EXPERIMENTAL INVESTIGATION OF CONDENSATION AND MIXING DURING VENTING OF A STEAM / NON-CONDENSABLE GAS MIXTURE INTO A PRESSURE SUPPRESSION POOL

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Experiments have been performed in the LINX facility to investigate condensation and mixing phenomena in pressure Suppression Pools (SPs), in the context of the European Simplified Boiling Water Reactor (ESBWR) study. As a contribution to the TEPSS project of the 4th European Framework Programme, eight medium-scale, separate-effect tests were carried out in which constant steam/air flowrates were injected below the surface of a two-metre diameter water pool, maintained at constant pressure, through a large downward vent. The vessel pressure was regulated, the pool temperature rising until equilibrium conditions with the incoming gas were reached. The SP temperature distribution was measured, as well as the inlet and outlet gas flowrates, and the overall condensation rate was estimated using mass and heat balances. The test matrix was based on steam mass flowrate and air mass fraction of the injected gas, the vent immersion depth, and the vessel pressure.

Overall, the condensation was shown to be efficient for all tests performed, even for high non-condensable gas concentrations of the injected gas. Thermal stratification above the vent outlet was shown to be moderate.

The tests performed allowed a better understanding to be gained of the mechanisms of condensation and mixing in the SP and Wetwell, and results were incorporated into an ORACLE database, to be used for further model development.

1 GENERAL FRAMEWORK

The concept of Passive Containment Cooling Systems (PCCSs), which use no active components, such as pumps, is a significant advance in terms of nuclear safety and is implemented in the new generation of Light Water Reactors currently under design. The LINX-2 facility at PSI has been used to address specific thermal-hydraulic issues encountered in these systems, and recently contributed to the TEPSS project ("Technology Enhancement for Passive Safety Systems") of the Euratom Research Framework Programme 1994-1998, whose objective was to make significant additions to the technology base of the ESBWR\(^1\). This project included an extensive experimental programme based on the PANDA facility for large-scale system tests, and on the LINX facility for medium-scale, separate-effects tests. The LINX experimental programme was focused on the investigation of condensation and mixing phenomena in pressure suppression pools (SPs), which are of particular significance to passive safety systems.

In the ESBWR (a schematic view of which is shown in Fig. 1), the depressurization of the reactor pressure vessel following an accident leads to air and steam flowing into the SPs through both the main vents and the PCCs\(^3\) vents. In the long term, air is vented from the Drywell through the PCC vents, together with any residual steam not condensed in the PCCs. While steam condenses in the SP, the non-condensable gas, i.e. the nitrogen which originally filled the containment volume, together with any residual steam raises to the gas space of the Wetwell.

Any steam mass fraction in excess of equilibrium conditions associated with the pool surface contributes to an increase in the Wetwell pressure, and thus in the overall containment pressure. Furthermore, any stratification in the pool, which would lead to higher pool surface temperatures, would enhance this effect.

Consequently, the SP venting system must be able to condense a maximum amount of steam, even for high injection flowrates, and despite the presence of non-condensable gases which would tend to degrade heat transfer between the gas and the ambient water in the SP. On the other hand, the gas injection must ensure good water circulation in the SP, so that the maximum amount of water is involved in the condensation process, and any effects due to thermal stratification are mitigated.

In the framework of the ALPHA\(^4\) project, initiated at PSI, tests were performed in the LINX-1 rig to investigate the thermal stratification induced by a heater immersed in a water pool, and generating a single-phase, buoyancy-driven plume \(2\). These tests exhibited significant thermal stratification, well predicted by accompanying, numerical computations. However, the presence of a gas phase significantly alters the problem, since liquid entrainment is considerably increased, and any stratification is expected to be quickly destroyed by the liquid motion.

The dynamics associated with the injection of concentrated or distributed gas sources in large pools is of interest to a number of industrial and environmental applications such as gas stirring in liquid-metal ladles used in metallurgical processes, aeration of lakes, limitation of the consequences of underwater well blowouts, destratification of water reservoirs.

1 Large Scale Investigation of Natural Circulation, Condensation and Mixing Processes
2 European Simplified Boiling Water Reactor
3 Passive Containment Condenser
4 Advanced Light Water Reactor Passive Heat Removal and Aerosol Program
Fig. 1: Schematic view of the ESBWR Passive Cooling System.

These applications have been the subject of extensive research, and provide a useful source of information. Nevertheless, venting in suppression pools introduces several new aspects into the study, which turn this process into an intricate, thermal-hydraulic problem: i.e., large vents, high mass flowrates, and the presence of a condensable phase. There is a clear lack of knowledge on the structure of the resulting two-phase flow (flow regime, gas bubble size, fragmentation length, etc.). The characteristics of the heat transfer between the condensing gas mixture and the ambient liquid are also missing since the available correlations for direct-contact condensation are based on data relating to moderately sized spherical bubbles, which are not expected in prototypical SP conditions. As described in [3, 4, 5], a large bubble is expected to periodically develop at the vent outlet, and then break up into a swarm of smaller bubbles.

Consequently, the development and assessment of computational tools modelling such phenomena require an experimental base for better physical understanding, and the establishment of a reference data bank.

2 THE LINX-2 FACILITY

2.1 Basic capabilities

The LINX-2 rig consists of a pressure vessel (rated at 10 bar and 250°C), 2 m in diameter and 3.4 m in height (2.5 m for the cylindrical part). The vessel is connected to steam and nitrogen/air supply lines, and is carefully insulated to minimize heat losses and improve the accuracy of heat balance estimation. Windows located at various elevations allow direct visualization into the tank, and the vessel internals are directly accessible through a manhole. Regulated steam injection into the vessel can be provided over the range 3-50 g/s, and air injection in the range 0.02-30 g/s. The vessel is connected to a demineralized water network, and external heating and cooling systems are available for system pre-conditioning or pool temperature regulation. The heating and cooling powers are 140 kW and 120 kW, respectively.

2.2 LINX configuration for the TEPSS tests

A schematic of the facility is seen in Fig. 2. This configuration allows injection of a mixture of steam and/or air into the water pool through a downward vent, of 40 mm inner diameter and 57 mm outer diameter. The downcomer is composed of two welded, concentric tubes with a vacuum in between, which creates an efficient thermal insulation and prevents steam condensation before the gas reaches the pipe outlet. Thermocouples allow control of the insulation efficiency during the experiments.

The injection mass flowrates are measured and regulated. The measurement accuracy is 1% and 2% of the measured value for air and steam flowrates, respectively, within the specified experimental ranges, and the flow is choked 4.20 m upstream from the injection pipe outlet. Since condensation of steam in the pipe would invalidate the flowrate measurement, the supply lines are insulated with mineral wool, and heaters and temperature measurements ensure that the steam remains slightly superheated until it reaches the vessel.

A regulating system, composed of a pressure transducer and a pneumatic valve, keeps the pressure in the vessel constant by venting the excess gas. The gas flowrate vented out of the vessel by the regulation system can be deduced from the pressure loss through a calibrated valve located at the vessel outlet. Eighty four K-type thermocouples, 1 mm in diameter, are used for temperature measurements in the vessel. They are attached by small pinch-screw clips to 1 mm stainless steel wires stretched between metallic arms located at the bottom and at the top of the vessel. One of the arms is moveable, which allows the pool temperature profile to be scanned. Thermo-resistances are also used as reference measurements.

A special calibration procedure was performed for a number of thermocouples located in the vessel. The resulting temperature measurement accuracy was thereby established as +/- 0.3°C. The pressure near the top of the vessel is monitored, and the water level can be deduced from a differential pressure measurement between the top and the bottom of the vessel. A customized oxygen probe is also used to measure the air partial pressure in the upper part of the vessel.

The data acquisition system allows scanning of all measuring channels with a 1 Hz frequency.

3 TEST MATRIX AND EXPERIMENTAL STRATEGY

During the ESBWR LOCA\(^5\), steam venting begins in the "blow-down" period, corresponding to the early stage of the accident, but the flowrates to the SP are

\(^5\) Loss of Coolant Accident
so high in this phase that the entire pool is considered to be in such violent turbulent motion that condensation may be considered complete. Issues concerning the SP arise approximately 1 hour after the beginning of the accident, when PCC venting resumes, after the GDCS discharges. At this time, calculations predicted that the vented gas flowrate would reach 6-7 kg/s, but would then decrease slowly [6]. During this period, the amount of air in the gas mixture released through the PCC vents is high (up to 60% of the mixture mass during start-up, 20% for the maximum flowrate). The influence of such high non-condensable gas fractions on condensation is difficult to predict, and this phase is thus of concern in relation to the efficiency of the condensation process in the suppression pool. In the long term, the steam flowrate decreases, but the non-condensable gas mass fraction remains high.

Owing to the current lack of knowledge of the complex flow phenomena induced by venting of air and steam through large-diameter pipes, no proper scaling of the condensation process, in relation to a reference prototype, is readily achievable.

The test matrix (presented in Table 1), and the associated experimental programme, were thus established to investigate the influence of relevant parameters such as flowrate, non-condensable gas concentration, pool subcooling, pressure and vent immersion depth, on the condensation and mixing processes. The characteristics of thermal stratification, and the occurrence of excess steam release to the gas space assuming incomplete condensation), were investigated through eight different tests covering the extreme conditions of pure steam (for evaluating thermal stratification and high flowrate), and high non-condensable gas concentration (for evaluating the risks of steam by-pass).

Table 1: LINX Test Matrix for TEPSS Tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Flowrate (g/s)</th>
<th>Initial Pool Temperature</th>
<th>Final Pool Temperature</th>
<th>Steam Flowrate (g/s)</th>
<th>Mass % of Air in Mixture</th>
<th>Vent Submergence (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>75 °C</td>
<td>127 °C</td>
<td>20</td>
<td>0%</td>
<td>Hp</td>
<td>Pure Steam - Reference Case</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>75 °C</td>
<td>127 °C</td>
<td>20</td>
<td>0%</td>
<td>Hp/2</td>
<td>Pure Steam - Low Submergence</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>75 °C</td>
<td>127 °C</td>
<td>50</td>
<td>0%</td>
<td>Hp</td>
<td>Pure Steam - High Flow Rate</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>75 °C</td>
<td>126 °C</td>
<td>20</td>
<td>5%</td>
<td>Hp</td>
<td>Steam + Air - Reference Submergence</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>75 °C</td>
<td>126 °C</td>
<td>20</td>
<td>5%</td>
<td>Hp/2</td>
<td>Steam + Air - Low Submergence</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>83 °C</td>
<td>123 °C</td>
<td>50</td>
<td>20%</td>
<td>Hp/2</td>
<td>Steam By-pass Experiment</td>
</tr>
<tr>
<td>7</td>
<td>Atmosphere</td>
<td>56 °C</td>
<td>96 °C</td>
<td>50</td>
<td>20%</td>
<td>Hp/2</td>
<td>Steam By-pass Experiment</td>
</tr>
<tr>
<td>8</td>
<td>Atmosphere</td>
<td>80 °C</td>
<td>96 °C</td>
<td>20</td>
<td>20%</td>
<td>Hp/2</td>
<td>Steam By-pass Experiment</td>
</tr>
</tbody>
</table>

(*) Hp=75 cm

The tests consist of injecting a constant mass flow of steam/air to the pool. The initial temperature in the vessel is obtained by preliminary injection of steam, and/or use of the pre-conditioning loop. The temperature profile is homogenized by a motor-driven propeller before starting the test. Pressurization is achieved by air injection. Before the start of a test, the vessel is isolated from the supply lines, and gas composition and flowrate are adjusted in a by-pass loop. Data acquisition starts when the gas mixture is diverted to the vessel by a set of shut-off valves.

The latent heat released by condensation is then transferred to the pool, which slowly brings the water up to the equilibrium temperature, at which the condensation process stops, and which roughly equals the final temperature indicated in Table 1.

During the tests, the vessel is maintained at constant pressure; 2.5 bar corresponds to a typical pressure expected in the wetwell at the onset of PCC venting, as determined from the PANDA experiments [7].

A series of 40 short visualization tests were also performed to characterize the flow pattern, the gas bubble size and fragmentation length, for a wide range of flow conditions.

The injector described above was also used for these tests. Earlier studies, dealing with non-condensable...
gas venting, suggested that the initial gas bubble size depended only on the volumetric flowrate [8], and the injector diameter should therefore have no significant influence. Though this statement may not be true in the presence of a condensable phase, the influence of the injector diameter has been left to possible complementary studies.

4 POOL THERMAL BEHAVIOUR AND MIXING / STRATIFICATION

4.1 Experimental results

Steam condensation takes place in a region located near the injection pipe, resulting in the development of a buoyancy-driven plume from the vent outlet to the pool surface. Entrainment of water from the bulk liquid to the plume also leads to progressive heating of the water pool. This may be accompanied by the development of thermal stratification, depending on the injection conditions.

Figure 3 represents maps of the temperature distribution in the pool at different times, for increasing noncondensable mass fractions of the injected gas. The region investigated corresponds to a radial slice through the pool, from the injection pipe, located on the symmetry axis of the vessel, to the wall. Dimensions are given in mm.

As can be seen, all the tests are characterized by strong thermal homogeneity in the region located above the vent, except for the plume region, close to the injection pipe, where the temperatures were, as expected, slightly higher. The presence of a cold water layer at the base, not involved in the heating process, could be observed for Tests 1-5, i.e. when the noncondensable gas concentration in the injected mixture is low or zero. In contrast, the entire pool was homogeneously heated in Tests 6-8, for which the noncondensable gas injection flowrate was higher. The gas bubbles strongly increase buoyancy effects in the plume region, thus enhancing liquid entrainment and recirculation, and promoting mixing in the pool.

For pure-steam tests, thermal stratification was particularly noticeable, and the location of the thermal front separating the heated region from the thermally inert "cold region" was found to change with time as the hot layer temperature increased.

Figure 4 shows some temperature readings at different elevations H from the vent. The selected temperature sensors are installed 350 mm from the vessel axis. They are all located in the pool, except for TF24, which is 7.5 cm above the water surface at the beginning of the test, but "falls" below the surface after about 5200 s, as the pool surface rises. The water level increase results from mass addition to the pool due to condensation, and from water density variations due to temperature rise.

Early in the test, no significant heating occurs below the vent outlet. At first, smooth temperature increases are detected by sensors TF46 and TF50 as the test proceeds, marking a progressively downward extension of the region involved in the heating process. They then reach plateaus where they stabilize temporarily.

Since the temperature variations depend, in particular, on the amount of heated water, each stratification step corresponds to a change in the slope of TF33, which measures the temperature of the hot region, close to the pool surface. One can thus identify 4 distinct periods where the slope of TF33 is relatively constant. These are marked in Fig. 4:

I - Temperature increase limited to the region above the vent outlet;
II - Downward extension of the heated region;
III - Transition - stabilization of the thermal front;
IV - Downward extension of the heated region.

The onset of Phase IV is marked by a particularly sharp change in the TF33 slope, taking place at 99°C. This phase differs from Phase II in that it is characterized by sudden, large-amplitude temperature shifts as the thermal front progressively moves down. The movement of the thermal front could be followed during the tests, and its location is represented as a function of time in Fig. 5 for Tests 1-3.

Pool stratification is particularly sharp during Phase IV: the thermal front thickness could be evaluated as about 10 cm in Test 2. The temperatures measured in the hot layer indicated homogeneous conditions.

4.2 Interpretation

Analysis of temperature measurements show that the hot layer tends to be slightly depressed far away from the vessel axis, which suggests that the thermal front motion is driven by water convection currents along the wall. Such currents arise because the steam injection creates a rising plume around the injection pipe, which spreads outwards at the water surface, entraining hot fluid, and is then carried downwards at the far wall to complete the pool circulation. The final momentum available as the current reaches the thermal front may be sufficient to compensate the buoyancy force induced by the temperature gradient, and thus thicken the hot layer.

This mechanism explains why the thermal front moves downwards during the tests. Indeed, the pool temperature does affect the condensation efficiency, as described below, having a direct effect on the characteristics of the two-phase flow generated at the injection pipe outlet, and therefore on the amount of water entrained in the rising plume. The increase in noncondensed steam volume fraction in the pool induced by the temperature rise clearly enhances water entrainment.

As can be seen from Fig. 5, the front-propagation characteristics differ between Tests 1-3. Clearly, the flowrate and the vent immersion depth have a significant influence, since the pool temperature increase depends directly upon them.
Fig. 3: Pool temperature distribution samples for increasing non-condensable mass fraction.
5. STEAM CONDENSATION EFFICIENCY

5.1 Pure steam tests

As long as the injected gas is pure steam, by-pass can be detected visually. Illumination from lateral windows allows direct visualization and use of video recording techniques. A high-speed video camera was used to follow the gas/liquid interface motion during the experiments.

The pattern of the flow induced by steam venting has already been described in the literature by various authors, whose aim was to establish a condensation map and study overall effects such as pressure loads on structures through chugging [9, 10].

In the early stages of a pure-steam injection test, the characteristics of the flow are the periodic growth and collapse of steam bubbles at the vent outlet, and water ingress into the vent between successive bubbles. As the pool temperature increases, complete condensation of steam requires more time, the flow regime progressively changes, and the steam bubble developing at the vent outlet starts to grow to envelop the pipe outlet. Steam bubbles of various shapes, generally asymmetrical, emerge from the vent, or from the bubble enveloping the vent outlet, and extend upwards along the pipe, driven by buoyancy, while condensing and eventually collapsing.

The evolution of the gas/liquid interface was accompanied by strong fluctuations, which were seen on the video records, and the condensation process was found to be extremely violent and turbulent. From time to time, a steam jet would emerge and quickly rise along the injection pipe ahead of the main bubble interface.

The final-collapse/full-condensation distance is of primary interest since no steam by-pass can occur as long as this distance remains below the vent immersion depth. The maximum collapse distance, i.e. the distance from the vent outlet to the highest location where the (occasional) presence of steam could be detected, was determined from video samples as a function of time, and plotted versus the bulk liquid temperature. The results are displayed in Fig. 6.

As expected, a comparison between Test 1 and Test 2 shows no influence of the vent immersion depth, whose only effect is to accelerate the temperature rise, since the amount of water located above the vent is different.

Surprisingly, an increase in the steam flow rate leads to a smaller collapse distance at low temperatures. This is actually due to the gas penetration into the liquid being enhanced by the higher velocity at the vent exit. At higher temperatures, and higher collapse distances,

Further, these parameters influence the geometry of the pool recirculation cell, and the momentum transferred from the rising plume to the downward currents along the wall.

The existence of four different phases, as identified in Fig. 4, can be qualitatively explained by the same mechanism. The momentum available to depress the thermal front must be able to compensate the buoyancy force induced by the temperature gradients. An increase in the hot layer temperature modifies the available momentum, but also enhances buoyancy. The onset of a "stabilization" period, such as Phase III in Fig. 4, can thus be interpreted as an equilibrium between the momentum of the entrained water and the buoyancy force.

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7 A Kodak Ektapro HS Motion Analyzer, Model 4520. Resolution 256x256, up to 4500 frames per second.
the steam flowrate no longer affects the collapse distance.

For sufficiently high vent-submergence, the onset of steam by-pass is thus determined by the pool temperature alone. An approximate value of 123°C, i.e. 4°C subcooling, marks the actual beginning of steam by-pass for a 75 cm submergence. This temperature limit is even higher for a 1 m submergence, the design value for the PCC vents in the ESBWR. For a lower submergence of 37.5 cm, the critical temperature is lower and close to 111°C.

It is worth remarking that the sudden change in slope of the curves shown in Fig. 6, at about 98°C for Tests 1-2, and about 105-110°C for Test 3, also corresponds, for each test, to the onset of Phase IV, as described previously and illustrated in Fig. 4. These temperatures actually mark the transition from an external chugging regime to an oscillatory bubble regime, as described in [9], which is characterized by the permanent presence of a steam region at the vent exit. In the Phase 4 regime, the gas region periodically grows, releasing well-developed bubbles, which detach above the vent exit before rising and finally collapsing. This certainly enhances upward water entrainment along the injection pipe, which was not as efficient in the chugging regime where water could be violently ejected after approaching or entering the pipe. The onset of this new regime at the injector outlet is thought to be responsible for the transition from Phase III to Phase IV in Tests 1-3, as previously described and illustrated in Fig. 4. The character of the two-phase flow at the injection pipe could thus influence the entire thermal stratification pattern in the pool.

Equation (1) assumes that the vessel walls are at the same temperature as the pool; this was confirmed experimentally, and is due to the efficient thermal insulation surrounding the vessel. It also implies that no heat transfer exists between the pool and the gas space as a consequence of evaporation from the pool surface. Temperature and steam partial pressure measurements in the gas space show that the steam partial pressure gradient existing between the water surface and the gas space was low throughout Tests 6-8, which justifies this approximation.

Equation (1) can be solved to predict a theoretical pool temperature corresponding to 100% condensation efficiency; that is, when the gas injected in the pool reaches thermal equilibrium with the ambient liquid before arriving at the water surface. Assuming that the gas bubbles reaching the surface contain a homogeneous mixture of perfect gases, the ratio of steam partial pressure to air partial pressure is equal to the molar ratio between steam and air, which results in the following expression for the steam flowrate released to the gas space :

$$m_{\text{cond}}(t)h_{\text{w}}(T_g) + m_s(h_s(T_g) - h_s(T_a)) + m_a(h_a(T_g) - h_a(T_a))$$

$$= m_w(t)C_{pw}(T)\frac{dT}{dt} + m_v(t)C_{pv}(T)\frac{dT}{dt} - q_{\text{nl}}(t)$$

where $m$ denotes mass flowrate, $h$ enthalpy, $t$ time, $m$ the mass of liquid in the pool, $C_{pw}$ is the specific heat of water at ambient pressure $P$, $C_{pv}$ is the specific heat of the vessel structures (walls), $q_{\text{nl}}$ denotes the heat losses through the vessel insulation, $T_g$ the temperature of the injected gas before reaching the pool, and $T_a$ is the temperature of the gas reaching the water surface. Subscripts $w, s, a, \text{cond}$, respectively, refer to pool water, injected steam, injected air and steam condensing in the pool; $m_v$ represents the mass of the structures heated by contact with the pool (function of the water level and thus of time), and $h_{\text{w}}$ is the latent heat of water.

Fig. 6: Steam collapse distance vs. pool temperature for (pure-steam) Tests 1-3.

5.2 Steam / air tests

Visualization was found to be inappropriate for the study of condensation if the injected gas mixture contained some non-condensable. The efficiency of steam condensation can, however, be estimated from a heat balance in the pool. Assuming a homogeneous temperature $T$ in the liquid, this yields:

$$m_{\text{cond}}(t)h_{\text{w}}(T_g) + m_s(h_s(T_g) - h_s(T_a)) + m_a(h_a(T_g) - h_a(T_a))$$

$$= m_w(t)C_{pw}(T)\frac{dT}{dt} + m_v(t)C_{pv}(T)\frac{dT}{dt} - q_{\text{nl}}(t)$$

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$$m_{\text{eq}} = m_a \frac{M_s}{M_a} \frac{P_{\text{sat}}(T)}{P - P_{\text{sat}}(T)}$$

where

$$m_{\text{eq}} = m_a - m_{\text{cond}}$$

Here, $M$ denotes the molar weight (of steam or air), $P_{\text{sat}}$ is the saturation pressure of steam, and $P$ is the total pressure. The temperature in the gas $T$ is assumed to be equal to the liquid bulk temperature.

Using the initial conditions of the tests, and the experimental values of $T_g$. Equations (1) and (2) were solved to deduce the pool temperature evolution for full condensation. The water mass and level variations were taken into account. Separate tests were performed to evaluate the heat losses from the vessel as a function of the inner wall temperature and to deduce
the heat losses from the pool, assuming that the heat loss flux is uniform over the entire vessel surface.

The calculated pool temperature $T_{th}$ turned out to be very close to the measured pool temperature $T_{xp}$ throughout Tests 6-8, and $|T_{th} - T_{xp}|$ remained below 1.5°C. This means that the condensation process was very efficient, and that the gas rising from the vent outlet was close to equilibrium with the bulk liquid before reaching the water surface, though this was only 37.5 cm above the vent outlet.

Figure 7 displays the amount of steam condensing in the pool, $m_{cond}$, versus pool temperature for Tests 6-8, and was deduced from Equations (1) and (2) using experimental values for $T_s$, $T_g$, $m_w$ and $T$ defined as the average of six thermocouple measurements in the pool. The results were then averaged over 30 s time steps. Equation (1) provides experimental values for $m_{cond}$, represented as light grey curves on the graph. Equation (2) provides an estimate of the condensation rate under the assumption of complete condensation, and results are plotted as dark curves in Fig. 7. The difference between the light and dark curves can thus be interpreted as a steam by-pass flowrate. Note that for all tests the steam condensation flowrate decreases as the pool temperature increases.

Experimental results agree very well with the full-condensation prediction, and by-pass is moderate or non-existent, even for high volumetric flowrates, as in Test 7.

While one would expect an increase of the condensation efficiency at higher pressure for the same mass flow, due to the decrease in volumetric flowrate, a comparison between Tests 6 and 7 in Fig. 7, performed at the same steam mass flowrate, and at respective pressures of 2.5 and 1 bar, does not support this. Indeed, in Test 6, the experimental predictions based on Equation (1) fall below the theoretical predictions of Equation (2) as the pool temperature increases. The resulting by-pass is modest, however, especially in view of the experimental uncertainties.

6 CONCLUSIONS

The tests performed enabled a better understanding to be gained of the mechanisms of condensation and mixing involved in a suppression pool. The results were incorporated into an ORACLE database for further model development.

Overall, condensation was efficient in all tests performed, even at 20% air mass fraction. For pure steam injection, steam by-pass could only be detected after reaching relatively high temperatures in the pool (4°C subcooling at 2.5 bar, and 20 g/s injection rate). Mixing was also found to be very efficient. No significant stratification in the region above the vent could be detected. On the contrary, the heated region could extend far below the vent, even in the case of pure steam injection.

However, the data obtained from the present medium-scale facility cannot be directly applied to full-size suppression pools, since the distance from the injection point to the wall might significantly alter the mixing/stratification pattern. Further, one cannot guarantee the efficiency of condensation for much higher flowrates and vent diameters. There is thus a need for some large-scale tests, and for semi-empirical predictive models to account for scale effects.

7 ACKNOWLEDGEMENTS

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8 REFERENCES


