DCC at sub-atmospheric pressure are available in literature, as already indicated.

In what follows, a description of the VVPSS and a description of the experimental apparatus built at the DICI- University of Pisa are provided in Sections 2 and 3 respectively. In Section 4 the steam DCC and test matrix are presented, while the results are discussed in Section 5.

2. Description of the VVPSS

The VVPSS is a key safety system aiming to condense the steam resulting from the Design Basis coolant leaks into the VV, thus limiting over-pressurization to 150 kPa absolute by opening the rupture discs to let the steam from the VV flow to the VVPSS STs, where it can condense.

It can also be utilized in a variety of other situations, such as a simple loss of vacuum, to provide over pressure protection and enhanced confinement by maintaining low pressure in the system.

The VVPSS is a safety relevant system of the International Thermonuclear Experimental Reactor (ITER). It is designed to protect the Vacuum Vessel (VV) and related components from over pressure that could evolve during the normal operation or baking conditions (ITER/IO Internal Report, 2013). Fig. 1 shows a part of the ITER plant layout with the VV and ducts for connection (coloured in green and yellow) to the VVPSS and its sub-system, that are located inside the Drain Tank Room (DTR).

The VVPSS configuration Fig. 1(b) consists of four Suppression Tanks (STs) with an identical volume (100 m^3), an inner diameter of 6.2 m and an overall height of about 4.7 m. The system is made of 3 Large Leak Tanks (LLTs) and 1 Small Leak Tank (SLT) located in the DTR Fig. 1. The LLTs contain about 60 m^3 of water each, and are supposed to manage bigger loss of coolant accident (LOCA) events (cat. III and IV), while the SLT contains 40 m^3 of water and it is supposed to manage smaller LOCA events (cat. II).

The STs are designed to limit the final water temperature to 95 °C (corresponding to a saturated vapour pressure of about 84.6 kPa), for any LOCA event (Lo Frano et al., 2016). During an in-vessel coolant leak (Ingress of Coolant Event (ICE)) the VVPSS acts together with the VV drainage system, the former discharging evolved steam to the STs where it is condensed, while the latter facilitates drainage of water from the VV. In consideration of that, it can be seen that DCC into the STs water is the thermal-hydraulic phenomenon which guarantees the VV pressure safety limit not to be exceeded in case of VV pressure build-up. They are filled with enough water (the total amount in normal operation is around 220 m^3) at room temperature such as to condense steam resulting from the most severe in-vessel coolant leaks, and to limit the over-pressurization within VV to about 150 kPa absolute. STs are connected to the VV through pipeline as shown in previous Fig. 1a.

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. With this design the amount of contaminated water following a Category II ICE is very limited. The LLTs are instead connected in parallel to DN500 relief line, along which two sets of rupture disks, working in parallel, for full redundancy are located (to guarantee that, in case of partial opening of one of the two sets of rupture disks, the opening pressure of the second set is not impacted by the pressure build-up downstream of the rupture disk assembly).

The rupture disks (main vacuum confinement boundary in normal operation) would cope with the design and beyond design basis events: when accident occurs, their opening will ensure the excess of steam is released to the DTR and condensed in STs. The system also can be used also to provide over pressure protection and to enhance confinement, maintaining thus continuously low pressure in the VV system. Fig. 2 shows the two different relief lines connecting the VV to the LLTs and SLT.

As shown in Fig. 2, the two relief lines (DN300 and DN500) are fully independent and are provided by redundant valves, whose opening occurs automatically when the pressure in VV overpasses 92 kPa for the small leak line, and 130 kPa for large leak line. The main role of the VVPSS is thus to control that the duct pressure is kept below the set value. A sub-atmospheric pressure is required within the STs because of the pressure drop on the piping at high flow rate.

To guarantee proper functionality, STs will be maintained at low pressure ("vacuum conditions"), slightly above the saturation pressure of the water at the prevailing temperature to avoid boiling at water head interface, in inert atmosphere by using the evacuation system of the Safety Drain Tanks.

The design of the SLT and LLT tanks is similar with slight differences mainly for what concerns the sparger system, the connections of some of the auxiliary systems, the amount of water and some of the operation parameters. As shown in Fig. 1c, each tank consists of a cylindrical pressure vessel about 6 m in diameter and 4.5 m in height and a support structure fixed to the DTR floor: STs are installed as two sets of two tanks one on top of the other.

2.1. Problem definition

STs operate at sub-atmospheric pressure, the latter being not standard and new operational mode for nuclear systems. In fact, the VVPSS operation conditions differ considerably from those experienced in the past for the suppression pools of BWR-based NPPs, operating at atmospheric pressure. Indeed, steam direct contact condensation (DCC) near