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

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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 Finally, some lessons learned for forthcoming experiments have been withdrawn, particularly concerning the high impact of hydrodynamics.

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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

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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,