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# Mitigation of source term in suppression pools: Large uncertainties in predictability ☆

L.E. Herranz *, R. Iglesias, J. Fontanet

*Unit of Nuclear Safety Research, CIEMAT, Av. Complutense 40. 28040 Madrid, Spain*

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ABSTRACT

The Fukushima accident has revived the interest of suppression pools as a passive way to scrub radioactivity from the gas reaching the aqueous volume in case of a severe accident. However, modeling of pool scrubbing is far from being mature. This paper focuses on the scrubbing occurring at the nearby of the injection point and, by illustrating how far from observations prediction can be, it highlights the importance of developing proper models at this region of the pool. To do so, a specific simple ASTEC model has been set-up and a jet scrubbing database has been gathered from the open pool scrubbing literature by picking suitable tests in which all the key initial and boundary conditions were recorded and reported. In particular, low-submergence experiments with high injection velocity experiments have been chosen to address what is known as jet scrubbing (i.e., scrubbing at the inlet region when particles are carried in the pool by a gas submerged jet).



## 1. Introduction

Suppression Pools were reminded to be a key safety feature of BWR technology by the Fukushima accident (Nuclear Emergency Response Headquarters, 2011). Their performance, though, had been profusely investigated back in the 70′s and 80′s, both as an energy and mass sink (Patterson, 1979; Su, 1981) and later in the 80′s and 90′s as an effective filter for fission products and aerosols (Escudero et al., 1995). Current investigations of the three accidents occurred at the Fukushima-1 site (Herranz et al., 2015a,b; Pellegrini et al., 2015) are highlighting that pools might have strongly affected the accidents unfolding and the resulting source term to the environment.

Recent investigations (Herranz et al., 2014) have pointed out that despite the progress achieved through previous research, there are still knowledge gaps concerning safety-significant phenomena that might dominate radioactive mitigation within aqueous ponds. Among them a few examples may be mentioned: high injection velocities of the carrier gas (i.e., jet injection regime), gas rise hydrodynamics under both bubbly regime (low gas velocity) and churn-turbulent flow (high gas velocity) or the effect of submerged structures. These and other phenomena have been either barely studied in the past or investigated in a non-systematic way, so that no sound model and/or correlation development has been feasible. Some of these phenomena are being studied accounting the results produced by the EU-PASSAM project of the 7th Framework Programme of EURATOM (Lind et al., 2015).

The present paper aims at assessing the ASTEC 2.0 code (Chatelard et al., 2014) capability for modeling pool scrubbing. In particular, the code ability to predict particles retention at the nearby of the injection point at high gas injection velocity, is to be checked against the experimental data available. To do so, a peer review of the database has been previously conducted and the specific useful experiments chosen and fully characterized accordingly with the modeling needs. Given the integral nature of ASTEC, the model built-up to run the code in a sort of stand-alone way is to be also described. This work is part of the CIEMAT contribution to the EU-CESAM project of the 7th Framework Programme of EURATOM.

## 2. Background

Removal of contaminating particles and/or vapours from a carrier gas passing through an aqueous pond is known as pool scrubbing. The scrubbing or filtration efficiency (η) is usually expressed in terms of the Decontamination Factor (DF), which is defined by the ratio of the aerosols mass entering ($m_{in}$) and leaving ($m_{out}$) the pool (or the filtration system):

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

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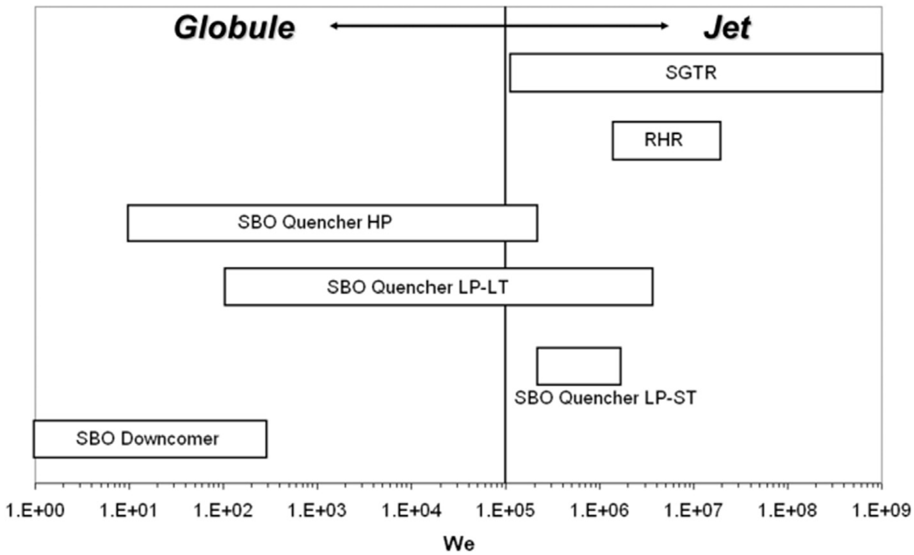


**Fig. 1.** Map of accident sequences as a function of the injection regimes (SGTR-Steam Generator Tube Rupture, SBO – Station Blackout, RHR-Residual Heat Removal).

$$DF = \frac{m_{in}}{m_{out}} = \frac{1}{1-\eta}$$

Based on the different nature of hydrodynamic and vapour/aerosol phenomena governing the pool scrubbing decontamination, the carrier gas pathway through the aqueous volume is split into three regions: injection, rise and pool surface. Consistently, the overall DF may be written as a multiplication of individual DFs:

$$DF = DF_{inj} \cdot DF_{rise} \cdot DF_{sur}$$

At the injection zone in the pool, the mechanical as well as the thermal gas-liquid interaction determine the scrubbing process. The gas composition and velocity are key variables in this region. The inlet gas regime is usually classified according to the non-dimensional Weber number ($We = \frac{\rho_l \cdot D_{inj} \cdot v_{inj}^2}{\sigma}$) as: jet regime ($We \geq 10^5$) and globule regime ($We < 10^5$), where $\rho_l$ is the pool liquid density, $D_{inj}$ is the injector diameter, $v_{inj}$ is the exit velocity of the gas, and $\sigma$ the pool liquid surface tension (Flanigan et al., 1983). Under the jet regime liquid drops are entrained in the gas bulk and decontamination through inertial and non-inertial droplet-particles and droplet-vapours interactions is enhanced. At moderate or low gas velocities a globule forms and grows attached to the injection point; until globule detaches, a number of mechanisms contribute also to contamination removal, but their net effect is less than under jet regime. Regardless injection regime, whenever partial steam pressure in the gas is higher than saturation pressure at pool temperature, steam condensation enhances scrubbing. During gas rise through the pool, hydrodynamics heavily affects scrubbing efficiency. Hydrodynamic phenomena in this region (i.e., globule break-up, swarm formation, gas internal circulation, etc.) have been traditionally described through laws governing the bubbly flow regime; however, as gas velocity increases other more stochastic 2-phase flow regimes may develop (i.e., churn-turbulent flow). At the pool surface, bubbles rupture causes micro-droplets. Some of them can be entrained by the gas flow while the others fall back due to their size by gravity. These entrained droplets transport very fine aerosol particles as well as dissolved fission products.

During the 80′s some pool scrubbing codes were developed: SPARC90, BUSCA and SUPRA. In fact, current integral severe accident codes, like MELCOR and ASTEC, do have integrated adaptations of the SPARC code (Owczarski and Burk, 1991). Extensive data-predictions comparisons have since been set (Fischer, 1998; Herranz and Fontanet, 2009), but a systematic validation process has not been feasible due to shortcomings in the available database (Herranz et al., 2014).

In-code implemented models are necessarily based on hypotheses and approximations, some of whom are far simpler than reality. For example, the application of globule formation model to high gas injection velocities, though, is not suitable since anticipated gas-liquid and droplets-particles interactions are drastically different (Berna et al., 2016). Unfortunately, separate effects data are often not available or are too uncertain, so that specific comparisons of model estimates and data cannot be reliably set (uncertainties in pool scrubbing models might result in factors around 100 in the containment radioactivity levels according to Fischer-1998). Therefore, a systematic validation of codes and models would require building up a suitable database for this purpose. This is particularly true for the decontamination near the injection point under high injection velocities (i.e., jet regime), although recently some tentative modeling has been proposed (Berna et al., 2016; Herranz et al., 2013), although it is still in an initial development phase.

## 3. Data base on “jet scrubbing

As shown in Fig. 1, in some of the most risk-significant severe accident sequences fission products are carried to aqueous ponds at high injection velocities characteristic of submerged jets. Given the high impact of inertial mechanisms at the injection nearby under such conditions (i.e., most radioactive mass is highly likely to be trapped at this pool zone), a thorough validation of the specific codes formulation for such region ($DF_{inj}$) is essential for analytical tools to gain some credit. For this purpose, a peer review of pool scrubbing database has been carried out. As no specific separate effect tests on “jet scrubbing” have been conducted to the best knowledge of the authors, a number of criteria have been set to choose those experiments from which at least indirect/qualitative insights on these phenomena might be gained:

- High gas velocities ($We \geq 10^5$); target condition of this work.
- Low submergence; minimization of any $DF_{rise}$ contribution to DF, so that measured DFs would mainly correspond to $DF_{inj}$.

**Table 1**
"Jet-scrubbing" database – No steam fraction.

| Experiments | **RCA** | | **EPRI** | | | | |
|---|---|---|---|---|---|---|---|
| | RCA1 | RCA2 | EPRI-V1 | EPRI-V2 | EPRI-V3 | EPRI-V4 | EPRI-V5 |
| *Thermalhydraulics* | | | | | | | |
| Pool temperature, K | 392.00 | 397.88 | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 |
| Vessel pressure, Pa | 2.330E + 05 | 2.538E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 |
| Gas temperature, K | 395.00 | 395.55 | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 |
| Injection pressure, Pa | 2.89E + 05 | 2.91E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 |
| *Aerosol and carrier gas* | | | | | | | |
| Composition | $N_2$ | $N_2$ | Air | Air | Air | Air | Air |
| Gas mass flow rate, kg/s | 7.490E-03 | 7.243E-03 | 5.000E-03 | 1.000E-02 | 1.500E-02 | 5.000E-03 | 1.000E-02 |
| *Particle characterisitics* | | | | | | | |
| Compound | Ni | Ni | CsI and $TeO_2$ | CsI and $TeO_2$ | CsI and $TeO_2$ | Sn | Sn |
| AMMD, μm | 3.52 | 3.88 | 0.40 | 0.40 | 0.40 | 2.70 | 2.70 |
| *Injector* | | | | | | | |
| Configuration | Hor. opening | Hor. opening | Hor. opening | Hor. opening | Hor. opening | Hor. opening | Hor. opening |
| Diameter, m | 1.00E-02 | 1.00E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 |
| Submergence,m | 0.25 | 0.5 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Experimental DF | 12.4–13.2 | 16.0–40.5 | 2.2–2.9 | 3.1 | 1.4 | 110 | 480 |

| Experiments | POSEIDON-II | ARTIST[(2)] | | | | PSP |
|---|---|---|---|---|---|---|
| | PA13 | ARTIST-E07 | ARTIST-E08 | ARTIST-E09 | ARTIST-E10 | PSP6 |
| *Thermalhydraulics* | | | | | | |
| Pool temperature, K | 336.15 | 298.95 | 299.25 | 301.45 | 301.25 | 296.00 |
| Vessel pressure, Pa | 1.013E+05 | 1.000E+05 | 1.000E+05 | 1.020E+05 | 1.020E+05 | 9.20E+04 |
| Gas temperature, K | 558.15 | 326.45 | 326.95 | 364.75 | 364.25 | 300.9 |
| Injection pressure, Pa | 5.00E+05 | 1.120E+05 | 1.120E+05 | 4.930E+05 | 4.830E+05 | 1.52E+05 |
| *Aerosol and carrier gas* | | | | | | |
| Composition | $N_2$ | $N_2$ | $N_2$ | $N_2$ | $N_2$ | Air |
| Gas mass flow rate, kg/s | 3.4720E-02 | 1.389E-02 | 1.389E-02 | 1.722E-01 | 1.719E-01 | 1.34E+01 |
| *Particle characterisitics* | | | | | | |
| Compound | $SnO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ |
| AMMD, μm | 0.31 | 1.40 | 3.70 | 1.40 | 3.70 | 0.9 |
| *Injector* | | | | | | |
| Configuration | Quencher[(1)] | Quencher[(1)] | Quencher[(1)] | Quencher[(1)] | Quencher[(1)] | Hor. opening |
| Diameter, m | 2.00E-02 | 1.670E-02 | 1.670E-02 | 1.670E-02 | 1.670E-02 | 8.85E-03 |
| Submergence,m | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Experimental DF | 2.59 ± 0.65 | 53 | 1370 | 1210 | 2780 | 140.8 |

| Experiments | RSE | | | | | |
|---|---|---|---|---|---|---|
| | RSE-1 | RSE-2 | RSE-3 | RSE-4 | RSE-5 | RSE-6 |
| *Thermalhydraulics* | | | | | | |
| Pool temperature, K | 293.15 | 293.15 | 293.15 | 293.15 | 299.65 | 299.65 |
| Vessel pressure, Pa | 1.01E+05 | 1.01E+05 | 1.01E+05 | 1.01E+05 | 1.01E+05 | 1.01E+05 |
| Gas temperature, K | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 |
| Injection pressure, Pa | 1.13E+05 | 1.13E+05 | 1.13E+05 | 1.13E+05 | 1.13E+05 | 1.13E+05 |
| Water characteristics | | | | | | |
| Composition | Demi water | Demi water | Demi water | Demi water | Sea water | Demi water |
| Salinity,% | n/a | n/a | n/a | n/a | 3.5 | n/a |
| pH | n/a | n/a | n/a | n/a | 8.2 | 6.0 |
| Surfactant, ml | n/a | n/a | n/a | n/a | n/a | 80.0 |
| Surface tension, N/m | 0.073 | 0.073 | 0.073 | 0.073 | 0.072 | 0.035–0.058 |
| Aerosol and carrier gas | | | | | | |
| Composition | Air | Air | Air | Air | Air | Air |
| Gas mass flow rate, kg/s | 0.005 | 0.0066 | 0.005 | 0.0066 | 0.005 | 0.005 |
| Particle characterisitics | | | | | | |
| Compound | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ |
| MMD, μm | 0.4 | 0.4 | 1.0 | 1.0 | 0.4 | 0.4 |
| *Injector* | | | | | | |
| Configuration | Upward Injection | Upward Injection | Upward Injection | Upward Injection | Upward Injection | Upward Injection |
| Diameter, m | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Submergence,m | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Experimental DF | 2.0 | 2.3 | 3.7 | 3.3 | 3.2 | 3.8 |

[(1)] Quencher: multiple holes configuration. The number of holes is equal to 1.
[(2)] ARTIST tests include submerged surfaces in the pool simulating the secondary side of a steam generator.

- Differentiation by steam content in the carrier gas; in no/low steam tests diffusiophoresis would not contribute to particle removal at the inlet, so that the steam content effect can be separately analyzed.

From the database gathered in the PASSAM project (Herranz et al., 2014), the above criteria have resulted in Tables 1 (no steam) and 2 (presence of steam). The so called "jet scrubbing" validation matrix includes tests from various sources: the RCA project (Peyrés

**Table 2**
"Jet-scrubbing" database – Presence of steam.

| Experiments | EPRI | | | | | | POSEIDON II | | |
|---|---|---|---|---|---|---|---|---|---|
| | EPRI-V1-steam1 | EPRI-V2-steam1 | EPRI-V3-steam1 | EPRI-V3-steam2 | EPRI-V4-steam1 | EPRI-V5-steam1 | PA07 | PA21 | PA24 |
| *Thermalhydraulics* | | | | | | | | | |
| Pool temperature, K | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 | 293.15 | 359.15 | 356.15 | 364.15 |
| Vessel pressure, Pa | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.010E + 05 | 1.013E + 05 | 1.013E + 05 | 1.013E + 05 |
| Gas temperature, K | 373.15 | 373.15 | 373.15 | 373.15 | 373.15 | 373.15 | 540.15 | 530.15 | 557.15 |
| Injection pressure, Pa | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.03E + 05 | 1.00E + 06 | 1.00E + 06 | 1.00E + 06 |
| *Aerosol and carrier gas* | | | | | | | | | |
| Composition | Air-Steam | Air-Steam | Air-Steam | Air-Steam | Air-Steam | Air-Steam | $N_2$-Steam | $N_2$-Steam | $N_2$-Steam |
| Steam mass fraction | 0.5 | 0.9 | 0.5 | 0.9 | 0.9 | 0.9 | 0.55 | 0.7 | 0.55 |
| Gas mass flow rate, kg/s | 5.000E-03 | 1.000E-02 | 1.500E-02 | 1.500E-02 | 5.000E-03 | 1.0000E-02 | 3.944E-02 | 2.417E-02 | 4.2500E-02 |
| *Particle characterisitics* | | | | | | | | | |
| Compound | CsI and $TeO_2$ | CsI and $TeO_2$ | CsI and $TeO_2$ | CsI and TeO2 | Sn | Sn | $SnO_2$ | $SnO_2$ | $SnO_2$ |
| AMMD, μm | 0.40 | 0.40 | 0.40 | 0.40 | 2.70 | 2.70 | 0.31 | 0.31 | 0.31 |
| *Injector* | | | | | | | | | |
| Configuration | Hor. opening | Hor. opening | Hor. opening | Hor.opening | Hor.opening | Hor.opening | Quencher(1) | Quencher(1) | Quencher(1) |
| Diameter, m | 1.27E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 | 1.27E-02 | 0.02 | 0.02 | 0.02 |
| Submergence,m | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Experimental DF | 5.3 | 200 | 18 | 18 | 300 | >4100 | 6.61 ± 2.25 | 2.45 ± 0.58 | 13.1 ± 3.3 |

| Experiments | PSP | | | | | |
|---|---|---|---|---|---|---|
| | PSP0 | PSP1 | PSP2 | PSP3 | PSP4 | PSP5 |
| *Thermalhydraulics* | | | | | | |
| Pool temperature, K | 305.30 | 307.90 | 306.80 | 306.80 | 307.20 | 307.80 |
| Vessel pressure, Pa | 9.240E+04 | 9.240E+04 | 9.250E+04 | 9.250E+04 | 9.240E+04 | 9.190E+04 |
| Gas temperature, K | 383.20 | 382.30 | 382.60 | 374.20 | 376.90 | 381.90 |
| Injection pressure, Pa | 9.640E+04 | 1.028E+05 | 1.269E+05 | 1.587E+05 | 1.699E+05 | 1.574E+05 |
| *Aerosol and carrier gas* | | | | | | |
| Composition | Air-Steam | Air-Steam | Air-Steam | Air-Steam | Air-Steam | Air-Steam |
| Steam vol fraction,% | 4.1 | 3.4 | 3.0 | 3.7 | 6.3 | 9.8 |
| Gas mass flow rate, l/min | 157.2 | 209.1 | 307.6 | 413.3 | 454.0 | 452.9 |
| *Particle characterisitics* | | | | | | |
| Compound | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ | $SiO_2$ |
| AMMD, μm | 0.9 | 0.7 | 0.9 | 1.0 | 0.8 | 0.8 |
| *Injector* | | | | | | |
| Configuration | Hor. opening | Hor.opening | Hor.opening | Hor.opening | Hor.opening | Hor.opening |
| Diameter, m | 6.53E-03 | 8.85E-03 | 8.85E-03 | 8.85E-03 | 8.85E-03 | 8.85E-03 |
| Submergence,m | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Experimental DF | 1.8 | 6.1 | 25.8 | 56.5 | 40.6 | 11.7 |

et al.,1995; Escudero et al., 1995; Herranz, 1997, the EPRI database (Kuhlman et al., 1985; Flanigan et al., 1983), the POSEIDON II project (Dehbi et al., 2001), the phase V of the ARTIST-II project (Lind and Suckow, 2010) and two experimental sets conducted under the PASSAM frame: the PSP project (Herranz et al., 2017) and the RSE project (Albiol et al., 2017). The phase V of the ARTIST-II tests, though, included a tube bundle inside the pool, factor that should be taken into account when discussing model-data comparisons. In the tables key characteristics of pools, particles and carrying gas are gathered together with the DF derived from measurements.

It should be underlined that often experiments are not thoroughly described and not all the parameters influencing pool scrubbing can be found in the open literature. This is the case for the EPRI experiments where key variables as steam mass fraction and mass flow rates are just given as ranges and therefore, numbers in the tables are their upper bounds. Other parameters like pool temperature, injection pressure and gas temperature are assumed to be successively room temperature, atmospheric pressure and steam saturation temperature at these conditions. This should be considered when discussing these tests modeling.

## 4. Modeling "jet scrubbing

Current integral severe accident analytical tools do have pool scrubbing modules based on the stand alone codes developed in the 80's (i.e., SPARC, SUPRA, BUSCA, etc.). Broadly used codes, like MELCOR and ASTEC, have slightly different versions of the same pool scrubbing code: SPARC (Owczarski and Burk, 1991). This paper explores the capability of the containment module of the ASTEC code (CPA) to model jet scrubbing as an illustration of the existing predictability in integral severe accident codes.

### 4.1. Description of the ASTEC model

The ASTEC-CPA v2.0r3p2 code uses the version called SPARC-B/98 for retention of aerosol and gaseous fission products in the pool (Klein-Hessling and Schwinges, 1998; Bestele and Klein-Hessling, 2000).

The nodalization used for the simulation of the tests is illustrated in Fig. 2. It comprises three zones: V1, pool and environment. The V1 cell is fed with gases and particles through the connection INJ_V1 so that it works as an aerosol source. Particle scrubbing is modelled in the pool compartment, which atmosphere is connected through an atmospheric junction to a reference volume called environment (i.e., in-pool cell pressure can be set by controlling the flow to the environment). The junction J1 simulates the injection into the pool (atmospheric type junction regulated by a valve, so that injection conditions can fit the experimental boundary conditions). The end of the junction can adopt different

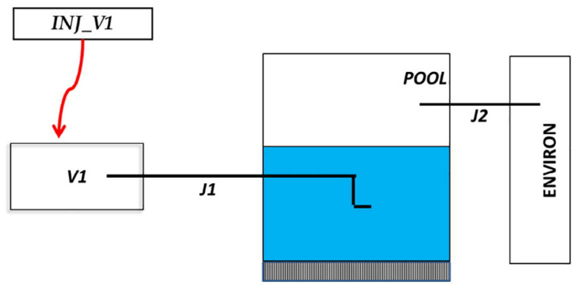


**Fig. 2.** Generic pool scrubbing tests nodalization.

**Table 3**
Experimental and calculated DFs for no-steam tests.

| Experiment | Experimental data | | | ASTEC-CPA | |
|---|---|---|---|---|---|
| | S, m | $X_S$ | DF | DF | Relative error,% |
| RCA | | | | | |
| RCA1 | 0.3 | 0.0 | 12.8–13.2 | 4.4 | (−65.2)–(−66.3) |
| RCA2 | 0.5 | 0.0 | 16.0–40.5 | 8.6 | (−46.0)–(−78.7) |
| EPRI | | | | | |
| V1 | 0.3 | 0.0 | 2.2–2.9 | 1.1 | (−49.5)–(−61.7) |
| V2 | 0.3 | 0.0 | 3.1 | 1.1 | −64.3 |
| V3 | 0.3 | 0.0 | 1.4 | 1.1 | −22.5 |
| V4 | 0.3 | 0.0 | 110 | 2.5 | −97.7 |
| V5 | 0.3 | 0.0 | 480 | 2.6 | −99.4 |
| POSEIDON-II | | | | | |
| PA13 | 0.3 | 0.0 | 2.59 | 1.0 | −60.5 |
| ARTIST-II | | | | | |
| E07 | 0.3 | 0.0 | 53 | 1.5 | −97.2 |
| E08 | 0.3 | 0.0 | 1370 | 5.3 | −99.6 |
| E09 | 0.3 | 0.0 | 1210 | – | – |
| E10 | 0.3 | 0.0 | 2780 | 2500.0 | −10.1 |
| PSP | | | | | |
| PSP6 | 0.3 | 0.0 | 140.8 | 1.2 | −99.1 |
| RSE | | | | | |
| RSE-1 | 1.0 | 0.0 | 2.0 | 1.3 | −33.00 |
| RSE-2 | 1.0 | 0.0 | 2.3 | 1.3 | −43.5 |
| RSE-3 | 1.0 | 0.0 | 3.7 | 3.3 | – |
| RSE-4 | 1.0 | 0.0 | 3.3 | 3.0 | −10.0 |
| RSE-5 | 1.0 | 0.0 | 3.2 | 1.3 | −58.1 |
| RSE-6 | 1.0 | 0.0 | 3.8 | 1.3 | −65.0 |

configurations according to the test description. The model includes a wall contacting the water in the pool.

### *4.2. Results and discussion*

Table 3 shows the CPA estimates of the experiments described in Table 1. As noted, CPA systematically underpredicts the fraction of particles trapped in shallow pools. Even further, assuming that decontamination at the inlet region (i.e., less than half a meter over the injection) is hardly affected by the water layer over it (i.e., $DF_{inj}$ is weakly dependent on the total submergence), the amount of particles entering the second pool region (i.e., bubble rise zone) in deep pools would be noticeably overestimated by CPA. The importance of this observation lies in the potential implication of error compensation in the inlet and rise regions, so that the overall DF could agree with observations although the phenomenological local picture was not captured. In other words, we might get a consistent prediction based on a wrong understanding of the scenario, which might yield to a misleading idea of pool scrubbing model maturity.

By averaging the individual relative errors in the table, one might approximate that CPA underestimates data in about 65%. At first sight this might look a reasonable accuracy but further analysis needs to be done. By defining the DF ratio, $R_{DF}$, as

$$R_{DF} = \frac{DF_{DATA}}{DF_{CPA}} = \frac{m^{out}_{CPA}}{m^{out}_{DATA}}$$

one may get information on how many times the mass leaving the inlet region estimated by CPA, either to the pool atmosphere (shallow pools) or to the bubble rise region (deep pools), is higher than what actually measured.

Fig. 3 shows that for low and moderate DFs (i.e., DF < 20; scrubbing efficiencies lower than 95%), CPA overestimates the outgoing mass from the inlet region in less than a factor of 3.0 over data. However, when actual scrubbing efficiency is higher than 98% (DF ≥ 50), the mass that CPA estimates moving out the inlet region turns out to be >30 times higher than observed and this factor might be substantially higher if retention grows (note the high retention test in which predictions are very close to data, this outstanding consistency is considered just a mere chance).

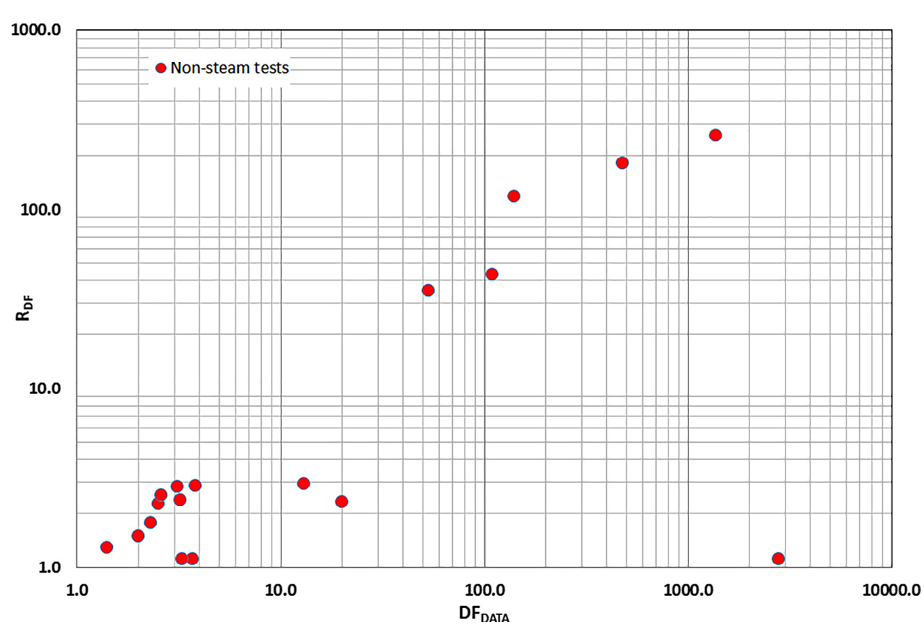


**Fig. 3.** DF ratio vs experimental DFs for “non-steam tests”.

Thus, apparently larger discrepancies between data and predictions might be found at high DFs. Nonetheless, these large deviations hardly make any difference concerning mass retained in the region, since the calculated mass deviations from data will always be <2% of the total injected mass. In other words, when high retention occurs at the inlet region the mass moving out is a very minor fraction of the total mass injected, so that tiny absolute differences might mean high shares in $m_{out}$. As a consequence, comparisons of data-estimates DFs when high retention (DF > 50) has been measured is seen to be meaningless because large differences mean little in absolute mass terms.

Therefore, the most meaningful comparisons between data and estimates should be focused on low and moderate retentions (i.e., DF < 20).

Table 4 and Fig. 4 collect the results obtained when modeling the tests including steam in the carrier gas composition. As shown in Fig. 4, steam tests reinforce even further the previous discussion held on "non-steam" tests. This observation indicates that CPA deviations depend on the magnitude of the decontamination and not on the mechanisms responsible for it. This is even further stressed by the fact that an outstanding agreement is occasionally found out when modeling experiments with immersed surfaces (not accounted for in any way in the current modeling), like ARTIST E10.

The limited number of tests prevents from doing any sound statistical analysis. Nonetheless, if RCA tests and ARTIST E10 test were dismissed as outliers, one might derive a simple correlation with an acceptable success ($R^2$ = 0.98),

$$DF_{CPA} = \frac{DF_{DATA}}{a \cdot b^{\log(DF_{DATA})}}$$

which would essentially highlight that in high retention conditions, one should expect large discrepancies between observed and calculated DFs, whereas under low retention conditions DF ratios would be notably more moderate. It is worth noting that this observation is nothing to do with models accuracy in the code; so, as other studies have shown (Herranz et al., 2014) pool scrubbing models need enhancement and/or extension. As for CPA predictions, the above expression would allow getting quick pseudo-CPA estimates once the observed DF is known.

**Table 4**
Experimental and calculated DFs for "steam tests".

| Experiment | Experimental data | | | ASTEC-CPA | |
|---|---|---|---|---|---|
| | S, m | $X_S$ | DF | DF | Relative error,% |
| EPRI | | | | | |
| V1-steam1 | 0.3 | 0.5 | 5.3 | 1.64 | −69.07 |
| V2-steam1 | 0.3 | 0.9 | 200 | 1.38 | −99.31 |
| V3-steam1 | 0.3 | 0.5 | 18 | 1.48 | −91.78 |
| V3-steam2 | 0.3 | 0.9 | 18 | 1.31 | −92.73 |
| V4-steam1 | 0.3 | 0.9 | 300 | 5.16 | −98.28 |
| V5-steam1 | 0.3 | 0.9 | 4100 | 3.95 | −99.90 |
| POSEIDON-II | | | | | |
| PA07 | 0.3 | 0.6 | 6.61 | 1.13 | −82.90 |
| PA21 | 0.3 | 0.7 | 2.45 | 1.38 | −43.67 |
| PA24 | 0.3 | 0.6 | 13.1 | 1.28 | −90.23 |
| PSP | | Xs, vol% | | | |
| PSP0 | 0.3 | 4.1 | 1.8 | 1.86 | 3.33 |
| PSP1 | 0.3 | 3.4 | 6.1 | 1.44 | −76.39 |
| PSP2 | 0.3 | 3.0 | 25.8 | 1.35 | −94.77 |
| PSP3 | 0.3 | 3.7 | 56.5 | 1.35 | −97.61 |
| PSP4 | 0.3 | 6.3 | 40.6 | 1.27 | −96.87 |
| PSP5 | 0.3 | 9.8 | 11.7 | 1.34 | −88.55 |

## 5. Conclusions

Through the comparisons set between ASTEC V2.0 and a database built based on already existing tests, one may conclude that there seems to be a sort of systematic underprediction of data on decontamination in the pool inlet region at high gas injection velocities. It has been shown that the higher the decontamination, the larger the ASTEC deviation (expressed in DF), regardless the boundary conditions of the experiments here considered (i.e., steam and submerged surfaces presence). Nonetheless, in high retention scenarios experimental uncertainties are likely to be large enough as to hinder meaningful comparisons and, no less important, large DF differences might mean little in terms of mass.

In order to go farther three major elements are indispensable to continue:

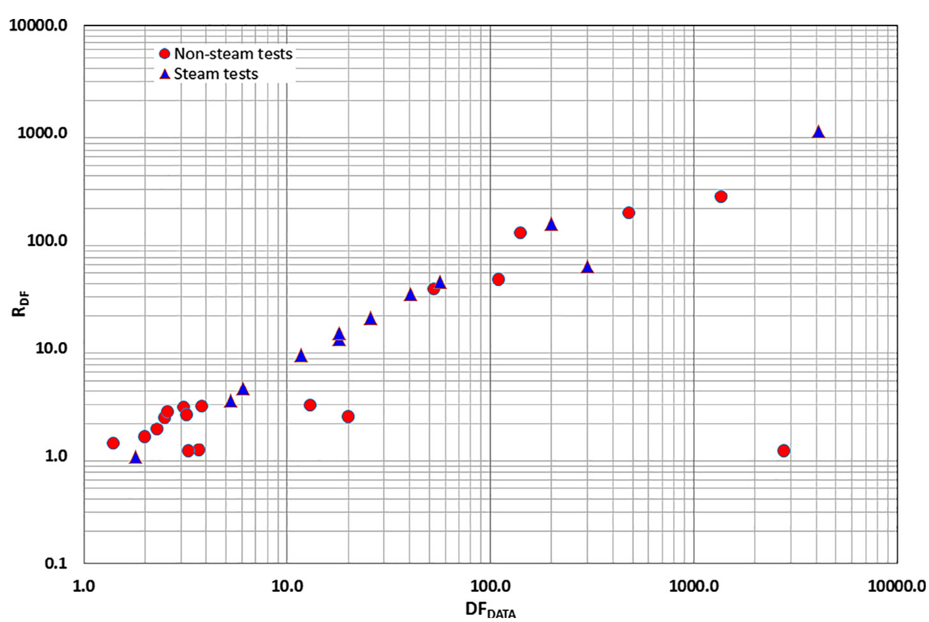


**Fig. 4.** DF ratio vs experimental DFs for "steam and non-steam tests".

- Data to consolidate the observations made in the work.
- Experimental errors that affect DF data to be able to set meaningful comparisons, if possible.
- An assessment of uncertainties affecting models to know how far analysts should go.

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