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EXPERIMENTAL MEASUREMENTS OF DROPLET SIZE AND VELOCITY DISTRIBUTIONS AT THE OUTLET OF A PRESSURIZED WATER REACTOR CONTAINMENT SWIRLING SPRAY NOZZLE

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Abstract
During the course of a hypothetical severe accident in a nuclear Pressurized Water Reactor (PWR), hydrogen may be produced by the reactor core oxidation and distributed into the containment. Spray systems are used in order to limit overpressure, to enhance the gas mixing to avoid hydrogen accumulation, and to wash out the fission products. In order to simulate these phenomena with CFD codes, it is first necessary to know the droplet size and velocity distributions close to the outlet nozzle. Furthermore, since most of the phenomena relative to droplets (condensation, gas entrainment, collision) are of particular importance in the region below the nozzle, accurate input data are needed for real-scale PWR calculations. The objective is therefore to determine experimentally these input data.
Experimental measurements were performed on a single spray nozzle which is routinely used in many PWRs. This nozzle is generally used with water at a relative pressure supply of 350 kPa, producing a mass flow rate of approximately 1 kg/s. At a distance of 20 cm, where atomization is just achieved, it is found that geometric mean diameter varies from 305 to 366 µm, Sauter mean diameter from 430 to 600 µm and mean axial velocity from 14.1 to 18.4 m/s.

1. INTRODUCTION

One of the main contributors to the containment early failure during a PWR severe accident is associated to the presence of hydrogen within the containment building. The hydrogen produced by the reactor core oxidation and released from the reactor coolant system could mix or accumulate in different parts of the containment. If the composition of hydrogen-steam-air mixture reaches a certain threshold, combustion could occur. In order to prevent such a risk, array of spray nozzles systems are positioned at the top of the containment. They are used to limit overpressure, to enhance the gas mixing and avoid hydrogen accumulation, and to wash out fission products and structure materials which can be released. The spray system efficiency may depend on the evolution of the droplet size and velocity distributions during their fall (Rabe et al., 2009), especially in the region just below the spray nozzle where most of the droplet phenomena occur: condensation (Mimouni et al., 2009), gas entrainment (Lavieville et al., 1995) and collision (Qian and Law, 1997, Rabe et al., 2010).
Nozzles which are usually used for the spray system in many PWR have already been characterized by Powers and Burson (1993), using photographic and freezing methods, and Ducret et al. (1993), using a micro-video system. These data can be considered as a first approximation for this spray nozzle characterization. However, considering recent developments of CFD codes as well as experimental techniques involving laser diagnostics, improvement of this spray characterization is necessary and can now be achieved. The objective of this work is thus to provide a more detailed characterization of the PWR spray nozzle, in terms of spray shape, spray size and axial velocity distributions as close as possible to the nozzle outlet. Such measurements will give accurate and detailed boundary conditions for CFD numerical simulation spray of spray behaviour, which constitutes valuable improvement,

since it is known that appropriate boundary conditions for CFD calculations are mandatory for relevant CFD calculations.

2. PWR CONTAINMENT SPRAY SYSTEMS

Spray systems are emergency devices designed for preserving the containment integrity in case of severe accident in a PWR. The French PWR containments have generally two series of nozzles placed in circular rows (Coppolani et al., 2004). More precisely, for the 900 MWe PWR, there are exactly four rings of nozzles having the characteristics presented in Table 1. A schematic view of these spray rings and the associated spray envelopes are given in Fig. 1.

Table 1: Characteristics of spray rings for the French 900 MWe PWR.

	Height (m)	**Diameter (m)**	**Number of nozzles**	**Estimated minimum distance between nozzles (m)**
1st Ring	54.8	10.0	66	0.5
2nd Ring	54.2	14.8	68	0.7
3rd Ring	52.3	22.5	186	0.4
4th Ring	51.0	27.0	186	0.4

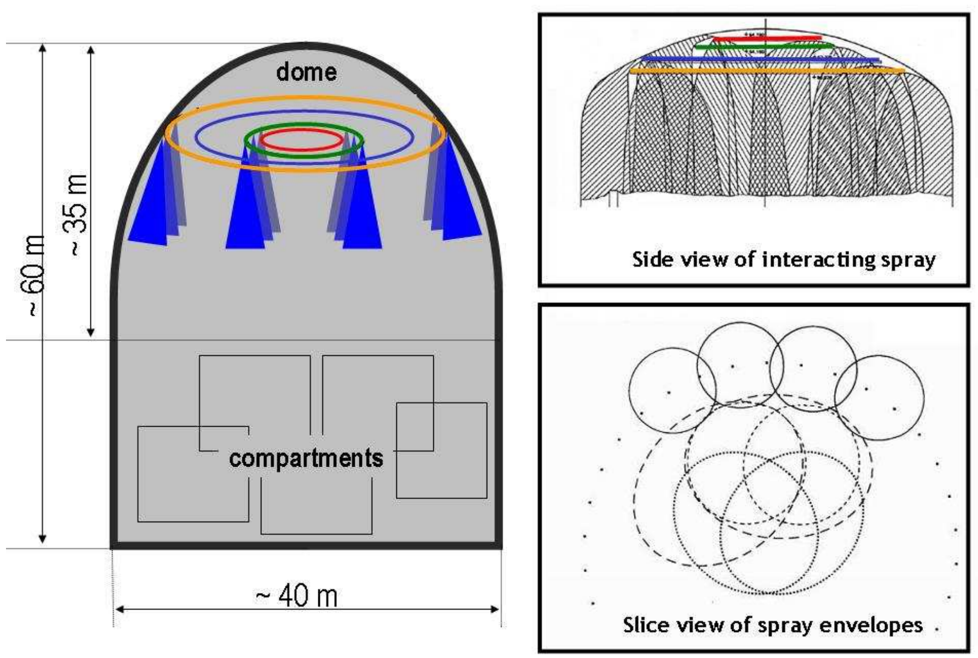


Fig. 1: Spray rings and envelopes in a French PWR (not at scale).

The nozzle type used in many PWRs, in particularly French 900 MWe PWRs, is the so-called SPRACO 1713A, distributed by Lechler (Fig. 2). This nozzle is generally used with water at a relative pressure of 350 kPa, producing a flow rate of approximately 1 l/s. The outlet orifice diameter is 9.5 mm. The temperature of the injected water during a hypothetical nuclear reactor accident is either from 20°C or 60°C to 100 °C, depending on the kind of process (the 60°C to 100°C process is the so-called recirculation mode).

Fig. 2: Spray nozzle SPRACO 1713A (Lechler).

The droplet size distribution measured by Powers and Burson (1993) for this nozzle is presented in Fig. 3 and the one obtained by Ducret et al. (1993) in Fig. 4. These results can be considered as a first estimation of the size distribution. Nowadays, more information can be obtained using methods such as Phase-Doppler Interferometer (PDI), Diffractometry or Shadowgraphy. Furthermore, the advanced techniques as PDI allow the determination of the spatial distribution of the droplet size and velocity close to the nozzle outlet.

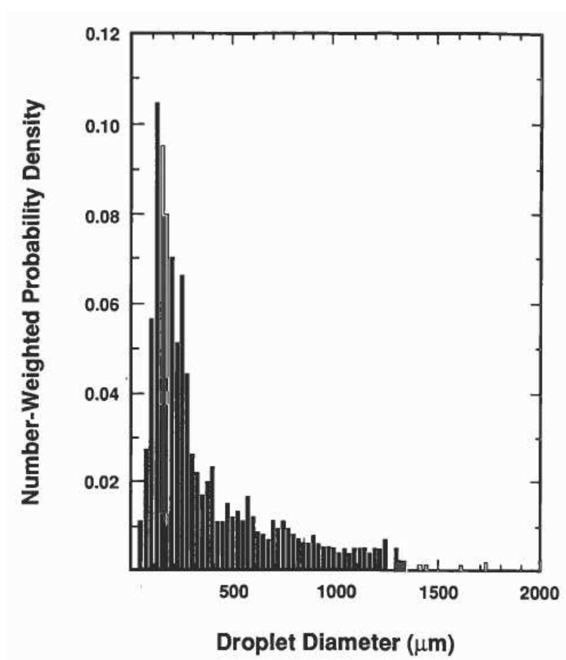


Fig. 3: Droplet size distribution for the nozzle displayed in Fig. 2, as measured by Powers and Burson (1993) using photographic and freezing methods.

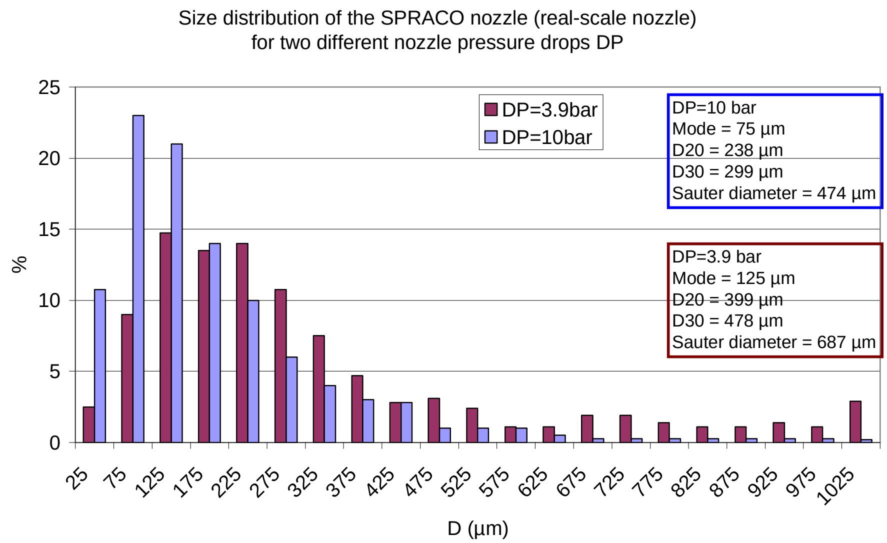


Fig. 4: Droplet size distribution measured by Ducret et al. (1993), at 6 m under the nozzle, with a micro-video system, for two relative pressure supplies ΔP.

3. EXPERIMENTAL FACILITY

The experiments have been carried out at the Von Karman Institute (VKI) in Belgium, in the VKI-Water-Spray facility sketched in Fig. 5. The set-up is composed of a hydraulic circuit supplying, for those experiments, a single spray nozzle with a flow-rate of 1 l/s at 350 kPa. The pulverized water is collected in a 12 m^3 pool. The position of the spray nozzle may be changed using a monitored three-axes carriage.

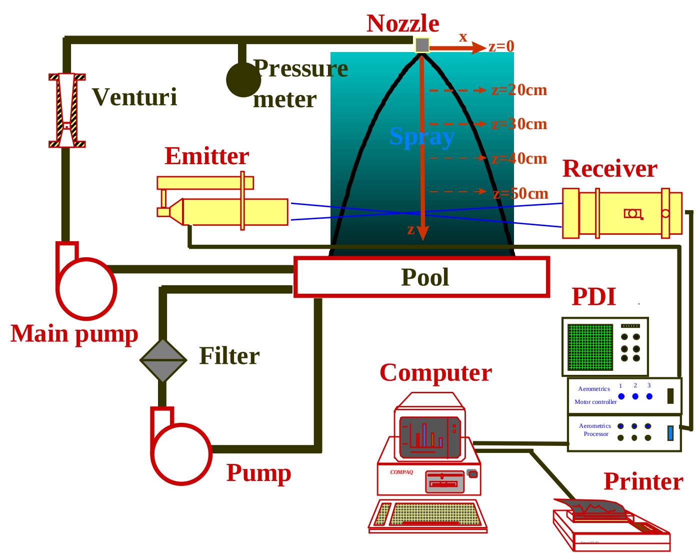


Fig. 5: VKI water-spray experimental facility.

The measurement of the spray characteristics requires a technique such as the light diffraction, shadowgraphy or Phase-Doppler Interferometry (PDI). The latter was chosen since it provides local high resolution information about the spray drops. Indeed, PDI measures the size and velocity of drops passing through an optically defined probe volume (Bachalo and Houser, 1984). The laser light source of the present ARTIUM PDI system is a continuous-wave He-Ne laser. The laser probe volume is formed by the intersection of two laser beams, depicted as blue lines on Fig. 5. The off-axis angle (scattering angle), at which the receiving optics unit is placed, is 30°.
PDI can only measure droplets of spherical shape. In order to determine where atomization is achieved, visualization has been performed with a Phantom high-speed camera used with a resolution of 800x600 pixels at a frequency of 4796 Hz, with an exposure time of 10 µs. The spray close to the nozzle outlet, where atomization occurs, is illuminated from the back in order to obtain consistent and machine readable images.

4. EXPERIMENTAL RESULTS

4.1. Global spray characterization

A spray is usually created by the instability of either a liquid jet or sheet at the outcome of the nozzle (Dumouchel, 2006). When surface forces become weaker than inertial forces, atomization occurs: the liquid jet/sheet breaks into filaments that shatter into droplets. The high-speed visualization shows that the distance from the nozzle exit at which most of the liquid is atomised into droplets (for a relative pressure of 350 kPa) is approximately at 20 cm as depicted in Fig. 6. Therefore, it can be anticipated that at such a distance, PDI measurements of droplets are reliable. It is also noticed that the spray is not symmetrical, the droplet density being higher on the right side. This observation is probably due to the inner geometry of the nozzle shown in Fig. 2.

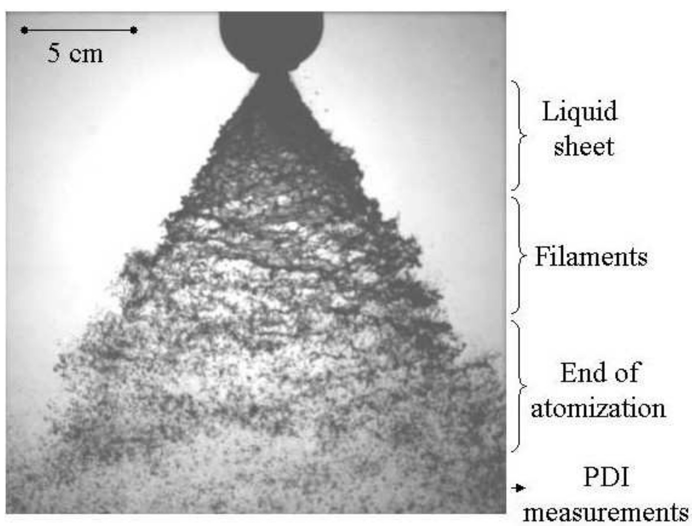


Fig. 6: High-speed camera imaging of the nozzle SPRACO 1713A at a relative pressure of 350 kPa.

It is also found, as by the nozzle manufacturer, that the SPRACO 1713A nozzle creates a hollow cone spray. No droplets are found in the core of the spray. The annular ring, in which droplets are found, is characterized by the internal and external diameters of the annulus, which are, respectively, about 18 and 26 cm at a 20 cm distance from the nozzle outlet (Fig. 7).

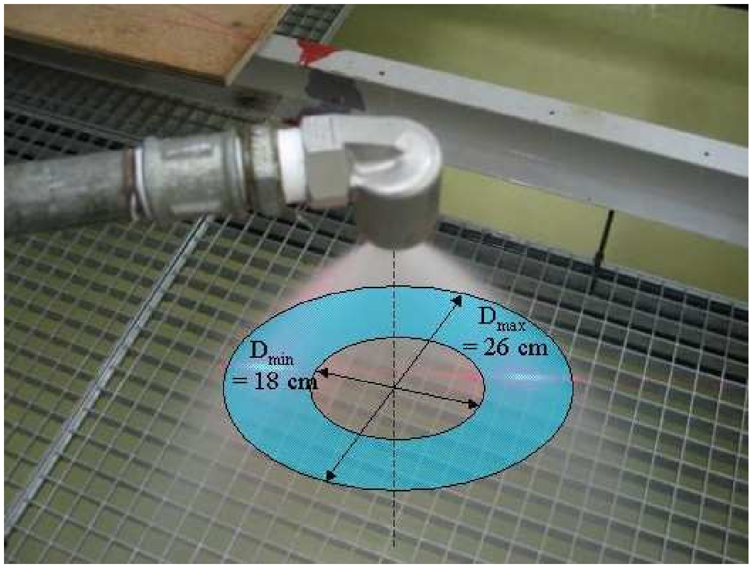


Fig. 7: Annular cross-section of the hollow cone spray at a 20 cm distance from the nozzle outlet.

The spray angle is found to be around 60° (Fig. 8).

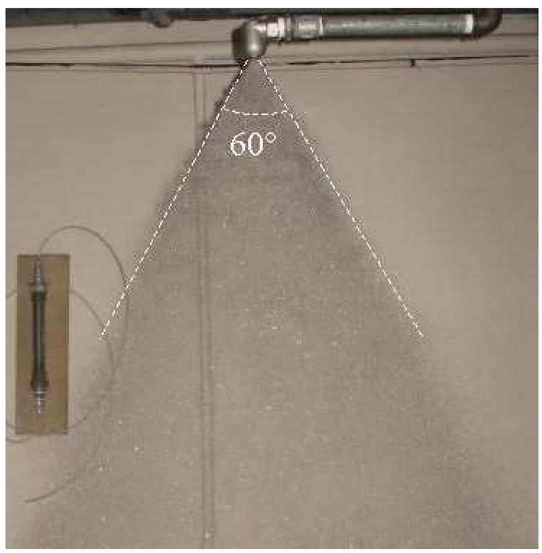


Fig. 8: Estimation of the spray angle.

4.2. Description of the measurement points

PDI measurements of droplet size and velocity distributions are performed at 20 cm from the nozzle outlet. Eight measurements points, separated by 45° angles, are chosen at a radial position situated at the centre of the annular ring as described in Fig. 9.

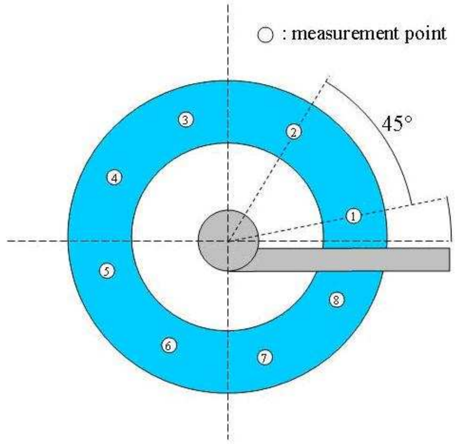


Fig. 9: Position of the measurement points in the cross-section of the hollow cone spray, as viewed from the top.

For each measurement point, droplet size and axial velocity distributions, are measured three times (three different days).

4.3. Drop size distribution

Size distributions measured at different angles at a distance of 20 cm from the nozzle outlet are presented in Fig. 10. For each graph of this figure, the three size distributions corresponding to the three day tests are given, as well as an "average" distribution obtained from the three others. This averaging has no physical meaning but helps to visualize the shape of the size distribution. Two main conclusions can be drawn from Fig. 10:

- the shape of the droplet size distribution at each position is rather repeatable from test-to-test;
- this shape is rather similar for all positions on the annular ring of the spray envelope.

For each measured size distribution, global spray features, as the Geometric Mean Diameter D_{10} or the Sauter Mean Diameter D_{32}, are calculated. Their evolution with the azimuthal angle is plotted in Fig. 11 and Fig.12 respectively. On these figures, the specified diameter for each test is given, as well as the average of this diameter on the three tests. These figures show that the tests exhibit good repeatability, even if small differences can be observed: the D_{10} diameter changes slightly with the angle position, from around 300 µm to 350 µm, and the Sauter mean diameter changes from around 400 to 600 µm. Two reasons may explain this dissymmetry:

- the liquid flow inside the spray nozzle is not symmetrical, since the inner geometry of the nozzle is not symmetrical; first CFD calculations with the CFX commercial code seem to confirm this effect;
- an experimental bias can also occur: depending on the measurement position, the laser beam has to cross more or less spray, and the gain of the receiver has to be adjusted so that this could influence the detection of the smallest or biggest droplets. The calculations of the mean diameters can then be modified by the presence of those smallest or largest droplets. This is why the use of the size distribution as an input data appears to be more accurate than the use of an average diameter in order to characterize the spray in CFD codes.

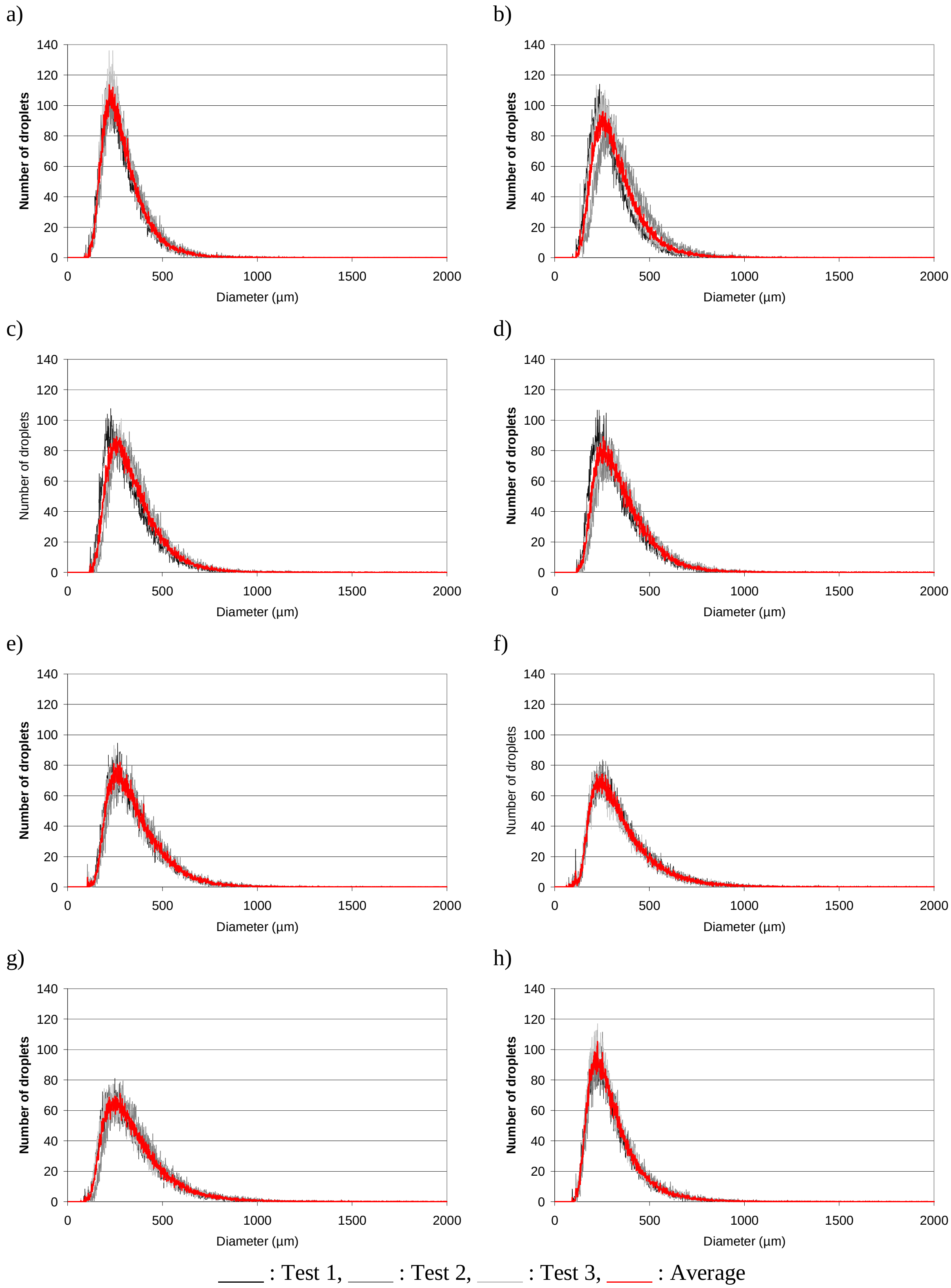


Fig. 10: Experimental droplet size distributions at 20 cm from the nozzle outlet for an angle of a) 15°, b) 60°, c) 105°, d) 150°, e) 195°, f) 240°, g) 285°, h) 330°.

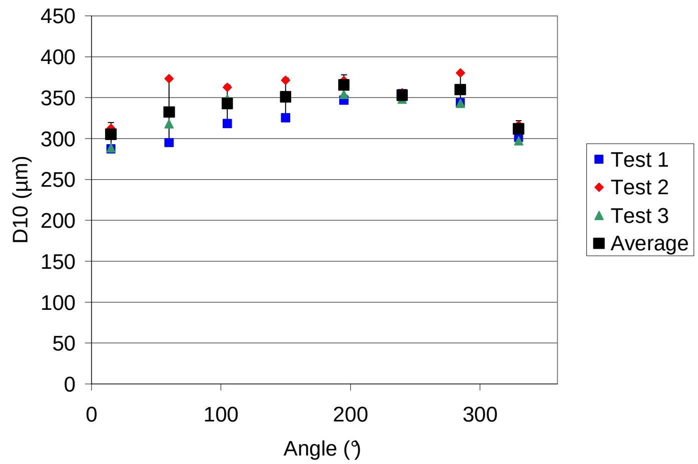


Fig.11: Geometric Mean Diameter D_{10} for different angles around the annular section of the spray envelope, at 20 cm from the nozzle outlet. Error bars represent the dispersion over the mean value.

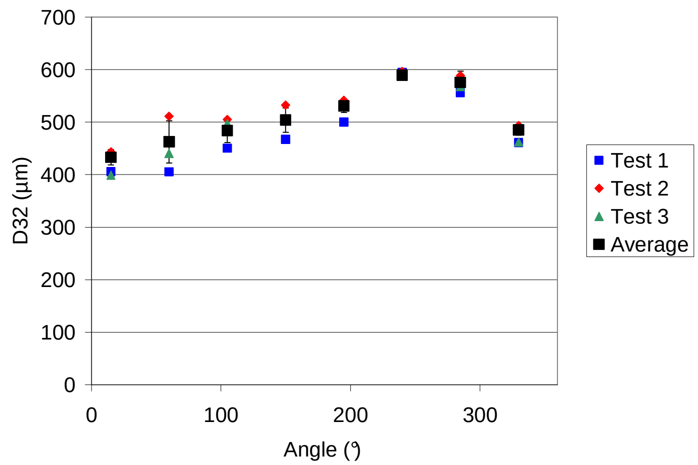
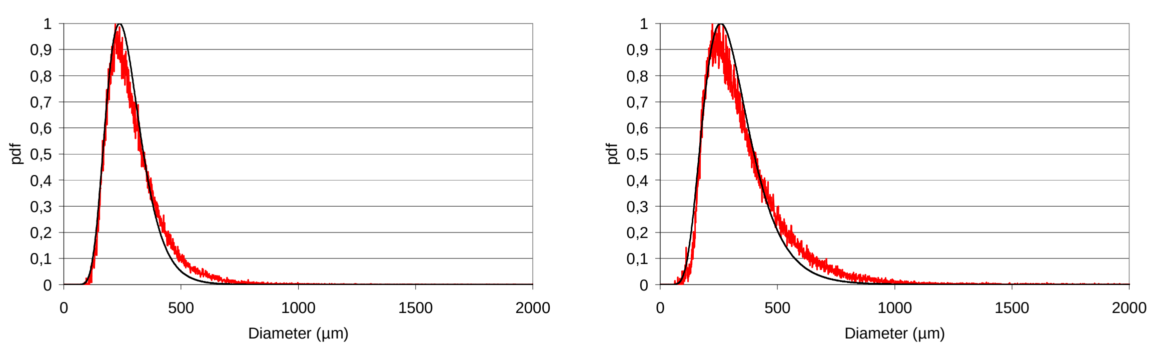


Fig. 12: Sauter Mean Diameter D_{32} for different angles around the annular section of the spray envelope, at 20 cm from the nozzle outlet. Error bars represent the dispersion over the mean value.

The experimental size distributions can be approximated with a log-normal distribution, as it can be seen in Fig.13 for two different angular positions. The same kind of results is observed for all the other angular positions.



____ : Experimental average distribution, ____ : Log-normal fitted distribution

Fig. 13: Experimental average and fitted log-normal droplet size distributions at 20 cm from the nozzle orifice for an angle of 15° (left) and 240° (right).

4.4. Axial velocity distribution

Measurements of the droplet axial velocity have also been performed at a distance of 20 cm from the nozzle orifice. Normalized results are plotted in Fig. 14 and fitted with a Gaussian distribution function presented in the same figure. The average value of the axial velocity around the annulus of the spray envelope is given in Fig. 15. It can be observed from those figures that:

- the shape of the axial velocity distribution at each position is very repeatable from one test to another;
- this shape is rather similar for all positions on the annular ring of the spray envelope;
- the axial velocity distribution at this position can be approximated by a Gaussian function (Sellens and Brzustowski, 1986);
- the mean droplet axial velocity varies with the angle position, probably due to the nozzle inner geometrical dissymmetry and the resulting swirling behaviour of the spray discussed earlier;
- the mean axial velocity varies from 14.1 to 18.5 m/s; associated experimental relative uncertainties have been estimated to be between 1 and 4 %.

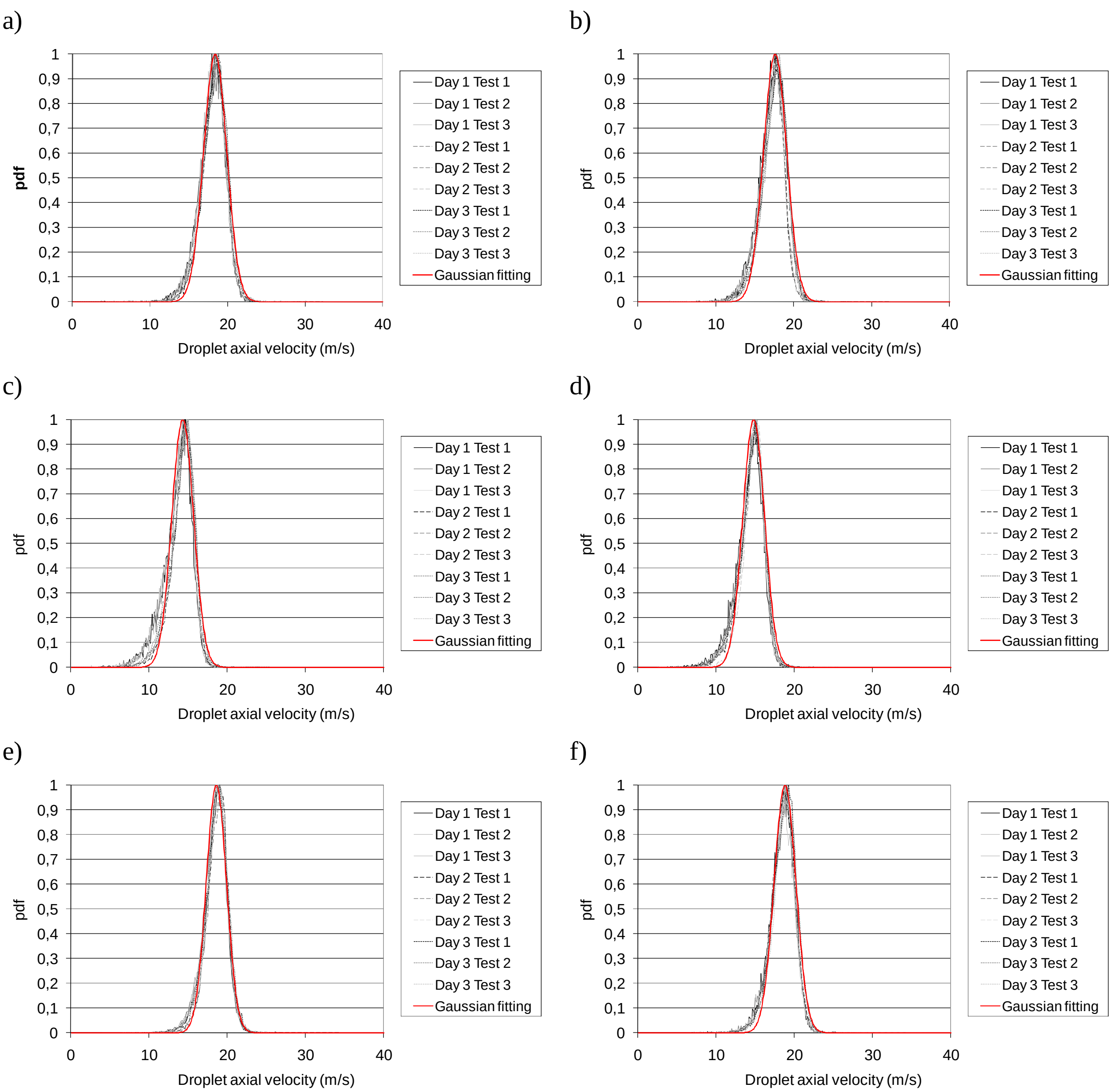


Fig. 14: Droplet axial velocity distribution and Gaussian fitting at 20 cm from the nozzle orifice for an angle position of a) 15°, b) 60°, c) 150°, d) 195°, e) 285°, f) 330°.

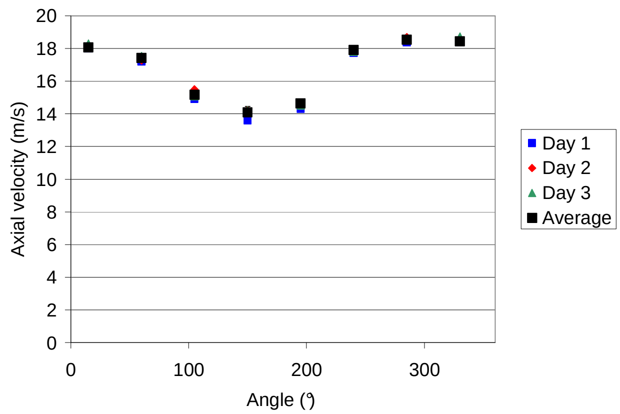


Fig. 15: Mean value of the axial velocity for different angles around the annular section of the spray envelope, at 20 cm from the nozzle outlet. Error bars represent the dispersion over the mean value.

4.5. Radial velocity

Experimental measurements were only performed on the axial velocity of droplets, since a 1D PDI was used. However, an approximation can be given using the angle of the spray cone and the axial velocity (Fig. 16). On the Fig. 8, the angle of the cone is estimated at a value of 60°, and the mean value for the droplet axial velocity, at 20 cm from the nozzle outlet, is about 16.8 m/s (Fig. 15). Radial velocity is therefore given by $v_r = v_z \tan(\alpha)$ with $\alpha = 30°$. The radial velocity is found to be equal to about 10 m/s.

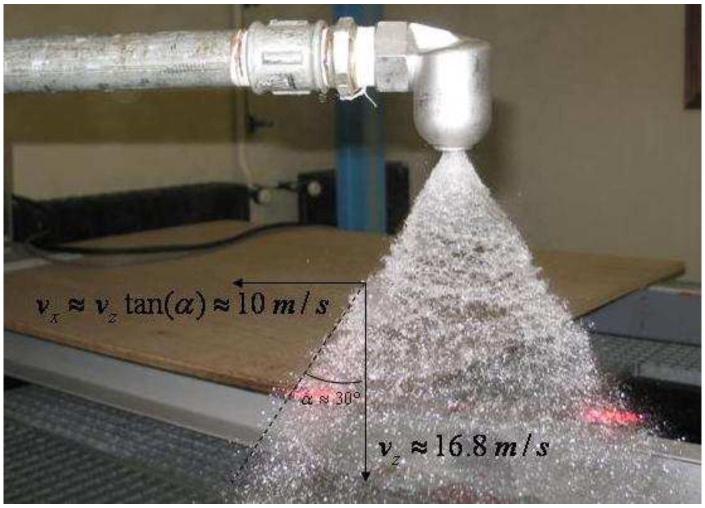


Fig. 16: Estimation of the droplet radial velocity, from the angle spray cone and the droplet axial velocity.

5. CONCLUSION

Measurements of hydrodynamic characteristics of a real-scale spray nozzle (SPRACO 1713A) used in many PWRs, have been performed for the first time ever in terms of droplet size and axial velocity distributions, have been achieved for the first time ever. The detailed information obtained is now available as input data for CFD simulation. Measurements have been conducted as close as possible to the nozzle outlet, i.e. at 20 cm from the nozzle orifice, where the atomization process appears to be completed, as observed experimentally with a high-speed camera. Droplet size and velocity distribution have been obtained for typical conditions used in nuclear reactors, i.e. a relative pressure supply of 350 kPa.

Observations show differences across the spray section, in terms of droplet mean diameters and droplet mean axial velocities. These differences are supposed to be mainly due to the inner geometry of the nozzle which leads to a non symmetrical liquid flow just at the outlet of the spray nozzle. It is also found that the droplet size distribution can be well fitted by a Log-Normal distribution and the droplet axial velocity distribution by a Gaussian distribution. It is recommended to use these distribution functions as input data for CFD calculations of real-scale sprays in nuclear reactors.

Further improvements in the analysis of these experimental data will include the velocity-size correlation and the axial velocity distribution for each droplet class. Other experimental data can also be obtained, in particular the radial and ortho-radial droplet velocities which are important quantities for the determination of the droplet cross-trajectories that lead to droplet collision.

All these results are of particular importance to determine the input data for sprays in real-scale PWR calculations, since most of the phenomena relative to droplets (condensation, gas entrainment, collision) are enhanced in the region below the spray nozzle.

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