Progress in Nuclear Energy 107 (2018) 72–82

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

# Investigation on jet scrubbing in nuclear reactor accidents: From experimental data to an empirical correlation

Luis E. Herranz*, Claudia Lopez, Jaime Penalva

*Unit of Nuclear Safety Research, Division of Nuclear Fission, CIEMAT, Avda. Complutense 40, 28040, Madrid, Spain*

ARTICLE INFO

*Keywords:*
Source term mitigation
Pool scrubbing
Jet regime
PASSAM project

ABSTRACT

The Fukushima accident stressed the significance of suppression pools as passive systems for fission product trapping. Even though pool scrubbing was extensively investigated in the past, there are gaps in the existing data base and modeling that need to be addressed, particularly those relative to high gas injection velocities in the pool. In this paper, the main results of an experimental campaign (PSP tests) on particles scrubbing at the pool inlet region when the carrier gas forms a submerged jet ("jet scrubbing"), are presented and discussed. The tests have been conducted in the PECA-PS facility of the Laboratory for Analysis of Safety Systems (LASS) and the experimental conditions have been based on two non-dimensional variables: the Weber non-dimensional number, which has been set to values over the threshold from globule to jet regime; and the gas saturation ratio, which has ranged from under saturation to over-saturation. Jet scrubbing efficiency at the pool inlet has been measured to be over 90% whenever the gas enters the pool within the jet regime ($We_{test} \geq We_c$), regardless thermal boundary conditions. Analysis of gas steam content, though, has not shown any clear trend. Based on the PSP experiments and some others gathered from the open literature, a tentative correlation dependent on non-dimensional Stokes number (Stk), which accounts for inertial impaction, and saturation ratio (S), which captures diffusiophoretic deposition, has been proposed as a first step to empirically model jet scrubbing. Finally, some lessons learned for forthcoming experiments have been withdrawn, particularly concerning the high impact of hydrodynamics.

This work has been done within the framework of the 7th FWP of EURATOM through the EU-PASSAM project (Grant agreement No. 323217 – Euratom 7FP).

## 1. Introduction

The Fukushima accident occurred on March 11th, 2011 and stressed the need of providing Nuclear Power Plants (NPP) with technological safeguards capable of effectively mitigating severe accidents in case all the preventive measures have been unsuccessful. The BWR designs of Units 1 through 3 in Fukushima had a suppression containment (Mark I) which performance relies on steam condensation in a huge volume of water (suppression pool). Along with steam absorption, fission products are also supposed to be effectively trapped by different mechanisms involved in what is known as pool scrubbing.

Pool scrubbing or wet scrubbing (i.e., the removal of contaminant particles and/or vapours carried by a gas when passing through an aqueous pool) is not restricted to nuclear BWR reactors. In PWR reactors, for instance, pool scrubbing might occur in the secondary side of a steam generator during a meltdown SGTR sequence and it would turn out to be a key source term attenuation process, given the containment bypass in such sequences. Common to all reactor types, whenever molten material reaches the containment as a result of a severe accident and some water exists and/or is injected in the pedestal, fission products and aerosols carried by gas bubbling stemming from the molten core concrete interaction are captured by the water layer overlaying corium. And, finally, just as another example of pool scrubbing scenarios, all filtered containment venting systems of a wet type drive the radioactive material coming from the containment through a water pool were the first decontamination stage, mainly of particles and of some gaseous iodine, would take place. In summary, there are many scenarios in which pool scrubbing might mitigate source term, which in turn means that pool scrubbing boundary conditions entail broad ranges of some variables.

Pool scrubbing was heavily investigated in the 80's and 90's of last century. However, Herranz et al. (2014a) reviewed the available database and found out some major weaknesses: lack of systematic analysis of the parameters influencing pool scrubbing (i.e., submergence, particle size, steam content, etc.); no experimental track of variables like bubble size and shape; conditions hardly addressed in the past, like

---

* Corresponding author.
*E-mail address:* luisen.herranz@ciemat.es (L.E. Herranz).

https://doi.org/10.1016/j.pnucene.2018.04.019
Received 11 September 2017; Received in revised form 22 March 2018; Accepted 24 April 2018

jet injection or churn-turbulent regime during gas rise; and few data on scrubbing of fission products vapors. As a consequence, a number of issues were considered worth to be investigated: jet injection regime; gas rise hydrodynamics at high velocities (i.e., churn-turbulent flows); scrubbing of fission product vapors; re-entrainment in the long run of a severe accident; and the effect of boundary conditions like submerged structures and presence of surfactants. Some of those investigations were addressed in the recently finished EU-PASSAM project (Albiol et al., 2017).

The jet injection regime has been barely investigated in the past (Herranz et al., 1997), despite that during some key accident sequences fission products enter the pool carried by a gas at high velocity (Herranz et al., 2012). According to Zhao and Irons (1990), the transition from globule to jet regime occurs at values of the Weber non-dimensional number, We ($We = \frac{\rho_g \cdot v_g^2 \cdot d_{in}}{\sigma}$), higher than a threshold defined by $We_c$ ($We_c = 10.5 \cdot \sqrt{\frac{\rho_\ell}{\rho_g}}$), which for aqueous and carrier gases anticipated during a severe accident ranges in the interval 300–400 The significance of such regime is that gas-liquid interface phenomena change drastically and, as a consequence, the aerosol removal mechanisms also do: liquid drops are entrained in the gas bulk and sweep out a fraction of airborne particulate matter and fission product vapours. Even though recently some studies have analytically addressed these scenarios (Berna et al., 2016), the database to develop an empirical model and/or to validate any mechanistic or semi-mechanistic modeling is scarce and not fully representative.

This paper summarizes the research carried out by CIEMAT within the PASSAM project on the scrubbing efficiency of pools when the particle carrier gas enters the liquid phase at high velocity forming a submerged jet (hereafter PSP test campaign). The experiments have been conducted in the PECA-PS facility of the Laboratory for Analysis of Safety Systems (LASS). By combining several key boundary conditions in non-dimensional magnitudes, an experimental matrix has been constructed to explore the effect of gas velocity and saturation on jet scrubbing. In the coming sections the results obtained and their interpretation are described, along with a preliminary attempt to encapsulate the observations into an empirical correlation that will be further developed as database gets enlarged in the future. Additionally, key experimental insights for further experimentation on jet scrubbing are also discussed.

## 2. Experimental program

The PSP experiments have been carried out in the PECA-PS (Plant for Experimental Characterization of Aerosols on Pool Scrubbing) facility of the Laboratory for Analysis of Safety System of CIEMAT. Even though the facility had been used for such purposes more than two decades ago (Marcos et al., 1994; Peyrés et al., 1995), a short description is given in this section with emphasis on those systems and components that have been updated.

### 2.1. PECA-PS facility

The PECA facility is a multi-purpose, mid-scale installation mostly used for aerosol studies under postulated severe accident conditions in NPPs. The PECA-PS configuration (Fig. 1) consists of several systems: the main injection line; the vessel; the instrumentation; and the control and data acquisition systems (PLC, Programmable Logic Controller; and SCADA, Supervisory Control And Data Acquisition). Fig. 2 gives a side view of the main injection line.

The gas supply system is able to provide up to 300 kg/h with oscillations of ± 5 kg/h around the flowrate setting. This tank is connected to the gas distribution line where most of the gas is driven to the main injection line, and a fraction is extracted for the aerosol generation process (a minor portion is derived for the facility pneumatic valve control). The thermal conditioning of the main gas stream is achieved through a 5.5 kW pre-heater.

The aerosols have been generated with a RBG-1000 device. The powder to be dispersed is put into the cylindrical solid reservoir and compressed. Then a rotating brush at a controlled feeding sends the particles in a secondary gas flow that blows through the RBG up to carrying the particles into the main gas stream. The 1 μm $SiO_2$ particles generated in the PSP campaign were driven through a Venturi nozzle into the main line (downstream of the steam injection and upstream of the inlet aerosol characterization station).

The gas-steam mixture used in the experiments has required an entire section for steam generation in the PECA facility (bottom left in Fig. 1), which main component is a steam boiler (4 bar, 150 °C, nominal conditions). Steam injection (located right upstream of the particle injection) has made all the piping to be insulated to avoid any potential condensation.

The injection line is the section of the pipe from the particle injection location to the inlet of the pool. Several control valves regulate and control the pressure and mass flow rate in the line. The station for inlet characterization of aerosols is located at the injection line near the injection point; isokinetic samples from the injection line allow monitoring aerosol concentration and size distribution in the corresponding instrumentation.

The air-steam mixture reaches the pool through a horizontally oriented injector which diameter was 0.88 or 0.65 cm, depending on the test (the rationale behind this flexibility being to gain some flexibility in terms of gas injection velocity).

The vessel is a vertical cylinder with upper and lower hemispherical heads, 5.0 m in height and 1.5 m in diameter. It was designed under ASME VIII DIV-1 code requirements, and is able to withstand up to 3.5 bar and 140 °C. It is made of stainless steel of 8.0 mm in thickness. The total volume is 8.4 $m^3$ and its weight is 2.5 tons. The vessel is equipped with 26 glass windows which allow visual observation and image acquisition of the phenomena occurring inside during a test. In these tests, the vessel bottom is filled with water up to a depth that is roughly 0.3 m over the end of the injection line.

The facility uses several types of instruments and sensors for the measurement and control of the thermal-hydraulic variables. Multiple pressure and flowrate valves control the air/steam mixture in the injection line and upstream. Two blowers relieve the pressure to ensure atmospheric conditions at the vessel. All the variables were controlled every 700 ms through the PLC which incorporates a SCADA system for the acquisition and storage of the variables.

As for the instruments used for aerosol characterization, the main devices used have been a DLPI (DEKATI Low Pressure Impactor) at the inlet and a DLPI + at the outlet. Both instruments have the same range of particle diameters and sampling flow rate limit (0.028–10 μm and 10 lpm, respectively). The sampling has been intended to be as isokinetic as possible, according to the criterion proposed by William (1999). Over the pool, a conical hood collects gases and particles coming out from the water surface, so that gas streamlines do smoothly converge to the sampling point at the top of the hood.

### 2.2. Experimental matrix and test protocol

As said above, in some of the most significant severe accident sequences, like SBOs and SGTR (Allelein et al., 2009), the gas mixture carrying particles to aqueous ponds is estimated to enter the pool as a submerged jet. This injection regime has been scarcely studied in the past and the poor database needs to be enlarged, so that it can support any model development (in case of empirical approaches) and/or validation (in case of mechanistic/semi-mechanistic approaches).

As already mentioned, Zhao and Irons (1990) found that whenever the We non-dimensional number,

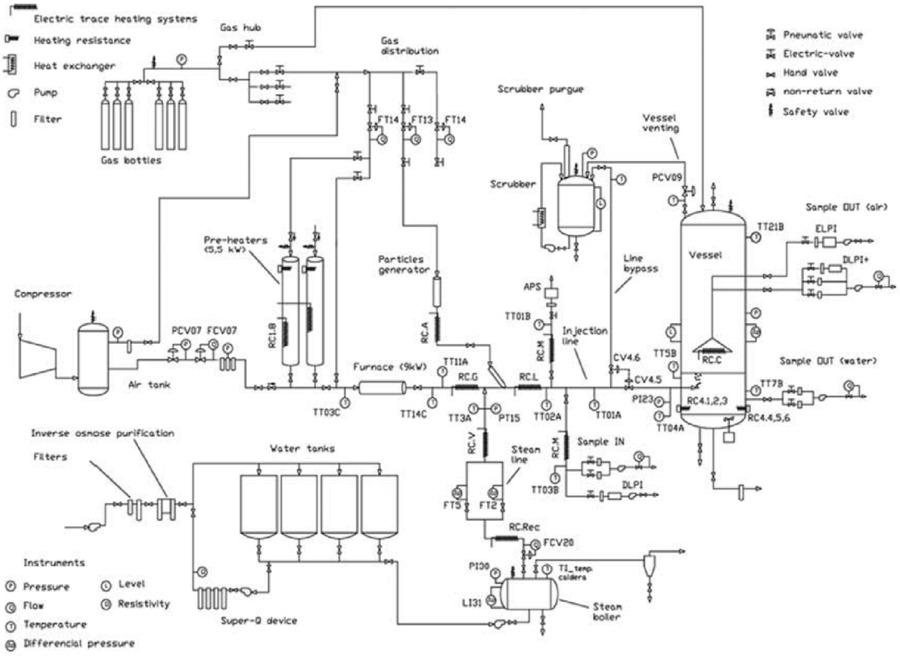

**Fig. 1.** Flow chart of the PECA-PS facility.

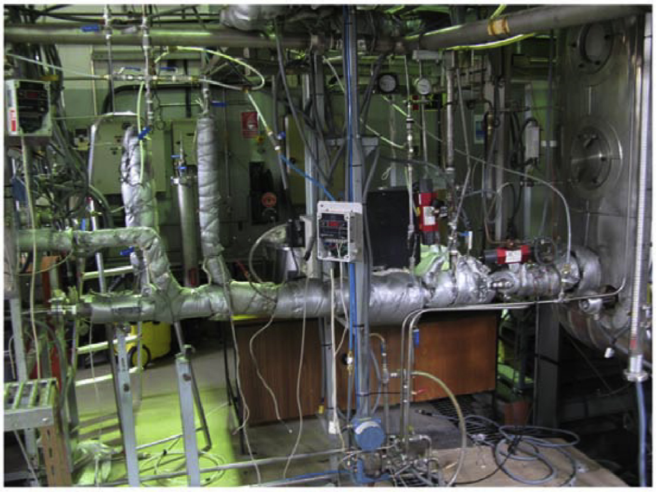

**Fig. 2.** Side view of the main injection line and the vessel.

$$We \ = \frac{\rho_g \cdot v_g^2 \cdot d_{in}}{\sigma} \tag{1}$$

exceeds a critical value $We_c$,

$$We_c = 10.5 \cdot \sqrt{\frac{\rho_\ell}{\rho_g}} \tag{2}$$

gas momentum is capable of penetrating the denser aqueous phase forming a jet. In the experiments, a suitable combination of the injection diameter ($d_{in}$) and the gas velocity ($v_g$) made $We_{Test}$ to be well over $We_c$ in all the cases. Hereafter, $v_g$ will be expressed as flowrate ($\dot{m} = \rho_g \cdot Q_g = \rho_g \cdot v_g \cdot A$), since this is the control variable in the PECA-PS configuration.

At the injection location, phase changes can also play a significant role in the particles scrubbing if water is far from saturation with respect to the steam content of the incoming gas. This makes the steam fraction in the particle-laden gas mixture ($X_{steam}$) an influencing boundary condition to be accounted for in the present investigation. The pool saturation status can be characterized through the saturation ratio (S):

$$S = \frac{P_{steam}}{P_{sat\,(T_{pool})}} \tag{3}$$

As a result of the previous discussion, a test matrix to explore the high region of We (jet regime) under all possible conditions for steam phase change at the inlet, from substantial condensation (high S) to evaporation from the gas-water interface (very low S), has been set up (Table 1). The total gas flow rate and the volumetric steam fraction are true variables of the matrix, whereas gas and pool temperatures are boundary conditions imposed to either prevent steam condensation on the inner walls of the injection line or allow saturation ratios over 1.0 with small amounts of steam in the carrying gas. In order to focus on the already discussed dependencies, other variables like submergence (i.e., water height over the injection point), particle diameter and composition (i.e., soluble vs. non-soluble), have been left out of the matrix so far, despite their potential impact on the scrubbing process. The submergence was set to 0.3 m in all the tests and the same particles were used all across the test matrix: 1 μm $SiO_2$. As observed, the first 4 tests explore the effect of an ever increasing We under weakly evaporating conditions; whereas the last 4 tests study the effect of phase changes at constant flowrate. Worth to note that PSP0 was performed with a smaller diameter injection pipe than the others, in order to obtain We above the $We_c$ at a low flow rate.

The reduced submergence is set to preclude the bubble swarm rise region as much as possible. This way particle scrubbing is foreseen to be mostly due to processes at the nearby of the injection point, which is the

**Table 1**
PSP experimental test matrix.

| Test | $T_g$ | $T_{pool}$ | $Q_{steam}$ | $Q_{total}$ | $X_{steam}$ | $We_g$ ($We_c$) | S |
|---|---|---|---|---|---|---|---|
| | ºC | ºC | l/min | l/min | % (vol) | | |
| PSP0 | 100 | 35 | 5 | 160 | 3.13 | 698 (341) | 0.60 |
| PSP1 | 100 | 35 | 6 | 210 | 2.86 | 482 (341) | 0.54 |
| PSP2 | 100 | 35 | 9 | 310 | 2.9 | 1050 (341) | 0.56 |
| PSP3 | 100 | 35 | 15 | 460 | 3.26 | 2312 (341) | 0.66 |
| PSP4 | 100 | 35 | 30 | 460 | 6.52 | 2312 (341) | 1.32 |
| PSP5 | 100 | 35 | 45 | 460 | 9.78 | 2312 (341) | 1.98 |
| PSP6 | $T_{env}$ | $T_{env}$ | 0 | 460 | 0 | 2312 (304) | 0.00 |

focus of this research. Nonetheless, a contribution of removal mechanisms other than those at the inlet region cannot be entirely ruled out. The $SiO_2$ particles have been chosen so that no solubility effects had to be considered when discussing the results (a 1 μm diameter is considered suitable for the range of particles foreseen during severe accidents in several of the scenarios described in the introduction).

The experiments lasted about 30 min. Once the facility preconditioning was over (i.e., anticipated thermal-hydraulic boundary conditions like temperatures, flow rates, steam fraction, etc., became steady), the main experimental phase started with the particle injection and lasted about 15 min. Aerosol characterization was done at the same time periods at the inlet and outlet sampling stations. Along the injection phase two aerosol characterizations were intended by sampling at the inlet and outlet lines at the same time during about 7 min.

## 3. Results and discussion

The PSP experiments have been aimed at determining the retention efficiency at the inlet of the pool when particles are carried by a submerged jet. Hence, the main target variable of this research has been the retention efficiency (ε):

$$\varepsilon\ [\%] = \frac{m_{ret}}{m_{in}}\cdot 100 = \frac{m_{in} - m_{out}}{m_{in}}\cdot 100 \tag{4}$$

ε has been estimated from the concentration measurements (C) of DLPI and DLPI + taken at the inlet and outlet of the facility, respectively; according to the following equation:

$$\varepsilon\ [\%] = \left[1 - \frac{C_{out}}{C_{in}}\right]\cdot 100 \tag{5}$$

Note that ε is closely related to the so called Decontamination Factor (DF) used in many fundamental safety documents (Soffer et al., 1995),

$$DF\ [-] = \frac{m_{in}}{m_{out}} = \frac{1}{1 - {}^{\varepsilon}/_{100}} \tag{6}$$

so that, any result, discussion and/or conclusion from this study can be translated in terms of DF. This is particularly acceptable because in no test ε has resulted to be over 99%; if this had been the case, data uncertainties would have meant orders of magnitude in terms of DF (Herranz et al., 2017).

### 3.1. Primary observations

The PSP tests reached gas velocities characteristic of jet injection at the PECA pool inlet. As shown in Fig. 3, the image captured from one of the experiments (PSP5) resembles the widely known form of a submerged jet (Abd Alaal, 2012). Even though hydrodynamics is beyond the scope of this study, some remarks might be of interest for later discussions on scrubbing efficiency and tests representativity:

- Jet injection occurred in a pulsated way which frequency grew with gas flowrates (at the same pressure conditions at the injection point).
- The submerged jet trajectory was not steady and, once bending upwards, the location of the jet vertical axis oscillated; this effect looked tightly linked to water circulation loop set up in the pool between the injection point and the surface.
- Despite the low submergence set in the experiments, the transition from a quasi-horizontal jet to a bubble swarm region started in the water bulk; the latter was never fully developed, though.
- The water surface was rather rough and it looked heavily dependent on gas injection flow rates; the higher the flow rate, the more intense the water waviness and the larger the surface area affected by gas bubbling.

**Table 2**
Actual boundary conditions and test results.

| | | PSP0 | PSP1 | PSP2 | PSP3 | PSP4 | PSP5 | PSP6 |
|---|---|---|---|---|---|---|---|---|
| $T_g$ | ºC | 110.1 | 109.2 | 109.5 | 101.1 | 103.7 | 108.8 | 27.8 |
| $T_{pool}$ | ºC | 32.2 | 34.8 | 33.6 | 33.6 | 34.1 | 34.7 | 22.9 |
| $Q_{total}$ | l/min | 157.2 | 209.1 | 307.6 | 413.3 | 454.0 | 452.9 | 457.7 |
| $X_{steam}$ | % | 4.1 | 3.4 | 3.0 | 3.7 | 6.3 | 9.8 | 0.0 |
| $M^{a}_{in}$ | mg | 60.85 | 23.79 | 56.55 | 65.58 | 82.66 | 91.77 | 86.0 |
| $AMMD_{in}$ | μm | 0.9 | 0.7 | 0.9 | 1.0 | 0.8 | 0.8 | 0.9 |
| $GSD_{in}$ | [-] | 1.4 | 1.6 | 1.4 | 1.3 | 1.4 | 1.4 | 1.4 |
| $M^{**}_{out}$ | mg | 4.27 | 0.527 | 0.279 | 0.22 | 0.28 | 0.98 | 0.28 |
| $AMMD_{out}$ | μm | 1.4 | 1.4 | 1.4 | 1.6 | 1.3 | 3.9 | 1.4 |
| $GSD_{out}$ | [-] | 1.4 | 1.3 | 1.8 | 1.8 | 1.4 | 1.5 | 1.4 |
| ε | % | 92.92 | 97.78 | 99.51 | 99.66 | 99.66 | 98.93 | 99.68 |
| $\delta_\varepsilon$ | % | 0.14 | 0.30 | 0.06 | 0.18 | 0.07 | 0.05 | 0.19 |

[a] Mass obtained from the DLPI; **Mass obtained from the DLPI+.

Given the tight coupling between hydrodynamics and particle removal mechanisms (Herranz et al., 2014b), the gas behavior described presumably impacted in a strong way the entire scrubbing process.

Table 2 summarizes the actual boundary conditions of the experiments, the target measurements (i.e., inlet/outlet particles sizes and masses) and the derived efficiencies with their corresponding uncertainties. As can be noted, the thermal-hydraulic boundary conditions achieved have been close to the ones initially proposed (Table 1), particularly concerning temperatures and total flow rates; steam content was a bit more deviated, but still within an acceptable range. In Fig. 4 an example of the evolution of gas flow rates and temperatures along two of the experiments is shown. The most noticeable observation is the steadiness of the thermal-hydraulic variables during the periods of particle injection.

As for the injected particles, there are several observations to make. The particle mass taken to the pool has been in all the cases high enough as not to jeopardize reliability of gravimetric measurements at the outlet sampling station, which amounted to the range of 10 mg (the

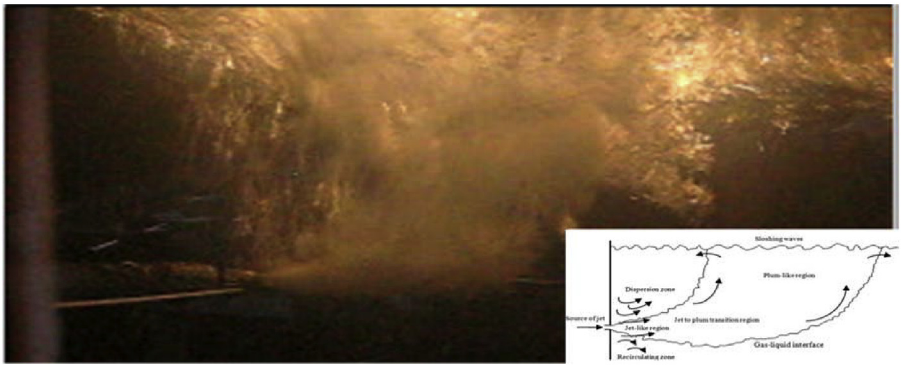

**Fig. 3.** Inlet region during PSP experiments (PSP5 test).

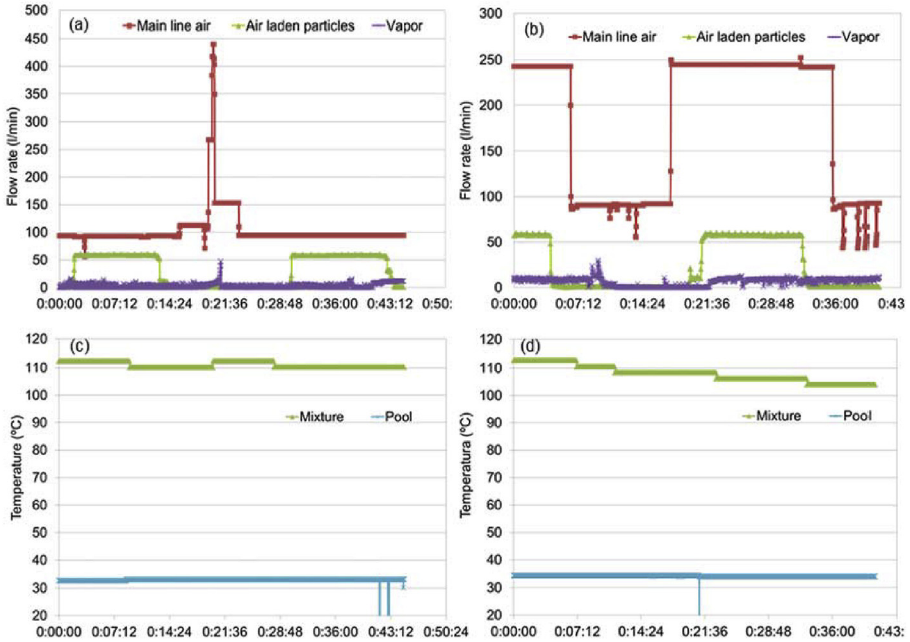

**Fig. 4.** Test boundary conditions (a) Gas/steam flow rates (PSP0); (b) Gas/steam flow rates (PSP2); (c) Gas and pool temperatures (PSP0); (d) Gas and pool temperatures (PSP2).

scale precision being more than $10^3$ times smaller, down to the μg range). Based on these measurements, it can be estimated that the total injected mass into the pool ranged from around 500 mg–1500 mg, depending on the experiment. As postulated, those particles' Aerodynamic Mass Median Diameters (AMMD) were in all the cases around 1 μm in a nearly monodisperse distribution (most GSD values being equal or lower than 1.4).

Concerning measurements at the outlet characterization station, DLPI + collected masses look consistent with the inlet ones, as they were lower than those in all the experiments. However, the size measurements were unexpected: after scrubbing AMMDs were larger than those at the inlet station. This unexpected result is discussed further below.

### 3.2. Scrubbing efficiency

From the data in Table 2 the scrubbing efficiency has been calculated through Eq. (4) and the results are plotted in Fig. 5. As noted, in all the tests most of the aerosol injected was retained in the pool. In the next paragraphs, the effect of different variables is analyzed.

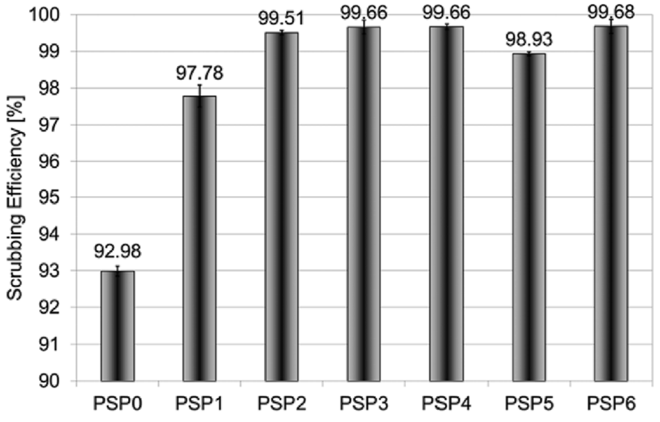

**Fig. 5.** PSP scrubbing efficiency.

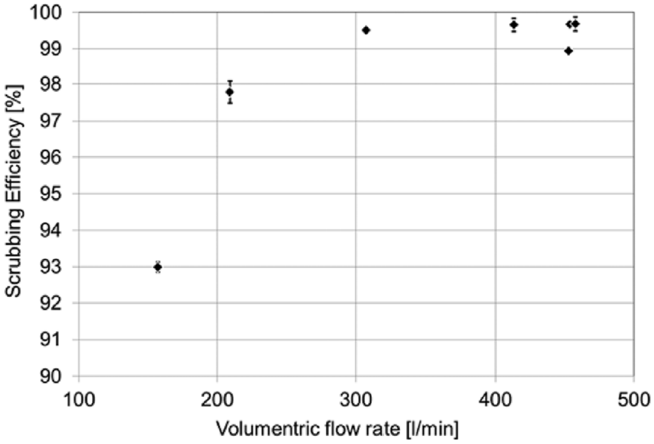

**Fig. 6.** PSP scrubbing efficiency vs. volumetric flow rate.

As expected, the volumetric flow rate plays a major role in the pool absorption of the particulate matter injected (Fig. 6). The growing trend observed when flow rates are increased from about 150 l/min to 300 l/min gets to a sort of asymptotic value around 99.5% at even higher rates. This is consistent with the fact that a high gas flow rate means a strong interaction in the gas-water interface (i.e., shear stress) that eventually causes water entrainment in the form of droplets within the gaseous bulk. In principle, three types of phenomena can affect particles removal in the jet (Berna et al., 2016): particle-droplet mechanical interactions; phoretic processes; and diffusion. Inertial impaction (i.e., bending of gas streamlines around obstacles makes particles leave their trajectories and collide with the obstacle surface) and interception (i.e., particles get so close to the obstacle surface that they hit this surface and deposit) are the main contributors to the mechanical phenomena. Thermal gradients (thermophoresis) as well as steam concentration gradients (diffusiophoresis) might cause particles removal from the gas phase; unlike the mechanical processes, these are not (or just weakly) dependent on particle size. Finally, diffusion (i.e., passive motion in particle concertation gradients) could also contribute to aerosol depletion in the jet, but this phenomenon is only effective for particles smaller than 0.1 μm.

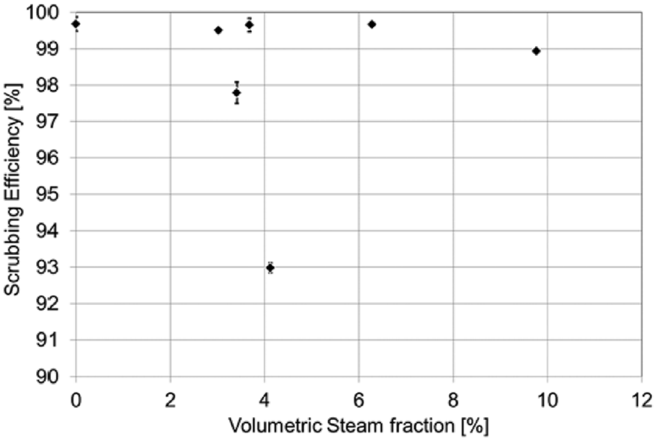

**Fig. 7.** PSP scrubbing efficiency vs. volumetric steam fraction.

Water entrainment mass flux is known to be proportional to the gas velocity whenever the liquid Reynolds number exceeds a threshold value (Fernandes et al., 2004). On the other side, the droplet size is inversely proportional to the gas velocity squared (Wallis, 1969). Both effects make an increase in the gas flow rates to result in more water in the gas bulk of the jet dispersed in the form of smaller droplets. In other words, airborne particles in the jet would be swept out from the gas more effectively due to the total gas-droplet interface surface. Under the prevailing conditions in the gas bulk of the jet the removal mechanism supposed to be dominant is inertial impaction, although interception may also contribute significantly (Herranz et al., 2014b). This discussion is consistent with the correlations derived for inertial impaction efficiency (Yung et al., 1978; Flagan and Seinfeld, 1988), which increases with gas flow rate. This trend is not observed in interception, which efficiency depends only on particle and drop sizes (Zhao and Zheng, 2008).

Contrary to what observed with gas flow rates, scrubbing efficiencies were not apparently affected (at least not noticeably) by steam fraction and gas-pool temperature difference (Fig. 7 and Fig. 8). Namely, neither phase changes nor thermal gradients at the gas-water interface of the jet had the potential to disturb the dominance of mechanical removal mechanisms, like inertial impaction. That is, the condensation of steam in those cases in which $P_{steam} \geq P_{sat}(T_{pool})$ (or evaporation from the water surface into the gas bulk if $P_{steam} < P_{sat}(T_{pool})$) does neither enhance nor hinder particle removal due to mechanical processes in such a significant way as to make this effect measurable.

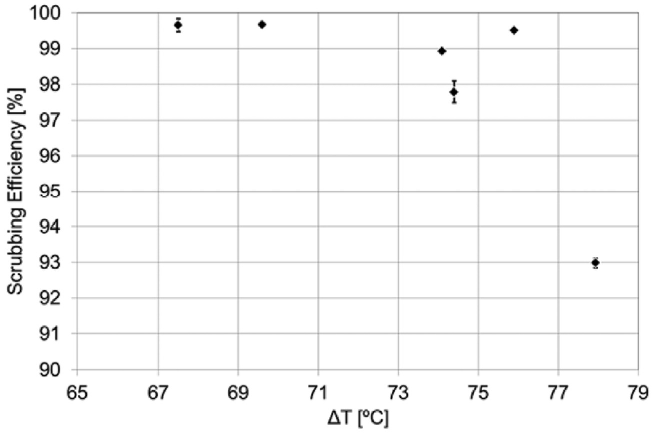

**Fig. 8.** PSP scrubbing efficiency vs. gas-water temperature difference.

In Fig. 5 through 8, the associated uncertainties to the scrubbing efficiency have been estimated from the error propagation theory. Accordingly, Eq. (7) has been used,

$$\delta\varepsilon\,[\%] = \delta\left(\left[1-\frac{C_{out}}{C_{in}}\right]\cdot 100\right) = \delta\left(\left[1-\frac{m_{out}}{m_{in}}\frac{V_{N_{in}}}{V_{N_{out}}}\right]\cdot 100\right)$$
$$= \left[\left|\frac{1}{m_{in}}\frac{V_{N.in}}{V_{N.out}}\right|\delta m_{out} + \left|\frac{m_{out}}{m_{in}^2}\frac{V_{N.in}}{V_{N.out}}\right|\delta m_{in} + \left|\frac{m_{out}}{m_{in}}\frac{1}{V_{N.out}}\right|\delta V_{N.in} + \left|\frac{m_{out}}{m_{in}}\frac{V_{N.in}}{V_{N.out}^2}\right|\delta V_{N.out}\right]\cdot 100 \tag{7}$$

where $m_{in}$ and $m_{out}$ are the mass measured at the inlet and outlet of the facility with DLPI and DLPI+, respectively, $\delta m_{in}$ and $\delta m_{out}$ their respective uncertainties, $V_{N\_in}$ and $V_{N\_out}$ are the sample volume normalized at the inlet and outlet of the facility, respectively, and $\delta V_{N\_in}$ and $\delta V_{N\_out}$ their respective uncertainties.

The uncertainty of each device ($\delta m_i$) has been obtained by adding the uncertainties associated to the individual stage measurements ($\xi_{stg(i)}$):

$$\delta m_i = \sum_{i=1}^{N} \xi_{stg(i)} + N\cdot\Delta\xi_{sys} \tag{8}$$

Where N is the number of stages, $\Delta\xi_{sys}$ is the systematic error of the balance affecting the last significant digit. As for $\xi_{stg(i)}$, it is estimated as the absolute difference between two consecutive weights of the stage ($\Delta m_{ij}$):

$$\xi_{stg(i)} = |m_{i1} - m_{i2}| \tag{9}$$

In the case of anomalous reading of weights (i.e., a specific stage weighs less after than before sampling), the stage error ($\xi_{stg(i)}$) is assumed to be the interpolated weight of the previous and subsequent stages whenever no major discontinuities exist between them.

This would result in the minimum uncertainty associated to the measurement, since mass loss may occur when managing the weighing process and this is hard to be quantified.

### 3.3. Particle size

The inlet and outlet AMMDs are displayed in Fig. 9 as a function of scrubbing efficiency. As observed, no trend with efficiency can be identified. Except for the PSP5 test (98.9% scrubbing efficiency), which outlet AMMD looks anomalous, the rest of tests shows an outlet-inlet ratio practically constant around 1.6 (2.0 in the PSP1 test). Nonetheless, as said in section 3.1, what might seem even more surprising is the systematic higher AMMD value at the outlet than at the inlet. During particle scrubbing in a mostly “inertial system”, as it is the one under investigation, when approaching a droplet, bigger particles would be more prone to abandon the flow streamlines and hit the water surface

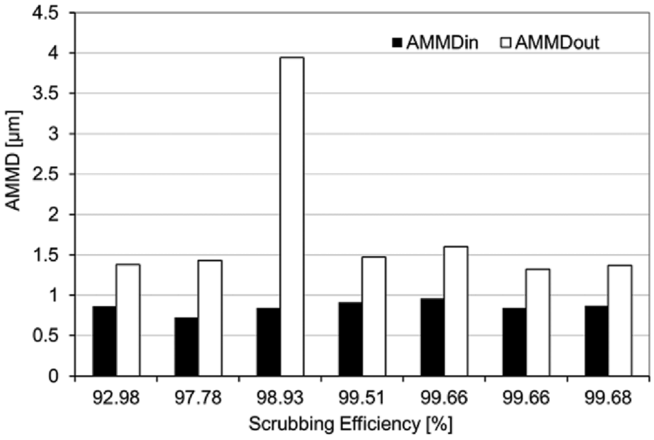

**Fig. 9.** Inlet and Outlet AMMDs of PSP tests.

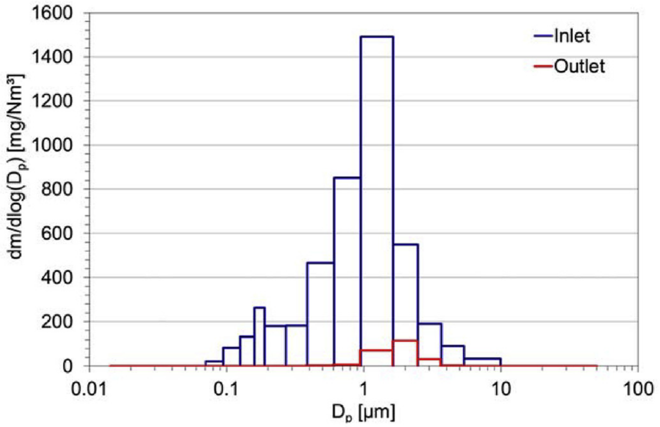

**Fig. 10.** Inlet and Outlet size distribution of the PSP0 test.

than smaller ones, so that size distributions would tend to shift towards smaller diameters. This rationale looks pointing right the reverse trend to the one observed (Fig. 9).

There might be several potential reasons for that observation, though: the sampling hood located right over the pool surface might have fostered gas recirculation loops making particles agglomerate before being sucked towards the measuring devices; the gas sampled sucked through the hood top might have contained not just particles but also tiny water droplets that might get to the measuring device; both contribute to some extent to the observations made; etc. Anyway, whatever the reason is, this slight particle shifting towards bigger sizes hardly has any significance. When looking deeper into any of those experiments, one might find size distribution profiles like the one in Fig. 10. The mass reduction in between both distributions is so large that withdrawing any conclusion from the comparison would be very uncertain, since very likely experimental errors when managing individual stage measurements of DLPI + might strongly affect observations. Note that the experiment chosen in Fig. 10 is the one with lower efficiency, so that in all the other tests this mass reduction is even larger.

### 3.4. Empirical correlation

Pool scrubbing codes (Owczarski and Burk, 1991), as well as specific modules in integral severe accident codes (MELCOR; Humphries et al., 2015), do not have proper models for jet scrubbing. Some attempts to model scrubbing under jet injection regime have been recently reported (Berna et al., 2016). The approach followed by Berna is in between mechanistic and empirical nature. Even though phenomena are individually modelled, final expressions rely on empirical correlations in most cases, sometimes based on scenarios other than submerged jets, like annular regime in in-pipe flows. Despite the efforts made, the validation of this approach is rather limited and the parameters that the modeller should feed into the model are too many. Given the nature of the investigation described in the preceding sections, a purely empirical approach is presented next.

In order to derive a robust correlation, the most extensive and sound database addressing jet scrubbing during severe accidents has been gathered. A literature survey has been conducted and in addition to the 7 PSP experiments, 17 more tests from other 4 experimental programs have been considered (RCA, Peyrés et al., 1995; Escudero et al., 1995; Herranz et al., 1997; EPRI, Kuhlman et al., 1983; Flanigan et al., 1983; POSEIDON, Dehbi et al., 2001; ARTIST, Lind and Suckow., 2010). The selected tests have two common features: particles were driven into the pool under jet regime and pool submergence was limited to less than 0.5 m. According to Zhao and Irons (1990), the first criterion is met whenever the test non-dimensional Weber number is calculated to be over the so called Critical Weber number (i.e., $We_{Test} \geq We_c$). On the other side, the low submergence condition is postulated to guarantee that most scrubbing can be attributed to jet-related particle removal mechanism. Table 3 collects and describes all those data in terms of $We_c$, $We_{Test}$, Stk and S, which have been derived from the data reported in the references cited above. The first two have been used to confirm the gas injection under jet regime, whereas the last two are included to characterize two of the most significant particle removal mechanisms in jet scrubbing at the entrance region of the pool: inertial impaction (Stk) and steam condensation/evaporation (S). Namely, the correlation intended could be generally expressed as:

**Table 3**
Jet scrubbing database.

| Test | $We_c$ [-] | $We_{Test}$ [-] | Stk [-] | S [-] | ε [%] |
|---|---|---|---|---|---|
| **RCA tests** | | | | | |
| RCA1 | 334 | 1935 | 0.4107 | 0.0000 | 92.187 |
| RCA2 | 333 | 1849 | 0.4832 | 0.0000 | 96.46 |
| **EPRI tests** | | | | | |
| EPRI-V2 | 301 | 891 | 0.0025 | 0.0000 | 67.742 |
| EPRI-V3 | 301 | 2004 | 0.0038 | 0.0000 | 28.571 |
| EPRI-V5 | 301 | 891 | 0.1155 | 0.0000 | 99.791 |
| EPRI-V2-steam1 | 342 | 1143 | 0.0033 | 39.8148 | 99.5 |
| EPRI-V3-steam1 | 330 | 2760 | 0.0049 | 26.2145 | 94.444 |
| EPRI-V3-steam2 | 330 | 2760 | 0.0049 | 39.8148 | 94.444 |
| EPRI-V5-steam1 | 342 | 1143 | 0.1482 | 39.8148 | 99.975 |
| **POSEIDON tests** | | | | | |
| PA07 | 371 | 9276 | 0.0074 | 1.5509 | 84.871 |
| PA13 | 382 | 6498 | 0.0066 | 0.0000 | 61.39 |
| PA21 | 390 | 3027 | 0.0015 | 1.6992 | 59.184 |
| PA24 | 367 | 11743 | 0.0030 | 1.8417 | 92.366 |
| **ARTIST tests** | | | | | |
| ARTIST-E07 | 318 | 853 | 0.0211 | 0.0000 | 98.113 |
| ARTIST-E08 | 318 | 855 | 0.1479 | 0.0000 | 99.927 |
| ARTIST-E09 | 337 | 148253 | 0.2946 | 0.0000 | 99.917 |
| ARTIST-E10 | 337 | 147455 | 2.0514 | 0.0000 | 99.964 |
| **PSP tests** | | | | | |
| PSP0 | 346 | 514 | 0.0274 | 0.8380 | 92.92 |
| PSP1 | 345 | 368 | 0.0102 | 0.6499 | 97.78 |
| PSP2 | 345 | 793 | 0.0241 | 0.7390 | 99.51 |
| PSP3 | 332 | 1551 | 0.0360 | 1.1115 | 99.66 |
| PSP4 | 331 | 1882 | 0.0303 | 1.9774 | 99.66 |
| PSP5 | 334 | 1848 | 0.0302 | 2.7917 | 98.93 |
| PSP6 | 295 | 2360 | 0.0327 | 0.0000 | 99.68 |

$$\varepsilon = f\,(Stk;\ S)$$

It is worth mentioning that the entire database includes particles ranging from submicronic to micronic diameters, presence and absence of steam in the carrier gas, upward and horizontal injection and bare and surface-submerged pools.

The best fit of all the data used was achieved by the equation,

$$\varepsilon\ [\%] = \frac{0.98}{1 + 1.0847{*}Exp(-1.0528{*}10^{8}{*}Stk^{3.7885} - 0.7257{*}S)}{*}100 \tag{10}$$

which showed a determination coefficient ($R^2$) of 0.8. Regardless the $R^2$ value the qualitative behaviour of the expression is physically consistent with the fact that inertial depletion mechanisms dominate water trapping of particles under jet injection regime. In Fig. 11 the Eq. (10) is plotted vs. the non-dimensional Stokes number (Skt) for several values of the saturation ratio (S). The characteristic sigmoidal profile of Stokes driven-mechanisms (Herranz and Lopez, 2012) shows a fast transition between the lower and upper bounds at Stokes numbers between 4E-3

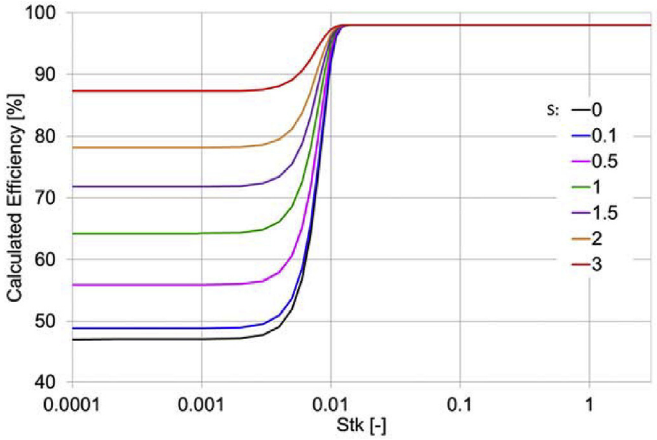

**Fig. 11.** Correlation efficiency vs. Stk for different S.

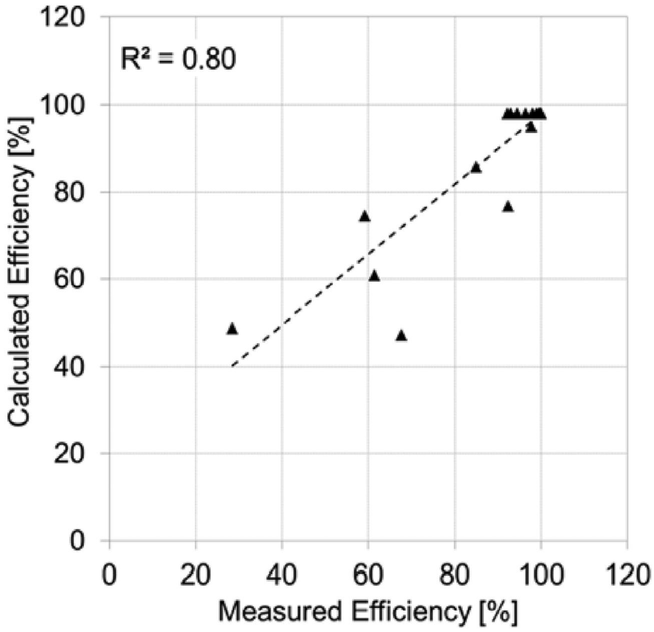

**Fig. 12.** Calculated vs. Measured scrubbing efficiencies.

and 1.4E-2 for all the S values; in other words, at Stokes values lower than 1.4E-2 the efficiency would experience a noticeable decrease.

Fig. 12 shows correlation estimates of scrubbing efficiencies vs. data. Two observations can be made: the equation allows following the efficiency growth trend measured with some deviations; and more of the 80% of the data available are in the efficiency band ranging from 0.9 to 1.0. Given the diversity of scenarios tested, this seems to point out that jet scrubbing is mostly associated with high particle retention in the pool entrance region. Only those experiments in which particle diameters were equal or smaller than 0.4 μm and with no steam in the carrier gas resulted in efficiencies lower than 0.8.

Fig. 13 shows the scrubbing efficiency ratio between the estimations and experimental data distributed along in the Stk (Fig. 13 a) and S (Fig. 13 b) domains. As noted, both Stk and S range over a wide interval, from $10^{-3}$ to 2.0 and from 0.0 up to 3, respectively. As displayed in the figure most of estimates get certainly near the corresponding data with only few deviations occurring in the low range of Stk ($Stk < 0.01$), when particles experience a weak inertial force; similarly, the larger derivation noted occurred in total absence of steam.

In fact, the correlation found has an average relative error of 7.8%. For particles with Stk higher than 0.01, the average relative error of the correlation would be less than 2.2%. In other words, the higher errors affecting correlation estimates will be associated to particles that would mean a small fraction of the total mass entering the pool. Therefore, the correlation derived can be said to be quantitatively and qualitatively acceptable for estimating jet scrubbing. Nonetheless, further data should be obtained in the region of scrubbing efficiencies lower than 0.8, so that this specific zone is better described.

### 3.5. *Insights for further experimentation*

The broad range of conditions, the difficulty of controlling and monitoring every variable that play a key role on the retention mechanism, the harsh prevailing conditions for some of the most important instrumentation, like presence of humidity and particle characterization and so forth, make pool scrubbing experimentation a challenging task. Thus, as a side outcome from this investigation a set of lessons has been withdrawn and is discussed next:

- **Injected particulate mass.** Given the high efficiency reached under jet regime, it is very important to inject particulate mass in such an amount that even at the upper bound of the efficiency range (over 95%), the mass coming out from the pool is sufficient to be measured properly, so that outlet measurements reliability and accuracy are not jeopardized.
- **Sampling enhancement and particle measurements.** Sampling is always a key aspect in aerosol experiments, but even more in case of tests with minor amounts of particulate material. Beyond the difficulty of conducting isokinetic samplings, there are two main issues to tackle with in pool scrubbing tests under representative conditions: experimenting with a gas mixture containing steam poses the challenge of avoiding any potential cold spot on which steam could condense (i.e., all the piping, particularly sample extraction lines, should be cautiously insulated); pool outlet measurements should take representative samples of the particulate mass escaping the water surface (i.e., this issue is particular relevant in mid and large scale facilities).

  Accuracy of data would be enhanced if integral measurements of particle characterization (i.e., those steming from the analysis of a sample taken over a period of time, like DLPI and DLPI+) were supplemented with instantaneous measurements (like those from devices like APS and/or ELPI); nonetheless, this would require a powerful pre-test campaign addressing the anticipated experimental conditions to overcome the difficulties that these devices might experience (Pagels et al., 2005). Of course, adding filters to the mass balance would also strengthen the database.
- **Test matrix extension.** Despite the key insights provided by this investigation, a comprehensive analysis of jet scrubbing would require an extension of the available database (these data included). In particular, more experiments should be conducted near the lower range of the jet regime; even some of the experiments should be exactly repeated but at much lower gas velocities characteristic of globule regime ($We < We_c$). As for the in-jet saturation, several additional experiments would be also recommendable at under- and over-saturated conditions, and some should be done under identical conditions, but with different saturation ratios and steam fractions. Concerning the domain extension of the database to some other variables, particle composition and multiple orifices injection should be considered. The PSP matrix explored non-hygroscopic $SiO_2$ particles, so that some parametric tests using soluble materials, like CsOH or CsI, might be undertaken to complete the picture. Single-horizontal injection has been studied in the PSP experiments; given the significance of hydrodynamics in all the aerosol processes, some scaled-down experiments with several adequately oriented holes (ideally based on scaling down actual NPP quenchers) would complete the picture bringing data to more representative conditions.
- **Submergence parametric study.** Water depth was not an

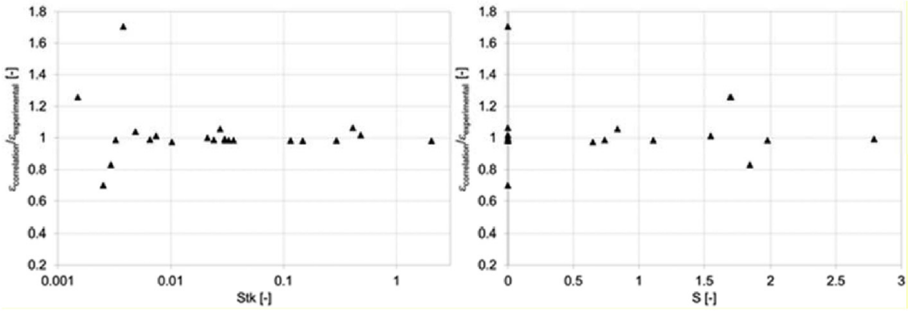

**Fig. 13.** Scrubbing efficiency ratio vs. Stk (a) and S (b).

experimental variable in the PSP tests, but it was set to a small value (0.3 m) in this research to intend to discriminate inlet and rising scrubbing regions. However, some observations indicated that the results from the investigation might be dependent on the submergence set, as discussed next.

Water motion (i.e., water moves upward near the injection radial position and returns back down next to the facility walls) strongly affects particles scrubbing through several key variables, like the relative gas-water velocity controlling droplet entrainment or the gas residence time in the pool. Gas-to-water momentum transfer responsible for such motion is heavily dependent on the water mass inside the pool over the injection point (horizontal/upward vertical injection assumed); that is, submergence. Beyond the effect on specific scrubbing variables mentioned, water motion also conditions pool-atmosphere exchanges by affecting water surface structure, smooth at low water velocities and rough (even wavy) at high water velocities. Finally, it is important to note that water motion is in turn affected by the facility dimensions, so that attention should be paid to the scale down issue for future experiments.

Submerged gas jets trajectories are usually split into momentum-driven and buoyant-driven regions (Abd-Alaal, 2012), and a transition between both occurs at some point in the water. It is likely that some of the experimentally observed retention in the PSP tests was associated to the buoyant (rise) region and not just to the momentum-driven (jet) one, which is the focus of this research.

Following the approach adopted in this study (i.e., constant low submergence), some tests should be repeated under the same conditions but with different submergences (0.1 m, 0.5 m and 1.0 m, for example) to be able to assess the impact of the phenomena discussed above.

- **Supplementary hydrodynamic studies.** Hydrodynamics has been demonstrated to be a “hard” boundary condition in pool scrubbing experiments (Herranz et al., 2014b). This is even further stressed in the pool inlet region under high gas velocities. Therefore, it is highly recommended to carry out a supplementary hydrodynamic research when conducting scrubbing experiments. Such an investigation might be either integrated in the scrubbing tests, which would result in very demanding experimentation where both particles and in-pool gas variables should be monitored and recorded, or conducted as a parallel experimentation under the same conditions as the scrubbing tests, since particles are supposed to have little feedback on jet hydrodynamics.

  Even though some of the most influencing variables on particles scrubbing seems to be hard to measure, like droplets features, some promising studies have progressed in this direction (Abd Alaal, 2012) and are worth to be continued. Ideally, in addition to variables like jet penetration, water entrainment or jet pinch-off frecuency, specific droplets variables (i.e., number, velocity and size) would be very valuable for a thorough scenario understanding and model development and validation.

## 4. Final remarks and conclusions

Here below the main insights from the investigation conducted on jet scrubbing are withdrawn together with the lessons learned for forthcoming research on the issue. The main conclusions worth to be highlighted are:

- Submerged gas hydrodynamics is crucial for jet scrubbing, not just because of the strong interfacial interaction between gas and water and the jet boundaries, but because of implications on in-pool water motion or pool-atmosphere interface morphology and dynamics.
- Particle scrubbing at the pool inlet region is highly effective once gas enters the pool as a submerged jet (i.e., jet scrubbing), regardless thermal boundary conditions. Whenever particle size and gas velocity result in Stokes values higher than $10^{-2}$, even if no steam condensation occurs, mechanical processes become responsible for a particulate mass removal higher than 90%; according to observations, inertial impaction is postulated to be the dominant aerosol removal mechanism. Factors like presence of submerged surfaces and the injection orientation have a negligible effect compared to the one of the intrinsic phenomena resulting from the high velocity injection.
- A correlation for the jet injection scrubbing at the pool inlet based on an extended database built up under the assumption that all particle scrubbing in low submergence tests is due to jet scrubbing, has been developed. The equation derived depends on non-dimensional Stokes number and saturation ratio and, according to data-estimates comparison, it seems a promising via of modeling. Nonetheless, it should be further assessed once the database is expanded with data points showing efficiencies lower than 90%. This approximation, although still premature, looks more defendable than just running traditional pool scrubbing codes with no specific modeling for jet injection regime or relying on semi-mechanistic approaches that in the end need the user to input a good number of parameters.

It should be emphasized that these conclusions should be confirmed with further experiments in which particle measurements should be enhanced as much as possible and data uncertainties more precisely estimated, particularly when aiming to the high efficiency region between 90 and 100%.

Regarding major takeaways for future pool scrubbing related experimental campaigns:

- Experimental investigation on jet injection scrubbing should be further continued. In order to build a broad and reliable database supporting development and/or validation of suitable models through phenomenological understanding, the experimental domain to be addressed should be stretched out by extending the range explored in the PSP tests (i.e., lower We numbers; particle diameter and composition; etc.) and by including presumably influencing variables which effects have been discussed to have the potential to be significant (i.e., submergence).

- Hydrodynamic tests aimed at characterizing specific variables of submerged jets are indispensable. To gain key insights into the process of jet scrubbing hydrodynamic variables should be tracked, particularly those related to entrained droplets (i.e., size, velocity, trajectories, etc.). Needless to say that test boundary conditions should be those anticipated during risk-dominant severe accidents involving jet scrubbing (i.e., high pressure SBO in BWRs or SGTR in PWRs).
- Measurement techniques should be given utmost attention. Jet scrubbing entails huge challenges to achieve good particulate and hydrodynamic characterizations. Significant efforts might be needed for identification and optimization of techniques to be used and protocols to be implemented. In this regard, it is highly likely that specific developments are necessary before undertaking the main experimental campaign.

On line with a point made earlier and intrinsically related to measurements, accurate estimation of data uncertainties should be given an outstanding relevance in any forthcoming experimental program.

At the heart of the first two bullets is possibly the main concern raised from the observations made during the PSP campaign: the need to conduct properly scaled-down experiments. Given the strong interaction among the multiple phases in jet scrubbing (i.e., particulate matter, non-condensable gas, steam and water), the experimental work to be planned should carefully look at scaling. Set-ups should guarantee that phase-to-phase interactions do suitably capture all influencing factors playing a key role in the scenario, like potential phase changes and gas-to-water and water-to-gas momentum exchanges. In case tests do not meet this requirement, their contribution for model development and/or validation would be weak to say the least.

## Acknowledgements

The authors acknowledge the work done by the technical team of LASS in the upgrade of the PECA-PS facility and the preparation and execution of the experiments and thank particularly Jorge Faba for his enthusiasm.

This work has been partially funded by the 7th FWP of EURATOM through the EU-PASSAM project (Grant agreement No. 323217 – Euratom 7FP). The authors are indebted to all the EU-PASSAM partners for their technical support.

## Acronyms and nomenclature

*Acronyms*

| | |
|---|---|
| AMMD | Aerodynamic Mass Median Diameter |
| APS | Aerodynamic Particle Sizer |
| ASME | American Society of Mechanical Engineers |
| BWR | Boiling Water Reactor |
| CIEMAT | Centro de Investigaciones Energéticas Medioambientales y Tecnológicas |
| DF | Decontamination Factor |
| DLPI | DEKATI Low Pressure Impactor |
| ELPI | Electrical Low Pressure Impactor |
| GSD | Geometric Standard Deviation |
| LASS | Laboratory for Analysis of Safety Systems |
| NPP | Nuclear Power Plants |
| PECA-PS | Plant for Experimental Characterization of Aerosols on Pool Scrubbing |
| PLC | Programmable Logic Controller |
| PSP | PECA-PS experimental campaign |
| PWR | Pressurized Water Reactor |
| SBOs | Stations BlackOut |
| SCADA | Supervisory Control And Data Acquisition |
| SGTR | Steam Generator Tube Rupture |

*Nomenclature*

| | |
|---|---|
| A | Area |
| C | Aerosol concentration |
| d | Diameter |
| ε | Efficiency |
| i | Indicator of Impactor's Stage |
| m | Mass |
| N | Number of stages of the impactor |
| P | Pressure |
| Q | Volumetric flow rate |
| S | Saturation ration |
| Stk | Stokes number |
| T | Temperature |
| v | Velocity |
| V | Volume |
| We | Weber number |
| X | Fraction |
| δ | Uncertainty associated with a measurement |
| ξ | Error |
| ρ | Density |
| σ | Water surface tension |

*Subscripts*

| | |
|---|---|
| c | Critical |
| g | Gas |
| in | Inlet |
| l | Liquid |
| N | Normalized |
| out | Outlet |
| pool | Pool |
| sat | Saturation |
| steam | Steam |
| stg | Stage |
| sys | Systematic |
| test | Test |
| c | Critical |

## References

Abd-Alaal, K.H.M., 2012. Experimental and Theoretical Study of the Characteristics of Submerged Horizontal Gas Jets and Vertical Plunging Water Jets in Water Ambient (Doctoral Thesis at the Polytechnic University of Valencia Institute for Energy Engineering Department of Chemical and Nuclear Engineering). .

Allelein, H.-J., Auvinen, A., Ball, J., Güntay, S., Herranz, L.E., Hidaka, A., Jones, A.V., Kissane, M., Powers, D., Weber, G., 2009. State of the Art Report on Nuclear Aerosols. NEA/CSNI/R(2009)5 November 2009. .

Albiol, T., Herranz, L.E., Riera, E., Dalibart, C., Lind, T., Del Corno, A., Kärakela, T., Losch, N., Azambre, B., 2017. Main results of the European PASSAM project on severe accident source term mitigation. In: Proceedings of the European Review Meeting on Severe Accident Research, Warsaw (Poland), May 16-18, 2017.

Berna, C., Escrivá, A., Muñoz-Cobo, J.L., Herranz, L.E., 2016. Enhancement of the SPARC90 code to pool scrubbing events under jet injection regime. Nucl. Eng. Des. 300, 563–577.

Dehbi, A., Suckow, D., Guentay, S., 2001. Aerosol retention in low-subcooling pools under realistic accident conditions. Nucl. Eng. Des. 203, 229–241.

Escudero, M.J., Marcos, M.J., Swiderska-Kowalczyk, M., Martin Espigares, M., Lopez Jimenez, J., 1995. State of the Art Review on Fission Products Aerosol Pool Scrubbing under Severe Accident Conditions: Final Report. Report EUR 16241 EN. (1018-5593).

Fernandes, R.J.L., Jutte, B.M., Rodriguez, M.G., 2004. Drag reduction in horizontal annular two-phase flow. Int. J. Multiphas. Flow 30, 1051.

Flagan, R.C., Seinfeld, J.H., 1988. Fundamentals of Air Pollution Engineering. PrenticeHall, Englewood Cliffs, New Jersey.

Flanigan L.J., Paul D.D., Collier R.P., Cudnik R.A. and Oehlberg R.N., "Radionuclide scrubbing in water pools: bubble hydrodynamics", Proceedings of Conference on Thermal Hydraulics of Nuclear Reactors, Santa Barbara, USA, January 1983.

Herranz, L.E., Peyrés, V., Polo, J., Escudero, M.J., Espigares, M.M., López-Jiménez, J., 1997. Experimental and analytical study on pool scrubbing under jet injection regime. Nucl. Technol. 120, 95–109.

Herranz, L.E., Berna, C., Escrivá, A., Muñoz-Cobo, J.L., 2012. Pool scrubbing under jet injection regime: an enhancement of the SPARC90 code. In: Proceedings of the

International Conference of Advanced Nuclear Power Plants 2012, ICAPP'12, Chicago (USA), June 24-28, 2012.

Herranz, L.E., Lopez, C., 2012. ARI3SG: aerosol retention in the secondary side of a steam generator. Part I: model essentials, verification and correlation. Nucl. Eng. Des. 248, 270–281.

Herranz, L.E., Tardáguila, R.D., Betschart, T., Lind, T., Morandi, S., 2014b. Remaining issues in pool scrubbing: major drivers for experimentation within the EU-PASSAM Project. In: Proceedings of the International Congress of Advanced Nuclear Power Plants 2014, ICAPP'14, Charlotte (USA), April 6-9, 2014.

Herranz, L.E., Lind, T., Dieschbourg, K., Riera, E., Morandi, S., Rantanen, P., Chebbi, M., Losch, N., 2014a. Technical bases for experimentation on source term mitigation: the EU-PASSAM project. In: The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10), Okinawa, Japan, December 14-18, 2014.

Herranz, L.E., Iglesias, R., Fontanet, J., 2017. Mitigation of source term in suppression pools: large uncertainties in predictability. In: 8th European Review Meeting of Severe Accident Research (ERMSAR), Warsaw (Poland), May 16-18, 2017.

Humphries, L.L., Cole, R.K., Louie, D.L., Figueroa, V.G., Young, M.F., 2015. MELCOR Computer Code Manuals Vol. 2: Reference Manual Version 2.1.6840. SAND2015–6692 R.

Kuhlman, M.R., Gieseke, J.A., Merilo, M., Oehlberg, 1983. Scrubbing of Fission Product Aerosols in LWR Water Pools under Severe Accident Conditions. IAEA-SM-281/47. .

Lind T., Suckow D., "reportReport on the ARTIST II Phase V: Tests for the Aerosol Retention in the Flooded Bundle". TM-42-10-02 ARTIST-84-09, Feb. 2010.

Marcos, M.J., Gómez, F.J., Melches, I., Martín, M., López, J., 1994. Lace-españa Experimental Programme on the Retention of Aerosols in Water Pools. (0214-087X)CIEMAT, pp. 740.

Owczarski, P.C., Burk, K.W., 1991. SPARC-90: a Code for Calculating Fission Product Capture in Suppression Pools NUREG/CR – 5765.

Pagels, J., Gudmundsson, A., Gustavsson, E., Asking, L., Bohgard, M., 2005. Evaluation of aerodynamic particle sizer and electrical low-pressure impactor for unimodal and bimodal mass-weighted size distributions. Aerosol. Sci. Technol. 39, 871–887.

Peyrés, V., Espigares, M., Polo, J., Escudero, M.J., Herranz, L.E., López, J., 1995. Pool Scrubbing and Hydrodynamic Experiments on Jet Injection Regime. CIEMAT, pp. 785.

Soffer, L., Burson, S.B., Ferrell, C.M., Lee, R.Y., Ridgely, J.N., 1995. Accident Source Terms for Light-water Nuclear Power Plants. Final report, NUREG-1645. .

Wallis, G.B., 1969. One-dimensional Two-phase Flow. McGraw-Hill, New York.

William, C.H., 1999. Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, second ed. Wiley-Interscience, New York, USA.

Yung, S.-C., Calvert, S., Barbarlka, H.F., 1978. Venturi scrubber performance model. Environ. Sci. Technol. 12 (4), 456.

Zhao, Y.F., Irons, G.A., 1990. The breakup of bubbles into jets during submerged gas injection. Metall. Mater. Trans. 21, 997. http://dx.doi.org/10.1007/BF02670270.

Zhao, H., Zheng, C., 2008. Modeling of gravitational wet scrubbers with electrostatic enhancement. Chem. Eng. Technol. 31 (12), 1824.