# EXPERIMENTAL STUDY OF HEAT, MASS AND MOMENTUM TRANSFERS IN A SPRAY IN THE TOSQAN FACILITY

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#### Abstract

TOSQAN is an experimental program undertaken by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in order to perform thermal hydraulic containment studies. The TOSQAN facility is a large enclosure devoted to simulate typical accidental thermal hydraulic flow conditions in nuclear Pressurized Water Reactor (PWR) containment. The TOSQAN facility which is highly instrumented with non-intrusive optical diagnostics is particularly adapted to nuclear safety CFD code validation. The present work is devoted to studying the interaction of a water spray injection used as a mitigation means in order to reduce containment pressure and to produce a mixing of air, steam and hydrogen induced by spray entrainment and condensation on droplet. In order to have a better understanding of heat and mass transfers between spray droplets and gas and to analyse mixing effects due to spray activation, we perform detailed measurements of the two phases flow.

#### Introduction

During the course of a hypothetical severe accident in a Pressurized Water Reactor (PWR), hydrogen can be produced by the reactor core oxidation and distributed into the reactor containment according to convection flows and water steam walls condensation. In order to assess the risk of detonation generated by a high local hydrogen concentration, hydrogen distribution in the containment has to be known. The TOSQAN experimental program has been created to simulate typical accidental thermal hydraulic conditions in the reactor containment. The specificity of the TOSQAN facility consists of a high level of instrumentation that allows to give a local and non intrusive characterization of the two phases flow in order to validate CFD code. The present work is devoted to study the interaction of a water spray injection used as a mitigation means in order to reduce steam containment pressure and to decrease local hydrogen concentration by the mixing induced by spray entrainment and steam condensation on droplets. In order to have a better understanding of physical phenomena, a detailed characterization of the spray and the gas is needed. Spray tests are performed in hot conditions to analyze the heat and mass transfers between spray droplets and gas mixtures composed of air and steam or air, steam and helium (entitled respectively 101 and 101He spray tests). Another test performed with cold condition was designed in order to study the effect of spray activation on helium mixing (entitled 113 spray test, [1]). 101 and 113 spray tests are involved for benchmarking in the European network of excellence SARNET (Severe Accident Research NETwork) that is presented in a companion paper [2]. Local measurements performed in the TOSQAN facility such as, steam volume concentration, droplets velocity and gas temperature, are used to be compared with CFD codes results in order to check their capability for the modelling of physical phenomena involved in the spray test.

## **Description of the TOSQAN facility**

The TOSQAN facility presented in Figure 1 consists of a closed cylindrical vessel (7 m<sup>3</sup> volume, 4 m high, 1.5 m internal diameter) into which steam is injected [3]. The scaling factor between the TOSQAN facility and a PWR containment is about to 1/5000.

The walls of the vessel are thermostatically controlled by heated oil circulation, thus walls are regulated at a constant temperature. Over 100 thermocouples are used to measure the gas temperature in the whole vessel. Optical accesses are provided by 14 overpressure resistant viewing windows permitting non-intrusive optical measurements along orthogonal enclosure diameters. The inner spray system located in the dome of the enclosure on the vertical axis, is composed of a single nozzle producing a full cone water spray. This nozzle is mobile along the vertical axis allowing to perform measurements at different distances from it. Helium, which is used for hydrogen simulation, can be injected in the top of the dome of the vessel to study light non condensable gas mixing due to spray activation.



Figure 1. Overwiew of the TOSQAN facility.

# Instrumentation

Both intrusive and non-intrusive techniques are implemented on the TOSQAN facility in order to achieve a detailed characterization of the spray droplets and gas. Droplets velocity is measured using Particle Image Velocimetry technique (PIV). One can find some informations of PIV technique

implementation on the TOSQAN facility [4]. In the field of spray analysis, various kinds of measurement techniques for droplet size measurements are available, such the Phase Doppler Anemometry (PDA). However, PDA technique cannot be used in TOSQAN facility because of optical access constraints. That is why we decided to develop the Interferometrics Laser Imaging for Droplet Sizing (ILIDS) [5]. The ILIDS technique is based on the principle that the individual droplet size can be measure from the instantaneous image of circular fringes resulting from the interference of a couple of scattering lights from a single droplet. ILIDS optical set-up is similar to PIV set-up but with an out-of-focus adjustment for CCD camera and with a specific image processing. Droplets temperature measurements are performed using global rainbow thermometry (Lemaitre *et al.*, 2006). For gas volume fractions measurements, two complementary techniques are implemented on the TOSQAN facility such as, Spontaneous Raman Scattering spectroscopy and mass spectrometry. Spontaneous Raman Scattering is an inelastic scattering process involving the interaction of a photon with a specific vibration-rotational state of a molecule. One can find some informations about Raman technique implementation and qualification on the TOSQAN facility [3].

# Spray test procedure

In this paper we present analysis of spray tests performed in hot conditions with heat and mass transfers between droplets and gas and in cold conditions where we only study the capability of spray system to induce light non condensable gas mixing such helium. For spray tests performed in hot conditions, the experimental test scenario consists of water spray injection in the TOSQAN heated vessel that is first pressurized with steam (101 spray test, see Table 1) or steam and helium (101He spray test). For 101He spray test, steam and helium are not injected neither at the same time, nor at the same location. Steam is first injected by the means of the vertical pipe and after helium is injected by a nozzle located on the top of the dome of the vessel (see Figure 1). For cold spray test (113 test), the vessel which contains initially air at atmospheric pressure and ambient temperature is pressurized with helium injected also at ambient temperature before water spray injection. For hot and cold tests with helium (101He and 113), the experimental test procedure was developed to reach a strong helium mass stratification before spray activation (high helium volume concentration in the upper part of the vessel). A similar spray is used for all the tests performed (101, 101He and 113), with same water mass flow rate and water temperature (see Table 1). At the beginning of the spray activation (t < 30 s), the temperature of the water injected is over than 30°C because the water which is initially present in the spray circuit is heated by conduction by the vessel. Due to the difference of vessel pressure of 101, 101He and 113 spray tests, droplets size is slightly different for each spray test according to the change of aerodynamics effect in liquid atomization processes [6]. Water spray falling into the sump of the vessel is drained out to avoid accumulation and to limit re-evaporation in the case of hot tests.

Test	Spray	Water	Water	Wall	Gas mixture composition		
name	nozzle	injection	mass	temperature	Air	Steam	Helium
	location	temperature	flow rate	(°C)	(bar)	(bar)	(bar)
		(°C)	(g/s)				
101	Vessel	20	30	120	1	1.5	0
	axis						
101He	Vessel	20	30	120	1	1.5	0.5
	axis						
113	Vessel	20	30	20	1	0	1
	axis						

Table 1. Spray test conditions.

#### Spray characterization

Water spray is produced by a nozzle (TG 3.5 from Spraying System, with an internal diameter of 1 mm), which allows to obtain droplets of almost uniform size. Spray characterization has been performed by the means of optical diagnostics in order to determine initial droplets velocity, droplets size distribution and spray angle. Spray angle is an important parameter to check because droplets do not reach the vertical heated wall of the TOSQAN vessel in order to prevent initial droplets vaporization. Spray angle was determined using laser visualization technique as shown on Figure 2. Droplets mean vertical and radial velocities fields measured close to the nozzle exit by PIV technique are presented on Figure 3 and Figure 4. On both velocity fields, spray nozzle is located at the height (z) equal to 100 mm. On the Figure 3, the shearing layer between the gas and the spray can be observed on the vertical velocity field according to momentum exchange between the two phases of the flow. The radial velocity field presents an usual pattern of spray expansion due to droplets inertia, with radial velocity component close to zero in the center part of the spray. Others droplets velocity measurements were performed in the far field of the nozzle exit in order to obtain a vertical profile of droplets velocity (Figure 5) and radial profiles of droplets velocity at different distances (d) from the nozzle (Figure 6). Close to the nozzle exit occurs the primary atomization, thus droplets velocity measurements can not be performed. So, the initial droplets velocity measured at 20 mm from the nozzle exit is about 12 m/s. We can observe a characteristic flat velocity profile at 50 mm from the nozzle exit. This kind of profile which delimits the spray area is significant of the near field of spray where the penetration of gas inclusions inside the spray is not very efficient due to the high droplets density. Along the spray periphery we can distinguish counter flow loop according to positive velocity. On the other radial profiles we can observe the spray development versus distance from the nozzle exit showing droplets velocity decreases according to momentum exchange with gas. An example of droplets size measurements performed by ILIDS technique is presented on Figure 7. ILIDS measurements were not performed close to the nozzle exit because of the high droplets density which induces laser multi-scattering and droplets overlapping.



Figure 2. Spray visualization in the TOSQAN vessel.







Figure 4. Spray droplets radial velocity U (m/s) field measured in the TOSQAN vessel (PIV measurements).



Figure 5. Spray droplets vertical velocity measured on vertical profile the TOSQAN vessel on the vessel axis (PIV measurements).



Figure 6. Spray droplets vertical velocity measured on radial profiles in the TOSQAN vessel (PIV measurements).



Figure 7. Droplets size distribution (ILIDS measurements performed at 1 m from the nozzle exit) – Arithmetic diameter value equal to  $146 \ \mu m$ .

# Analysis of spray interaction with air/steam and air/steam/helium mixtures for 101 and 101He spray tests

We now consider the time from that spray is injected in the vessel initially pressurized with steam (test 101) or steam and helium (101He test). Time evolutions of vessel pressure and mean gas temperature for 101 and 101He tests are presented on the Figure 8. The reference time t = 0 s corresponds to the spray activation.

## Global analysis of both spray tests

The mean gas temperature is the spatial average of gas temperature measured with thermocouples located along the vessel diameter at 6 different levels. Gas temperature fields measured in the TOSQAN vessel at different times for 101 spray tests are presented on the Figure 9 and the Figure 10.

According to vessel pressure time evolutions, spray activation is followed by an initial steam overpressure which is more important for the spray test 101He (0.11 bar) than for spray test 101 (0.03 bar). This overpressure that occurs during the first hundred seconds of the spray injection is induced by steam production and it is correlated with a strong decrease of mean gas temperature that is significant of droplets vaporization. For both spray tests, this initial overpressure is followed by a second phase characterized by a strong decrease of the vessel pressure and mean gas temperature according to steam condensation on water droplets and convective transfers between the droplets initially injected at 20°C and the hot gas mixture. The local gas cooling induced by the spray can be observed on the Figure 9 and the Figure 10 for 101 spray test.

The third phase of spray tests is characterized by a steady state in terms of pressure and mean gas temperature. The comparison of the pressure time evolutions related to 101 and 101He tests shows that helium has only influence on heat and mass transfers during the transient state but, for the steady state, the pressure gap between 101 and 101He tests corresponds to the helium injection performed for spray 101He test (0.5 bar of helium, see Table 1).



Figure 8. Time evolutions of vessel pressure and mean gas temperature during 101 and 101He spray tests (spray is activated at t = 0 s).



Figure 9. Gas temperature (°C) field in the TOSQAN vessel measured at t = 300 s for 101 spray test.



Figure 10. Gas temperature (°C) field in the TOSQAN vessel measured at t = 3000 s for 101 spray test.

#### Local analysis

We now focus on local behaviour of the gas mixture in order to analyze the different phases of both spray tests. Particularly, we try to localize the origin of steam source inducing overpressure during the beginning of spray tests (0 s < t < 100 s). Steam volume fraction measurements have been performed in the spray region by the mean of Raman spontaneous scattering spectroscopy (Figure 11a) and in the sump region by the mean of mass spectrometry (Figure 11b) for 101 spray test.

As we can observe on these results, steam distribution in the vessel before spray activation (t < 0 s) has not the same dynamic in the upper part (nozzle exit region) and in the lower part of the vessel (sump region). According to flow development in the TOSQAN vessel during vessel pressurization which induces very low flow velocity under steam injection pipe, steam distribution into the sump area has a poor efficiency (10% in comparison of 60% in the spray nozzle exit region). From the time where spray is activated we can distinguish two steam sources. The first one is located in spray region according to droplets vaporization until Saturation Ratio (SR, Eq. 1) reaches the value of 0.98. The second steam source is produced by the strong vaporization of droplets (droplets temperature equal to 105 °C [7]) falling in the sump region which contains initially 90% of air, so that is to say the local saturation ratio is very poor than in the other part of the vessel.

$$SR(t) = \frac{P_{steam}(t)}{P_{saturation}(t)}$$
(1)

$$P_{saturation}(t) = 10^{(16.37 - \frac{2818}{T_{gas\_mean}} - 1,069 \log T_{gas\_mean} - 5,75.10^{-3} \cdot T_{gas\_mean} + 4,01.10^{-6} T_{gas\_mean}^2)} \times \frac{10^5}{760}$$



Figure 11. Time evolutions of steam volume fraction close to the spray nozzle exit (a) and the sump region (b) for 101 spray test.

For 101He spray test, the same explanation can be done, but droplets vaporization phenomena are amplified. Actually, when spray is activated, a strong helium mass stratification is present in the vessel (Figure 12). In the spray region, hot gas mixture contains high helium volume concentration, thus poor saturation ratio (56% of helium, 32% of steam at t = 0 s, see Figure 12) which induces stronger droplets vaporization than for the 101 spray test (60% of steam in spray region at spray activation). Spray activation is very efficient leading to a helium mixing which is over at t = 200 s, when helium volume concentration is homogeneous in the vessel. A correlation can be made between the helium mixing duration and the time on which occurs the initial steam overpressure (Figure 8). During helium mixing, droplets vaporization is predominant against steam condensation on droplets according to the saturation ratio (Figure 13). From the time when helium mixing is done, the saturation on droplets phenomenon dominates droplets vaporization.



Figure 12. Time evolutions of steam and helium volume concentrations in spray region and sump region for 101He spray test.



Figure 13. Time evolutions of saturation ratio and mean gas temperature for 101He spray test (Eq. 1).

### Analysis of helium mixing due to spray activation for spray test 113

The purpose of the 113 cold spray test is to study helium mixing due to spray activation without heat and mass transfers between gas and droplets. Before spray activation, a helium mass stratification is performed by helium injection in the top of the dome of the vessel. 113 spray test specifications are presented in Table 1. Helium volume concentration measurements are performed at different level in the vessel in order to determine the initial helium stratification before spray injection (t < 0 s) and to follow the helium mixing dynamic during spray activation (t > 0 s). As illustrated on the Figure 14, the gaseous atmosphere is strongly stratified before spray activation. Helium volume fraction is closed to 100% in the upper part of the vessel where is located the spray nozzle and there is only a few percent of helium volume fraction in the sump region (less than 4%). Radial profiles of helium volume fraction that have been also performed at different levels show the good radial homogeneity of helium distribution in the vessel (Figure 15). Helium mixing due to spray activation can be divided in two stages. During the first stage (From spray activation up to 300 s), the main mixing of helium occurs. Resulting to spray entrainment, helium is moved toward the lower part of the vessel until the reach of a state characterized by a nearly homogeneity of helium volume fraction along a vertical profile of the TOSQAN vessel. From 300 s, the second stage of helium mixing starts, characterized by a low helium volume fractions increase until the reach of an equilibrium (t > 4000 s) which is a steady state. This second stage of helium mixing can be attributed to the fact that helium located in the upper part of the dome (above spray nozzle) keeps being distributing in the whole vessel according to circulating flows.



Figure 14. Time evolutions of local helium volume concentration measured at Rt/2 at different levels for 113 spray test.



Figure 15. Radial profiles of helium volume concentration during spray injection between 3600 s and 6000 s (steady state)

## Conclusion

Spray tests were performed in the TOSQAN large facility devoted to thermal hydraulic containment studies. Spray tests realized in hot condition allow us to study the interaction between spray droplets and gaseous mixtures such air and steam (101 test) and air, steam and helium (101He test). Detailed measurements such droplets velocity, droplets size, gas volume concentrations were performed in the two phase flows to analyse the heat and mass transfers between spray droplets and gas. Global and local analyses were conducted to explain the different phases of spray tests, such the initial steam overpressure followed by a strong vessel depressurization. The comparison between spray tests performed in air and steam and air, steam and helium shows that light non-condensable gas has only influence on droplets vaporization phenomena during helium mixing phase inducing a more important initial steam overpressure. When helium mixing is finished, helium has no significant influence on steady state vessel pressure that is to say, on steam condensation on droplets and droplets vaporization phenomena. Another spray test was conducted in cold condition in order to study non-coupled effects of helium mixing due to spray activation (113 test). Results show the good efficiency of spray activation that realizes the most important part of helium mixing in less than 300 s. Spray tests results represent original data for CFD code validation. Results of 101 and 113 spray tests are used for benchmarking in the framework of SARNET.

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