STUDY OF POOL SCRUBBING EVENTS UNDER JET INJECTION REGIME

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ABSTRACT

Submerged jet hydrodynamics might have a significant role in the attenuation of radioactivity releases during nuclear power plant accidents. In particular, these studies are important in Steam Generator Tube Rupture accidents (SGTR accident) for Pressurized Water Reactors (PWRs), Station Black-Out (SBO events) in Boiling Water Reactors (BWRs) or in severe accidents, like the one occurred at the Fukushima Daiichi Nuclear Power Plant.

Pool scrubbing has been habitually associated with globular discharges, i.e. at low injection velocities. Following this tradition, the SPARC90 code was developed to determine the trapping of fission products in pools during severe accidents, but only under these low injection velocity conditions.

SPARC90 code assumes that the carrier gas enters the water pond at low or moderate velocities, forming a big bubble that eventually detaches from the injection pipe. However, there are a number of possible scenarios in which the capture of fission products in aqueous ponds might also occur under the jet injection regime, in which particle laden gases may enter the water at very high velocities resulting in a submerged gas jet.

The present paper introduces the fundamentals, major hypotheses and code modifications developed in order to estimate particle removal during gas injection in pools under jet regimes. A simplified, yet reliable, approach to the submerged jet hydrodynamics was implemented based upon updated equations of jet hydrodynamics and aerosol removal, ensuring that both gas-liquid and droplet-particle interactions are correctly accounted for.

The resultant code modifications were validated as far as possible, however, no suitable hydrodynamic tests were found in the literature. Hence, an indirect validation approach, based on data from pool scrubbing experiments, had to be employed. Moreover, validation was further limited by the scarcity of pool scrubbing tests under jet regimes (e., g., ACE, LACE, POSEIDON II and RCA experiments). This confrontation has been satisfactory, the experimental data and the simulations follow the same trends. We must highlight some main points, such as the capability of SPARC90-Jet to capture the increasing tendency of DF with both, aerosol diameter and pressure-submergency, catching not only the experimental trend but also the magnitude.

Finally, emphasize the substantial improvement achieved with regard to the old SPARC90 code version, which has been clearly shown when comparing the SPARC90 and the SPARC90-Jet results against the available experimental data. But nevertheless, the work presented along this paper should be considered as a step towards an effective comprehension of the jet injection regime.

NOMENCLATURE

c	[m/s]	Wave Celerity
D	[m]	Jet Diameter
DF	[-]	Decontamination Factor
E	[-]	Entrained Fraction
N	[m^{-3}]	Concentration of Droplets
Oh	[-]	Ohnesorge Number
p	[Pa]	Pressure
$\dot{m}$	[kg/s]	Mass Flow Rate
N_μ	[-]	Viscosity Number
Pe	[-+	Peclet Number
R, r	[m]	Radius
Re_l	[-]	Liquid Reynolds number
Stk	[-]	Stokes number
u	[m/s]	Velocity
We	[-]	Weber number
z	[m]	Axial coordinate
Special characters		
ϕ_d	[m]	Droplet diameter
ψ	[-]	Parameter of the Kumar's correlation
λ	[-]	Rate parameter of the exponential distribution function
μ	[Pa·s]	Dynamic viscosity
η	[-]	Aerosol Capture Efficiency
ρ	[kg/m^3]	Density
σ	[N/m]	Surface tension
τ	[-]	Dimensionless response time
Subscripts		
0		Initial
$crit$		Critical
d		Droplet
g		Gas
l		Liquid
max		Maximum
vm		Mean Value

INTRODUCTION

Aerosol capture in aqueous ponds had been investigated over the lasts decades and computation tools, like the codes SUPRA [1], BUSCA [2] and SPARC [3], have been developed. But their straight application to high gas injection velocities is not suitable since they were developed to low gas injection.

This work is a step forward into the latest SPARC90 code developments of our research group towards its extension to the jet injection regime [4]. In the current SPARC90-Jet code can be seen several improvements compared to the immediately preceding reported works, for instance, some aspects of the hydrodynamic models (entrained droplets droplet, entrainment-deposition balance, etc.) and aerosols capture mechanisms (testing and implementation of new expressions).

Because of the very limited data available focused in discharges of gaseous jets in aqueous ponds, several of the chosen expressions have been taken from the annular two-phase flow regime. Regarding to the dominant mechanisms of particle removal (i.e., inertial impaction, interception and Brownian diffusion), all these expressions came from wet scrubbers due to its similarities with submerged jets. Finally, the SPARC90-Jet results have been compared to experimental data of the pool scrubbing, but only against the ones which met the actual code capabilities, i.e. discharges of non-condensable gases, concretely the experimental series of the ACE, LACE, POSEIDON II and RCA programs.

JET HYDRODYNAMICS

A submerged gas jet is usually divided in three regions (Figure 1): initial expansion (pool and gas pressures become equal); potential core (central velocity remains constant); and, a fully developed (central jet velocity decreases).

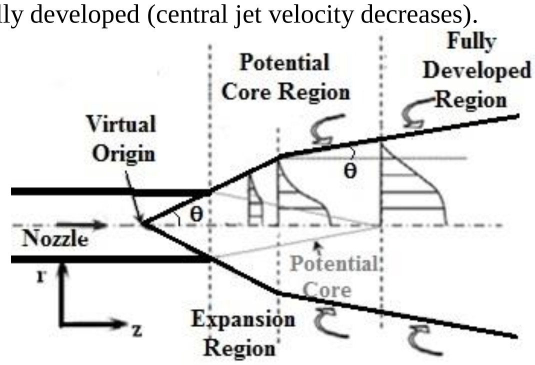

Figure 1 Schematic view of a submerged gas jet

General Gas Jet Characteristics

Someya et al. [5] investigated the jet expansion angle. They found that a large expansion occurred along 3 mm (10º at 0.5-1.0 MPa to 30º at 8.0 MPa); followed by a lower expansion rate (constant and about 7º).

The Bubnov model [6] has been chosen to characterize the flow conditions. According to this model, the critical pressure may be written as:

$$P_{crit} = P_0\left(\frac{2}{2+C_\alpha(1-C_\beta)(\gamma-1)}\right)^{\frac{\gamma}{\gamma-1}} \quad (1)$$

being C_α and C_β the correction factors of the kinetic energy to account for the pulsating motion of a jet; and γ is the isentropic expansion coefficient. The following empirical relation was obtained for a sudden flow expansion:

$$C_\alpha(1-C_\beta) = 2.6135 - 1.4891\frac{w_0}{w_1} \quad (2)$$

where w_0 and w_1 denote the cross-sectional areas before and after the flow expansion.

According to the flow conditions, there are two expressions to estimate gas flow velocity:

1- For critical condition (sonic velocity), $P_1 < P_{crit}$

$$u_{crit} = c_0\sqrt{\frac{2}{2+C_\alpha(1-C_\beta)(\gamma-1)}} \quad (3)$$

where $c_0 = \sqrt{\gamma R T_0}$

2- For sub-critical condition (subsonic velocity), $P_1 > P_{crit}$

$$u = \sqrt{\frac{2\gamma}{C_\alpha(1-C_\beta)(\gamma-1)}\left[\frac{P_0}{\rho_0}-\frac{P_1}{\rho_1}\right]} = c_0\sqrt{\frac{2}{C_\alpha(1-C_\beta)(\gamma-1)}\left(1-\left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right)} \quad (4)$$

The End of the Entrainment Zone

If the submerged jet has a high velocity, an intense mass, momentum and energy transfer takes place along the gas-liquid interface. So that a fraction of the surrounding water enters the gas core in form of droplets (i.e., entrainment) and at the same time that entrained droplets can abandon the gas stream to redeposit on the liquid phase. The point at which this mass exchange between the gas and liquid phases ends is called "onset of entrainment". A number of criteria have been proposed [7, 8] under annular flow configuration, but the Ishii and Grolmes' [8] is strongly credited.

For liquid Reynolds numbers higher than the onset of entrainment value, $Re_l > Re_{ffOE}$ ($Re_{ffOE} \approx 160$) the inception criterion proposed by Ishii and Grolmes is

$$u_g \geq 11.78 N_\mu^{0.8} Re_l^{-1/3}\frac{\sigma}{\mu_l}\sqrt{\frac{\rho_l}{\rho_g}} \quad for \quad N_\mu \leq \frac{1}{15};\ Re_l \leq 1635$$
$$u_g \geq 1.35 Re_l^{-1/3}\frac{\sigma}{\mu_l}\sqrt{\frac{\rho_l}{\rho_g}} \quad for \quad N_\mu > \frac{1}{15};\ Re_l \leq 1635 \quad (5)$$

and for the rough turbulent regime ($Re_l > 1635$)

$$u_g > \frac{\sigma}{\mu_l}\sqrt{\frac{\rho_l}{\rho_g}} \times N_\mu^{0.8} \quad for \quad N_\mu \leq \frac{1}{15};\ Re_l > 1635$$
$$u_g > \frac{\sigma}{\mu_l}\sqrt{\frac{\rho_l}{\rho_g}} \times 0.1146 \quad for \quad N_\mu > \frac{1}{15};\ Re_l > 1635 \quad (6)$$

where u_g is the superficial velocity of the gas phase (this limit value of the gas velocity is usually called "entrainment inception velocity", u_{inp}) and N_μ is the viscosity number, originally used by Hinze [9], this dimensionless number compares the viscous force induced by an internal flow to the surface tension force. It is defined as

$$N_\mu = \frac{\mu_l}{\left(\rho_l \sigma \sqrt{\frac{\sigma}{g\Delta\rho}}\right)^{1/2}} \quad (7)$$

The Entrained Droplets

The aerodynamic forces of the surrounding high speed gas might cause the deformation and fragmentation of the entrained droplets, then a maximum stable droplet size exists. Consequently, in-core gas droplets distribute in a size interval [7]. This maximum stable diameter can be estimated through non-dimensional Weber number (ratio of gas kinetic energy and liquid cohesive energy),

$$\phi_{d,\max} = \frac{\sigma We_{crit}}{\rho_g u_g^2} \quad (7)$$

which has been correlated through [10]:

$$We_{crit} = \begin{cases} 55\left(\frac{24}{\mathrm{Re}_d} + \frac{20.1807}{\mathrm{Re}_d^{0.615}} - \frac{16}{\mathrm{Re}_d^{2/3}}\right)\left[1+1.077Oh^{1.64}\right] & for\ 200 < \mathrm{Re}_d < 2000 \\ 5.48\left[1+1.077Oh^{1.64}\right] & for\ 2000 \le \mathrm{Re}_d \end{cases} \quad (8)$$

being Re_d the droplet Reynolds number defined as

$$\mathrm{Re}_d = \frac{\rho_g(u_g - u_d)\phi_d}{\mu_g} \quad (9)$$

and the Ohnesorge dimensionless number, which is a relation between viscosity and the product of inertia and surface tension forces, defined as

$$Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma D}} \quad (10)$$

Another way to estimate the droplet sizes is to use correlations directly based on fluid dynamic characterization of the scenario. A recent expression [11] has been chosen:

$$\frac{\phi_{vm}}{D} = 2.634 \cdot We_g^{-0.23}\,\mathrm{Re}_g^{-0.54}\,\mathrm{Re}_l^{0.13} \quad (11)$$

Due to the different values provided by these two kinds of equations, in this work the average of them, Eqns. (8) and (11), has been adopted. It has been combined the “aggressiveness” of the first kind (sudden exposure to a high speed gaseous stream), with the “smoothness” of the second one (fully developed annular flow).

There are very few data of entrained droplets velocities. Recently, Someya et al. [5] observed that the velocity of the entrained droplets is between 1/30-1/60 of the one of the submerged gas jet velocity. Other approximations, even though were developed for fully developed annular flows, assume that droplet velocities are much higher, between 0.5 – 0.8 of gas velocity in the vicinity of the pipe centreline [12, 13].

The expression selected considers the velocity at which the entrained droplets leave the interface (wave celerity, c), added to a percentage of the gas velocity. The expression is as follows

$$u_d = c + 0.15 \cdot u_g \quad (12)$$

being c the wave celerity (velocity of the interfacial waves), defined as Kumar suggested [14]

$$c = \frac{\psi \cdot J_g + J_l}{1+\psi} \quad (13)$$

and the parameter ψ is

$$\psi = 5.5\sqrt{\frac{\rho_g}{\rho_l}}\left(\frac{\mathrm{Re}_l}{\mathrm{Re}_g}\right)^{0.25} \quad (14)$$

Regarding the entrainment mass flux, an expression that depends on the scenario fluid properties [11] has been chosen:

$$\frac{E}{1-E} = 5.51x10^{-7} \cdot We_g^{2.68}\,\mathrm{Re}_g^{-2.62}\,\mathrm{Re}_l^{0.34}\left(\frac{\rho_g}{\rho_l}\right)^{-0.37}\left(\frac{\mu_g}{\mu_l}\right)^{-3.71} C_W^{4.24} \quad (15)$$

being C_W the surface tension factor (effect of the surface tension on the wave circulation/dissipation flow), defined as

$$C_W = 0.028 N_\mu^{-4/5} \quad for \quad N_\mu \le 1/15 \quad (16)$$
$$C_W = 0.25 \quad for \quad N_\mu > 1/15$$

Due to the jet continuous expansion as it evolves downstream, added to the unsteadiness and pulsating behaviour, the last expression has been modified, since the above equation was obtained for fully developed flows. Then, the adopted expression is the one proposed by Kataoka [15], but with a shorter and aggressive transition to developed flow (i.e., the constant has been increased from 1.87 10^{-5} to $2.75\cdot10^{-4}$):

$$E(z) = \left[1-\exp\left(-2.75\cdot10^{-4}\,\frac{(z/D)^2\,\mathrm{Re}_l}{We_g^{0.5}}\right)\right]E \quad (17)$$

being z the axial distance to the nozzle and D the jet diameter.

Mainly caused by the gas spread, the amount of droplets that remain into the gaseous jet decreases exponentially as it evolves downstream, this is caused by the deposition processes, i.e., opposite situation to the entrainment process. The used expression is

$$N_d(z) = N_{do}e^{\frac{-\Delta z}{l_c}} \quad (18)$$

where Δz is the distance in the axial jet direction from the droplet extraction, N_{do} is the initial droplet population, $N_d(z)$ is the population of droplets at a given distance from the nozzle, and l_c is the characteristic length of the droplet motion towards the liquid interface, i.e., the jet diameter at each position.

AEROSOL CAPTURE MECHANISMS

Single droplets may collect particles via one or more of the collection mechanisms, such as: inertial impaction, interception, Brownian diffusion, electrostatic attraction, diffusiophoresis, thermophoresis, etc. Of these capture mechanisms only the first three, droplet-particle mechanical interactions (Figure 2), are the dominant in our conditions. Consequently, considering that the aerosol capture mechanisms are not entirely independent, the final expression is:

$$\eta = 1-(1-\eta_{impact})\cdot(1-\eta_{intercep})\cdot(1-\eta_{diff}) \quad (19)$$

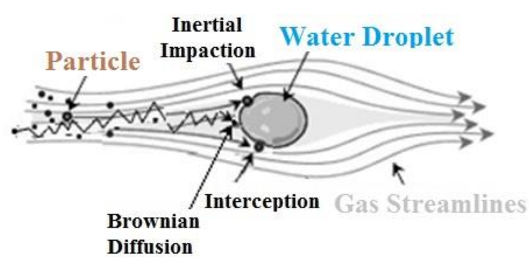

Figure 2 Sketch of droplet-particle mechanical interaction

The next step is to determine the contribution of each of them. The correlations listed below have been taken from wet scrubbers, as droplet hydrodynamics conditions are probably closer to submerged jets than annular flow ones.

Inertial Impaction

Inertia forces of aerosol particles would make them move away to the gas streamlines and eventually collide with the obstacle, i.e., water droplet. Among the available expressions, the one proposed by Slinn [16] is employed here

$$\eta_{impact} = \left(\frac{Stk - S*}{Stk + \frac{2}{3} - S*} \right)^{3/2} \left(\frac{\rho_d}{\rho_p} \right)^{1/2} \qquad for\ Stk > S* \tag{20}$$

where

$$S* = \frac{1.2 + \frac{1}{12} Ln\left(1 + \frac{Re_d}{2}\right)}{1 + Ln\left(1 + \frac{Re_d}{2}\right)} \tag{21}$$

being Stk the particle Stokes number [7],

$$Stk = \frac{C_c \rho_p \phi_p^2 \left(u_g - u_d\right)}{9 \mu \phi_d} \tag{22}$$

Interception

Interception takes place when the radius of the aerosol particle is larger than the distance between the gas streamline followed by the aerosol and the surface of the obstacle. Many expressions are available in the open literature, the selected here is the one proposed by Jung and Lee [17],

$$\eta_{intercep} = \frac{1-a}{J+bK} \left[\frac{\phi_p/\phi_d}{1+\phi_p/\phi_d} + \frac{1}{2} \left(\frac{\phi_p/\phi_d}{1+\phi_p/\phi_d} \right)^2 (3b+4) \right] \tag{23}$$

where $a = \left(r_d/r_g\right)^3$ being r_d is the sphere radius and r_g is the boundary radius (jet radius); $b = \frac{\mu_l}{\mu_g}$; $J = 1 - \frac{6}{5}a^{1/3} + \frac{1}{5}a^2$ and $K = 1 - \frac{9}{5}a^{1/3} + a + \frac{1}{5}a^2$.

Brownian Diffusion

Brownian motion is the random movement of particles suspended in a fluid. Several expressions have been tested too, finally the selected is the one proposed by Jung and Lee [17]:

$$\eta_{diff} = 0.7 \left[\frac{4}{\sqrt{3}} \left(\frac{1-a}{J+bK} \right)^{1/2} Pe^{-1/2} + 2 \left(\frac{\sqrt{3}\pi}{4Pe} \right)^{2/3} \left[\frac{(1-a)(3b+4)}{J+bK} \right]^{1/3} \right] \tag{24}$$

being the Peclet number defined as

$$Pe = \frac{\phi_d u_d}{D_{diff}} \tag{25}$$

where D_{diff} is the diffusion coefficient, the rest of coefficients are defined as in the previous impaction mechanism. This expression is useful when the viscosity ratios of both fluids are between 1 and 100, which is our case.

THE NEW SPARC90-JET IMPLEMENTATION

The SPARC90-Jet model has been implemented as a new subroutine of the original SPARC90 Fortran code [3]. The present work displays the physical and mathematical fundamentals, the main hypotheses and changes introduced into the code in order to estimate particle removal during gas injection in pools under jet regime. With this aim, a simplified and reliable approach to submerged jet hydrodynamics has been developed to describe both the gas-liquid and the drop-particles interactions.

As far as the SPARC90-Jet programming is concerned say that, when the jet option is activated the new subroutine of the SPARC90-Jet is called. This subroutine is active until the velocity of the gas jet falls below the onset of the entrainment velocity. From this point on, the code continues its calculations as in the original code, that is, determines the decontamination factor of the rising plume, although starting from different conditions. But with a significant difference, in our case, the initial region of the globule formation has been removed, consequently only the rising plume, in which the bubbles evolve with a single diameter to represent the swarm exists.

The new subroutine of the SPARC90-Jet code carries out two main groups of calculations: the submerged jet hydrodynamics and the aerosol capture processes, the key aspects of both of them are developed in the next two sections. Along with these calculations the expressions presented in the previous sections have been implemented. In addition, related with these calculations, several assumptions have been made, the most important are mentioned below.

Main Assumptions

The main assumptions introduced into this improved version of the SPARC90 code are the following:

- Constant conical expansion ratio of the submerged gaseous jet along the injection direction.
- Thermal exchanges have not being taken into account, neither sensible nor latent heat transfer.
- Thermophoresis and diffusiophoresis have been neglected, which might result in the DF underprediction, in particular for submicron particles.
- Droplets agglomeration/de-agglomeration processes have not been taken into account. It is assumed that interaction among droplets cannot take place during the pool discharge process.
- A mean diameter of the entrained droplets in each cell has been used, that is, only one constant diameter for the entrained droplets has been considered in each cell. Next step will be to consider a particle size discrete distribution function, among which the most appropriated for the present conditions seems to be the Log-Normal Distribution.
- Correlations for jet hydrodynamics have been mainly chosen from expressions developed for annular flows (for instance, correlations of droplet sizes, entrained fraction, etc.), due to the lack of information about submerged gaseous jets.
- Correlations for aerosol capture have been mainly chosen from expressions developed for wet scrubbers due to the lack of information specifically developed for submerged gaseous jets.

Therefore, the new model presented throughout this paper should be considered as preliminary, existing due to the existence of several improvements pending, which will be carried out in future works, even though an important step forward has been done with the development of the SPAR90-Jet code. In order to develop some of these improvements it is mandatory to conduct extensive experimentation works, but specifically on submerged jets. To thereby, on the one hand, be able to develop specific expressions to submerged jet, while on the other hand, be able to validate the results predicted by the new code SPARC90-Jet. The first set of experiments should be focused on two subjects, determination of jet hydrodynamics and aerosol capture processes. While the second group, should focus on the DF's determination.

THE SUBMERGED JET HYDRODYNAMICS MODEL - THE CONSERVATION EQUATIONS

The submerged jet in the SPARC90-Jet code has been divided into a large number of nodes (Figure 3). The jet velocity decreases as the jet spreads downstream, modelled based on the Epstein model [18]. Three conservation equations are considered (gas mass, liquid mass and momentum). So that, the final expression of the gas velocity is:

$$u_g(n) = u_0 - 2\frac{\rho_l}{\rho_0}\frac{\Delta z}{u_0}\frac{R^2(n)}{R_0^2}\sum_{k=1}^{n}\frac{u_e(k)\bar{R}(k)}{u_d(k)R^2(k)}u_d^2(n) - 2\frac{\Delta z}{\rho_0 u_0 R_0^2}\sum_{k=1}^{n}\tau_{friction,k}\,\bar{R}(k) \quad (26)$$

being u_e, $\tau_{friction}$ the entrained velocity and the interfacial shear stress force respectively.

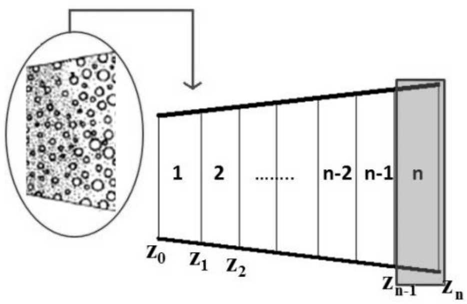

Figure 3 Schematic view of the submerged jet nodalization

The calculations of the entrainment velocity in each cell are made based in the Ricou and Spalding theory [19]:

$$u_e(k) = e_0\, u_d(k)\sqrt{\frac{\rho(k)}{\rho_l}} \quad (27)$$

the entrainment coefficient, e_0, varies from 0.058 to 0.116, and the density is given by

$$\rho(k) = \alpha(k)\rho_g + [1-\alpha(k)]\rho_l \quad (28)$$

The usual expression for the friction force has been used:

$$\tau_{friction} = \frac{1}{2}f_{gi}\,\rho_g\left(u_g - u_l\right)^2 \quad (29)$$

To determine the interfacial friction factor, f_{gi}, the Ohnuki´s correlations [20] have been chosen:

$$f_{gi} = 1.84 f_{wg} \quad (30)$$

being

$$f_{wg} = \begin{cases} \dfrac{16}{Re_g}; Re_g < 2100 \\ \dfrac{0.079}{Re_g^{0.25}}; 2100 < Re_g < 10^5 \\ 0.0008 + \dfrac{0.05525}{Re_g^{0.237}}; Re_g \geq 10^5 \end{cases} \quad (31)$$

The liquid velocity of the surrounding water of the submerged jet has been obtained from the instabilities of Kelvin–Helmholtz generated in the inviscid theory [21],

$$u_l = u_g\sqrt{\frac{\mu_g}{\mu_l}\frac{\rho_l}{\rho_g}} \quad (32)$$

CALCULATION OF THE DECONTAMINATION FACTOR

The Decontamination Factor, DF, is the ratio of the aerosol mass flow rate entering-going out of the system,

$$DF = \frac{\dot{m}_{in}}{\dot{m}_{out}} = \frac{1}{1-\eta} \quad (33)$$

being η the particle collection efficiency ($\eta = \dot{m}_{ret}/\dot{m}_{in}$).

Due to the fact that the decontamination process is composed of several stages, the particles DF of a given size is the product of the elementary DF's corresponding to each stage or cell:

$$DF(k) = \prod_{n} DF_n(k) \quad (34)$$

being k the particle size index and n the stage number. Then, the overall DF given by:

$$DF = \sum_k \frac{DF(k)}{w_0(k)} \quad (35)$$

where $w_0(k)$ is the mass fraction of each particle size class at the inlet.

RESULTS OF SPARC90-JET AND CONFRONTATION WITH EXPERIMENTAL DATA

This section presents the experimental data and the results of the old and new SPARC90 codes for the four experimental data series that have been studied throughout this paper (Table 1). Due to the fact that this first version of the new SPARC90-Jet code does not take into account the effect of condensable gases, only discharges of non-condensable gases (or with a small percentage of condensable gases) have been studied, i.e., ACE [22], LACE [22], POSEIDON II [23] and RCA [24] experimental programs.

Particle sizes are one of the key factors in the DF values, an increase in them leads to an increase in the DF. This upward trend can be clearly shown in the LACE experimental data (Figure 4). In both tests there are almost the same experimental conditions, the only noteworthy difference is the aerosol size. As can be seen in this figure, and as intuitively could be guessed, there is a direct proportionality between the aerosol size and the DF (tests RT-SC-01/02, ϕ_p = 1.7 μm versus RT-SC-P/01, ϕ_p = 5.6 μm). This proportionality is clearly shown in the experimental data, being very well captured by the SPARC90-Jet version, as opposed to the old SPARC version, which does no capture this tendency. This upward trend is confirmed by the lower submergence tests (i.e., PA13, RCA1 and RCA2), which are shown in Figure 5. In which the contribution of jet and rising plume regions to the DF are displayed separately, along with the total DF and the experimental data, it confirms that higher values of DF are reached for larger sizes of aerosols in both regions. Even though, without virtually decontamination in the rising plume region (DF ≈ 1), existing only a slight increasing slope with aerosol sizes.

Table 1 Summary of the DF experimental data and results

TEST		Aerosol	Experimental DF		SPARC90	SPARC90-Jet		
			min.-max.	Mean		Jet	Rising Plume	Total
ACE	AA1	Cs Mn I	145-160 11-33 47-80	58.12*	14.70	2.198	13.81	30.35
ACE	AA3	Cs Mn I	320-330 75-140 180-220	157.0*	33.23	2.315	30.76	71.21
LACE	RT-SC-01/02	CsI	116.0-128.0	122.0	9.500	14.33	11.32	162.2
LACE	RT-SC-P/01	CsI	491.0-526.0	508.5	21.90	14.10	32.63	460.2
POSEIDON II	PA10	SnO_2	8.22-12.98	10.60	1.196	6.174	1.173	7.242
POSEIDON II	PA11	SnO_2	3.95-6.75	5.35	1.150	4.190	1.081	4.529
POSEIDON II	PA12	SnO_2	2.80-4.04	3.42	1.055	3.909	1.033	4.038
POSEIDON II	PA13	SnO_2	1.94-3.24	2.59	1.026	2.599	1.006	2.615
RCA	RCA1	Ni	12.4-13.2	12.80	10.33	11.24	1.246	14.00
RCA	RCA2	Ni	16.0-40.5	28.25	11.73	11.91	2.148	25.58
RCA	RCA3	Ni	46.6-80	63.30	13.72	13.01	5.692	74.06
RCA	RCA4	Ni	719.0-1220.7	969.9	25.72	22.03	16.35	360.2

* Weighted with the aerosol composition at the nozzle exit

Other key variable to determine the DF is the pool depth, submergency. In Figure 6 are shown the four POSEIDON II experiments studied here. All of them took place in almost the same conditions (small aerosol size ≈ 0.3 µm, high jet and pool temperatures ≈ 250 – 75 ºC respectively, low fraction or cero condensable gases and pressures near the atmospheric values), apart from submergency, which varies from 4.0 to 0.3 meters (PA10 – 4.0 m, PA11 – 2.0 m, PA12 – 1.0 m and PA13 – 0.3 m). The rising trend of DF values with pool depth of the experimental data, is quite well captured by the new SPARC90-Jet code, but it is not captured at all by the old version. This increasing tendency of DF values with submergency can be explained by the higher residence time of the aerosols with the increase of the injector depth.

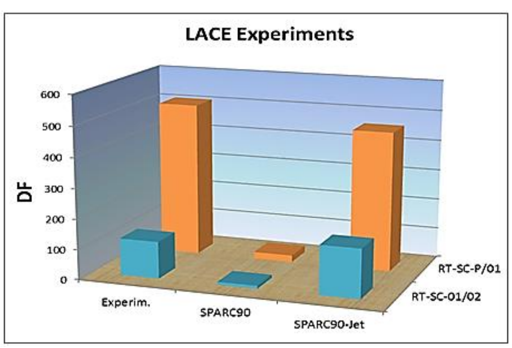

Figure 4 Experimental, SPARC90 and SPARC90-Jet results of DF for LACE experiments

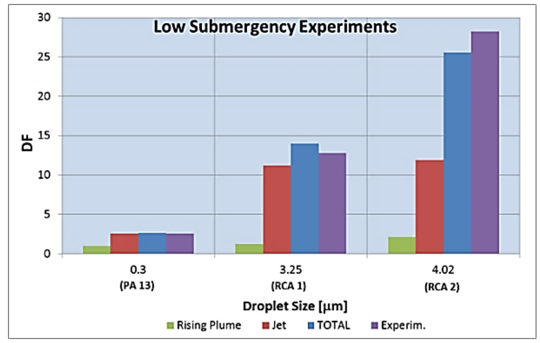

Figure 5 Experimental data vs SPARC90-Jet results (Total, Jet and Rising Plume regions) of the DF for the low submergency experiments

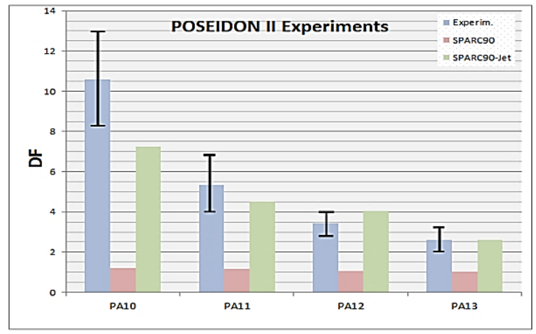

Figure 6 Experimental, SPARC90 and SPARC90-Jet results of DF for POSEIDON II experiments

Finally, to conclude this section of comparison of the SPARC90-Jet code with his old version and against the experimental data, we must noteworthy that SPARC90-Jet code provides much better results than his previous version, being closer to the experimental data in almost all the tests, despite that in certain tests the SPARC90-Jet results are not so close to the experimental data, but without being excessively away. Although, it should be reminded once again the fact that the old SPARC90 code version was not originally developed for high velocity gas discharges, but for globular discharges. Therefore, it is not surprising the weak performance of the old version in most of the experimental tests under study. Thus we conclude that the major effects on DF are the injection pressure (either directly or through the submergency) and the aerosol sizes, having both of them an increasing tendency, i.e. higher values of these variables leads to higher values of DF. Although further research is needed to confirm these findings and to try to capture possible new trends dependent on other entrance variables.

FINAL REMARKS AND FURTHER WORK

As it is broadly recognized, hydrodynamics of submerged jets have a significant implication in many industries, such as, nuclear, metallurgical, pharmaceutical, etcetera. Despite such importance of gas-liquid interactions in submerged gas jet, very little information is available in the open literature. Throughout this paper the main features of a new model are described, which has been developed based on existing equations, own studies and assumptions, this new model is called SPARC90-Jet.

This new version of the SPARC90 code enhances the capabilities of the old version, from low to high gas velocity injections. The development of this new code has been made through the choice of the last equations available of the open literature. Two main points have been modelled, the jet hydrodynamics and the aerosol capture mechanisms.

The theoretical results provided by the SPARC90-Jet code have been compared with four experimental programs, ACE, LACE, POSEIDON II and RCA, allowing the validation of the implemented models, thereby contributing to the strengthening of its reliability. This confrontation versus the experimental data has been satisfactory, since the experimental data and the simulations follow the same trends. We must highlight some key issues, the capability of SPARC90-Jet to capture the growing of DF with aerosol diameter and with pressure-submergency, capturing not only the experimental tendency but also the magnitude. Finally, note the significant improvement achieved with respect to the previous version of SPARC90, which has been clearly demonstrated over the comparison of the SPARC90 and the SPARC90-Jet results against the experimental data. All these comments should be made with caution because of the fact that the model developed up to now should be considered as preliminary and, consequently, subject to improvements in several areas. In addition, a broader experimental database is needed, in order to have a higher reliability when making comparisons. Nevertheless, the results are heartening, as the experimental tendencies are quite well captured, although the ultimate aim has not been achieved yet.

In summary, despite the promising results of the SPARC90-Jet model, it should simply be seen as a step forward in modelling of scrubbing under jet injection regime. There are many points of SPARC90-Jet susceptible to be improved, either because they are based on assumptions that need additional confirmation (most models and correlations were not specifically developed for submerged jets) or because the reduced experimental data are not as extensive as it would be desirable. Actually, this is the key question to develop any model of pool scrubbing under jet injection regime, the paucity of data. So that specific experimentation in this area is of crucial importance for two aspects, to have expressions specifically developed for submerged jets and to have a broader database against which compare the code results.

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