OPTICAL DIAGNOSTICS APPLIED FOR SINGLE AND MULTI-PHASE FLOW CHARACTERIZATION IN THE TOSQAN FACILITY DEDICATED FOR THERMAL HYDRAULIC CONTAINMENT STUDIES

Porcheron E., Brun P., Cornet P., Malet J., Vendel J.
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
CEA Saclay, DPEA/SERAC, BP 68, 91192 Gif-Sur-Yvette CEDEX, FRANCE
E-mail : emmanuel.porcheron@irsn.fr
Tel:+33 1 69 08 50 72 / FAX:+33 1 69 08 97 36

Thause L.
ADULIS, 91961 Courtaboeuf, France
Lylian.thause@irsn.fr

KEYWORDS
Optical diagnostic, containment, steam condensation, large facility

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. TOSQAN facility is a large enclosure devoted to simulate typical accidental thermal hydraulic flow conditions in Nuclear Pressurized Water Reactor containment, especially suitable for making detailed measurements by non-intrusive optical diagnostics. In the first part of this paper we describe several optical diagnostics used to characterize single phase flow during the course of steam condensation test, and in the second part, we present advanced optical diagnostics development that will be implanted in TOSQAN for spraying test.

1. INTRODUCTION

During the course of an 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 steam wall 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 flow conditions in the reactor containment and to study different phenomena such as steam wall condensation.
in the presence of non-condensable gases. A second part of TOSQAN program is devoted to study the water spraying effect used as mitigation mean (Malet et al., 2003). The first part of this study presents optical diagnostics implemented on TOSQAN facility, used to characterize an air / steam mixture. Simultaneous concentration and velocity measurements are performed with, respectively, Spontaneous Raman Scattering (SRS), Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) (Porcheron et al., 2002). The second part of this work concerns the development and the qualification of optical diagnostics that will be used in TOSQAN facility to study the interaction between a water spray and an air / steam mixture. Water droplet size is measured by an advanced technique called Interferometrics Laser Imaging for Droplet Sizing (ILIDS). An adaptation of standard LDV technique was undertaken in order to perform simultaneous velocity measurements on gas and spray droplets.

2. TOSQAN FACILITY

2.1. Set-up

The TOSQAN facility (Figure 1, Figure 2) consists in a closed cylindrical vessel (7 m$^3$ volume, 4 m high, 1.5 m i.d.) into which steam is injected by a vertical pipe located in the center part of the TOSQAN enclosure. The walls of the vessel are thermostatically controlled so that a water film can be obtained by steam condensation on a part of the wall vessel. Optical accesses are provided by 14 overpressure resistant viewing windows permitting non-intrusive optical measurements along an enclosure diameter at 4 different levels. A nozzle producing a water full cone spray constitutes the spraying system located at the enclosure dome.

2.2. TOSQAN test principle for condensation test

Condensation tests presented in this study consist of a steam injection into the enclosure that is initially at atmospheric pressure, with hot wall temperature of 396K, condensing wall temperature of 373K. After a transient stage corresponding to enclosure pressurization, a steady state is reached when the steam injection and the condensation flow rates are equal, which corresponds to constant enclosure pressure and thermal equilibrium. Steady state pressure level is function of steam mass flow rate. Results presented in this paper are obtained during the International Standard Problem n°47 (ISP47) experimental sequence (Vendel et al., 2003). ISP47 sequence contains a succession of two condensation steady states obtained for a 1 g/s steam mass flow and a 12 g/s steam mass flow rate (see Table 1).

| Steam mass flow rate $Q_{\text{steam,inj}}$ | Reynolds number $Re_{\text{inj}}$ | Richardson number $Ri_{\text{inj}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation steady state 1</td>
<td>1 g/s</td>
<td>2.5.10$^4$</td>
</tr>
<tr>
<td>Condensation steady state 2</td>
<td>12 g/s</td>
<td>3.10$^4$</td>
</tr>
</tbody>
</table>

Table 1. Steam injection for ISP47 sequence.
Figure 1. Overview of TOSQAN facility located at IRSN Saclay.

Figure 2. Optical diagnostics implementation on TOSQAN vessel.
3. OPTICAL DIAGNOSTICS PERFORMED FOR TOSQAN CONDENSATION TEST IN SINGLE PHASE FLOW CONDITION

3.1. Concentration measurement

3.1.1. Background

Few studies are available in the literature showing the possibility to make measurements of concentration in parallel with velocity measurements. The Raman effect, first observed in 1928, is the start of numerous molecular spectroscopy techniques. It is complementary to infrared absorption spectroscopy and is widely used in different fields such as chemistry allowing structural and kinetic studies of proteins and the monitoring of chemical vapor deposition for example. In the field of combustion Raman effect is used for concentration and temperature measurements in flames (Miles, 1999) or in sprays for internal combustion engines (Beushausen et al., 2000). Other investigations within the framework of studies on Pressurized Nuclear Reactor have already been done. Indeed, Goldbrunner et al. (2000) have investigated the heat transfer phenomena using linear Raman spectroscopy in order to obtain simultaneously profiles of concentration in the gaseous phase and water temperatures in the liquid phase in a small vessel. Spontaneous Raman Scattering (SRS) is a useful diagnostic tool because Raman spectra can be interpreted to yield the molar fractions or temperatures with good accuracy. Another interest of SRS is that the presence of impurities such oil droplets inside the flow have no consequence on the measurements (Labrunie et al., 1999). Therefore the possibility of making simultaneous laser velocimetry and SRS measurements can be considered.

3.1.2. Fundamental principle of Spontaneous Raman Scattering (SRS)

Spontaneous Raman scattering is an inelastic scattering process involving the interaction of a photon with a specific vibration-rotational state of a molecule. This scattering results of an inelastic interaction in which energy exchange occurs between the incident photons with frequency $\nu_0$ and a molecule. The generated energy flux will experience a frequency shift $\nu_n$ that is characteristic of each polyatomic molecule. In case of Stokes transition, the frequency is $\nu_0 - \nu_n$, for anti-Stokes transition the frequency is $\nu_0 + \nu_n$. Good reviews on single-point Raman measurements are available from Lederman (1977). For our experimental condition ($T<400 \, K$), the anti-Stokes transition is not taken into account since it is negligible (Long, 1977). In case of a mixture of several gases $i$, the Raman power for the Stokes response can be expressed by the following relation (Cohen-Tanoudji et al., 1986):

$$P_{\text{Raman, Stokes}}(i) = P_{\text{LASER}} \cdot N(i) \cdot \left( \frac{d \sigma}{d \Omega} \right) \cdot L \cdot \tau \cdot \Omega$$

With:

- $P_{\text{LASER}}$: incident LASER beam power (W)
- $N(i)$: molecular density (mol/cm$^3$)
- $\left( \frac{d \sigma}{d \Omega} \right)$: differential cross section (cm$^2$/sr)
- $L$: measurement volume length (cm)
- $\Omega$: collection angle (sr)
- $\tau$: optical set-up efficiency

(1)
The search for differential cross sections is rather delicate and a very detailed attention must be paid to the values chosen for the application. Indeed, this Raman differential cross section depends on many external parameters such as the temperature, the wavelength of the incidental laser beam, the angle of polarization between the incidental beam and the diffracted beam, the polarization of the incidental beam and the viewing angle of the diffracted beam. Values of differential Raman cross-sections used in this study were taken from the literature (Colthup et al., 1975).

3.1.3. SRS optical bench

The laser emission is produced by a continuous doubled Nd:YAG Laser (Millennia from Spectra Physics) emitting at 532nm with power laser of 5.5W. The optical bench includes an optic prototype probe that is used both to create the measurement volume and to collect the backscattered Raman light. The incidental and the backscattered signals are transported via two optical fibers (respectively single-mode and multimode) to the spectrograph that is laid out in an air-conditioned room (Figure 3). The dimensions of the measurement volume are equal to 40mmx0.5mmx0.5mm. A spectrograph TRIAX 320 (ISA Jobin-Yvon SPEX, Czerny-Turner configuration) (grating 600 line/mm) and a very sensitive detector that is a non-intensified CCD camera cooled by liquid nitrogen (Jobin Yvon, matrix 2000×800 pixels, pixel size 15µmx15µm) are used to analyze the backscattered light. The dark current is lower than 1 e−/pixel/hours. The quantum efficiency reaches 85% between 500nm and 700nm. A program (SPECTRAMAX) associated with the spectrograph and provided by the manufacturer then displays the results.

Figure 3. Optical set-up for Spontaneous Raman Scattering diagnostic.
3.1.4. SRS concentration measurement principle

In case of a mixture of perfect gases, the molar fraction or volume fraction \( X_i \) of one of them is a function of molecular density \( N_i \) (2).

\[
X_i = N_i \frac{1000RT}{N} \frac{P}{P_i}
\]  

(2)

With : \( N = 6.02 \times 10^{23} \), Avogadro number and \( R \), Planck constant.

If all the molecules (\( j \)) of the mixture are active in Raman scattering then molar fractions can be calculated independently of pressure \( P \) and temperature \( T \) (3).

\[
\sum_{j=1}^{L} X_j = 1
\]

\[
X_i = \frac{P_{\text{Stokes}_i} \left( \frac{d\sigma}{d\Omega} \right)}{\sum_{j=1}^{L} P_{\text{Stokes}_j} \left( \frac{d\sigma}{d\Omega} \right)}
\]  

(3)

In the case where \( X_i \) and \( T \) are constant, relation (1) can be written only versus pressure \( P \) (4).

\[ P_{\text{Stokes}_i} = K \left( \frac{d\sigma}{d\Omega} \right) P \]  

(4)

With \( K \) a constant

3.1.5. SRS concentration measurement characterization

The optical bench has been first characterized in airflow in order to check that the Raman signal intensity follows a linear evolution versus pressure (4) and to establish the accuracy of the concentration measurements. Raman spectrum acquisition is performed by accumulating the measurement during a time recording of 60s. This time is a good compromise for measurement accuracy and experimental constraints. Experiments were performed at constant temperature for several total air pressure in the TOSQAN enclosure. Figure 4 shows the linear evolution of the Raman signal intensity specifying the molar fraction measurement accuracy which is quite a constant function of the air pressure increase (6.5% for \( O_2 \), 2% for \( N_2 \), Porcheron et al. 2002). Tests are performed during a steam injection in the TOSQAN enclosure that was initially heated at atmospheric pressure. Raman measurement volume is located near the steam injection exhaust pipe. Results presented in figure 5 show again the linear dependence between the \( H_2O \) Raman signal and the steam partial pressure. The Raman signal intensity level for \( N_2 \) and \( O_2 \) (\( O_2 \) not plotted on Figure 5) remains quite constant during the steam injection.
Figure 4. Raman signal intensity evolution and accuracy measurement versus total air pressure.

Figure 5. Raman signal intensity evolution versus steam partial pressure.
3.2. Gas velocity measurement

Velocity measurements are performed with two kinds of optical diagnostics based on Mie scattering generated by the light reflected by small particles seeded in the flow in order to follow the gas velocity field.

3.2.1. Seeding of the flow

Flow seeding is quite difficult in our application because of the large volume of the enclosure and high moisture rate, pressure and temperature conditions. Particles of silicon carbide \( \text{SiC}, \phi=2\mu m \) are dispersed by a RBG 1000 generator (Palas) and injected under pressure after being heated to avoid condensation nucleus formation. A seeding procedure was developed to obtain a high particle concentration with good homogeneity in TOSQAN enclosure (Porcheron et al., 2000).

3.2.2. Laser velocimetry optical benches

Velocity measurements are performed by commercial PIV and LDV systems (Dantec). The LDV system is using a two components optic probe in backscatter configuration with a large focal length (2 m). The laser emission is produced by an Argon laser (514.5nm). The PIV system is composed of a doubled Nd:YAG laser (532nm) and a CCD camera used in cross correlation mode. Radial velocity profiles across TOSQAN enclosure are performed with LDV (vertical velocity component \( V \)). LDV can’t be used for boundary layer characterization very close to the condensing wall considering the length of the measurement volume (10mm). PIV allows to obtain velocity fields (radial component \( U \) and vertical component \( V \)) in the boundary layer spread on condensing wall (see Figure 2). Mean velocity fields are computed from 200 instantaneous fields.

4. RESULTS: GAS VELOCITY AND CONCENTRATION MEASUREMENTS PERFORMED IN TOSQAN DURING CONDENSATION STEADY STATES

4.1. TOSQAN enclosure radial characterization

LDV and Spontaneous Raman Scattering are used to characterize steam flow injection during steady state stage obtained for two steam mass flow rates (see table 1). Vertical velocity \( V \) and concentration radial profiles are performed on a whole diameter of the TOSQAN enclosure in front of condensation wall. The results are presented in Figure 6 for the smaller steam mass flow rate (1g/s) during the steady state 1 (see table 1). This steam mass flow rate corresponds to a plume injection according to the Richardson number \( \text{Ri}=0.5 \). The steam / air mixture is homogenous on a whole enclosure diameter as shown on figure 6 (steam concentration about 45%).
Figure 6. Steady state 1: Velocity and H$_2$O volume fraction radial profiles performed at $Z/r_{inj} = 36$.

The results are presented on figure 7 for the higher steam mass flow rate (12 g/s) during steady state 2 (see table 1). The jet region is clearly identified on both velocity and concentration profiles. Out of the jet region, air / steam mixture is nearly homogeneous with mean vertical velocity close to 0 m/s and even negative when moving closer to the condensing wall.

Figure 7. Steady state 2: Velocity and H$_2$O volume fraction radial profiles performed at $Z/r_{inj} = 36$. 
4.2. Condensing wall boundary layer characterization

Gas velocity measurements are performed with PIV, which can allow us to characterize the boundary layer spreading along the condensing wall of TOSQAN during both steady states. Velocity field are presented on Figure 8 and Figure 9. Contour legend colors indicate the vertical velocity intensity. For both steam injection conditions, we can see the usual near the wall flow structure, which is composed of a downward flow, with, near the wall in the boundary layer, a strong velocity gradient.

Figure 8. Steady state 1: Near-wall flow velocity field for steam mass flow rate of 1 g/s – Z/r_{inj}=36.

Figure 9. Steady state 2: Near-wall flow velocity field for steam mass flow rate of 12 g/s – Z/r_{inj}=36.
Close to the condensing wall, vertical velocity intensity is more important for the higher steam mass flow rate (Figure 9) but also for this case, there is a stronger interaction between the downward flow and the steam jet injected in the center part of the enclosure, according to the more important decrease of the vertical velocity as a function of the distance to the condensing wall (see Figure 11 comparatively to Figure 10).

Figure 10. Steady state 1: Near-wall flow velocity profile for steam mass flow rate of 1 g/s (data extracted from Figure 8).

Figure 11. Steady state 2: Near-wall flow velocity profile for steam mass flow rate of 10 g/s (data extracted from Figure 9).
5. OPTICAL DIAGNOSTIC DEVELOPMENT FOR TOSQAN SPRAYING TEST

5.1. Droplet and gas velocity measurements

The TOSQAN spraying program requires being able to measure simultaneously gas and droplet velocities in the enclosure. The goal of this study is to present that kind of velocity measurement performed in a water spray scaled down for TOSQAN experiment with similarity from Nuclear Pressurized Water Nuclear spraying system. Optical diagnostics used is Laser Doppler Velocimetry (LDV) (see section 3.2.2).

5.1.1. Background

Several techniques based on this principle were developed within the framework of two-phase flow velocity measurements. Lee and Dust (1982) developed an electronic processing scheme based on automatic filters and amplitude discriminators in order to separate the two phases. Another way to separate the two signals (fluid or particles) is by setting threshold values against pedestal and Doppler components of the photo multiplier signals, this technique was achieved by Tsuji et al. (1982). Unlike the two methods previously presented, the one developed at the laboratory does not implement external set-up or any kind of modifications of the signal but is simply based on a discrimination of the signals by various adjustments of the photo multiplier voltage. Indeed, depending on the voltage applied to the photomultiplier, it is possible to obtain the speed of only one of the two phases composing the flow. A different way was used for gas measurements in two-phase flow for a study undertaken in the field of coaxial atomization, in considering very small droplets as gas tracer, by the mean of Phase Doppler Anemometry measurements (Porcheron et al., 2002).

5.1.2. Experimental procedure

Measurements performed with LDV were first carried out for at a small distance from the nozzle (d_nozzle/meas ≈ 0.1m). The water spray is produced by full cone spray nozzle (nozzle from Spraying System). In order to make gas velocity measurements, the two-phase flow is seeded with small oil particles (1µm < Φ_particles < 2µm). First results are presented on Figure 12 in the form of velocity histogram. One easily observes two distinct peaks on this histogram. Each one contains a contribution from both phases of the flow. Similar results were obtained by Hamed et al., (2001) for velocity measurements performed in a vertical wind tunnel in two-phase flow conditions. The peak located on the right side of the histogram is representative of gas velocity (order of size of -1.5m/s). The second peak gives information on spray droplets and we can notice that there is a larger dispersal of measured velocity because of the correlation between size and velocity of droplets.
Applying two different photomultiplier voltages will allow us to focus on only one phase. It has been shown that lowering the voltage setting permit to have access only to the droplets velocity whether a high voltage will permit to measure the gas velocity. The radial velocity profile in the spray performed at a distance $d_{\text{nozzle/meas.}} \approx 1.1\text{m}$ from the nozzle is presented on Figure 13. Gas and droplet velocities are obtained by making two series of recording at a given radial position. Two different voltage adjustments on processor (Burst Spectrum Analyser) were used. This profil allows us to visualize the loop of re-circulation of gas on the edges of the spray. We can also verify that the velocities obtained with a high voltage (gas) are lower than those obtained for a low voltage (droplets) at a given radial position.

Figure 12. Sample velocity histogram obtained in two-phase flow – Measurements performed close to the nozzle exit ($d_{\text{nozzle/meas.}}=0.1\text{m}$).

Figure 13. Radial velocity profile in water spray for gas and droplets ($d_{\text{nozzle/meas.}}=1.1\text{m}$).
5.2. Droplet size measurement

In the field of spray analysis, various kinds of measurement techniques for droplet size measurements are available, such as the Phase Doppler Anemometry (PDA). PDA technique cannot be used in TOSQAN facility because of optical access constraints. That is the reason why we decided to develop the Interferometrics Laser Imaging for Droplet Sizing (ILIDS) (Kobayashi T., et al., 2000; Niwa Y., et al., 2000; Calabria R., et al., 2000). 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. On Figure 14a is presented an example of out-of-focus image obtained in the same full cone water spray presented in section 5.1, Figure 13). Image processing that is carried out using original code written with Matlab software is composed of several steps (see Figures 14b to 14d) where ILIDS code identifies the individual droplet, droplet fringes, fringes spacing, fringes number with two dimensional Fourier Transform (2D-FT). Size results are then presented in the form of instantaneous droplets size field (Figure 14e) or mean droplet size field, where colors give the size.
5.3. Gas concentration measurement in two-phase flow condition

The study on the response of the optical probe is divided into two parts: first of all we interested in the general form of the Raman spectra in order to visualize the influence of the water droplets that are passing through the volume of measurement and in the second time, we checked that the characteristics of the concentration measurements remained similar to those obtained during the tests in air presented in the previous section (3.1.4). This study was undertaken on a water spray (see section 5.1 Figure 13) injected at atmospheric pressure in the RAP enclosure presented on Figure 15 (large vertical cylinder made in plexiglas, \( \Phi = 1.85 \text{m} \)). Spontaneous Raman Scattering is a very low emission comparatively to Mie or Rayleigh scattering (factor \( 10^{-8} \) to \( 10^{-12} \) compared to the intensity of the incidental beam). Usually, because of the great difference in scattered intensities between Raman and Lorenz-Mie scattering, care must be taken that no particles or droplets are within the Raman volume during the measurement (Long, 1992).

A Notch filter placed upstream of the optical spectrometer dims Mie scattering generated by the illumination of the water droplets by the laser (Figure 15).

![Figure 15. Concentration measurement through a spray performed by Raman spectrometry on RAP facility.](image)

One easily can observe on figure 16 the non-influence of the liquid phase on the Raman signal. The contribution of the droplets in the volume of measurement is dominating on two wavelength intervals. Fortunately, in our experimental configuration, the majority of the representative peaks of the studied gases (\( \lambda_{\text{steam}} = 660.7 \text{nm} \), \( \lambda_{\text{N2}} = 607.3 \text{nm} \), \( \lambda_{\text{O2}} = 580 \text{nm} \)) are apart from the region of the Raman spectrum on which appears a large peak. In fact, this large peak corresponds to the liquid water Raman signal according to the location in the liquid core of the spray. However, the noise due to the droplets strongly decreases when the distance \( d_{\text{nozzle/meas.}} \) increases. Thus in the case of the series of measurements carried out on TOSQAN (\( d_{\text{nozzle/meas}} \geq 0.1 \text{m} \)), one is expecting that the influence of the spray is less, and does not prevent the precise measurement of the peak for steam.
The study undertaken on the accuracy of measurements on air in the presence of droplets shows that the values do not vary from the ones calculated in air single phase condition.

6. CONCLUSION

Advanced optical diagnostics such as Spontaneous Raman Scattering and laser velocimetry were used in the TOSQAN large facility devoted to thermal hydraulic containment studies. Non-intrusive detailed gas and velocity measurements were performed during steam condensation test in order to characterize steam jet development and boundary layer spread on condensing wall.

We presented some optical diagnostics new development for TOSQAN facility that will be used during spraying test campaign. With this kind of two-phase flow measurements, we will able to characterize droplet size and velocity, gas velocity and steam concentration during water spray injection in pressurized air / steam mixture.

We are also working on a Global Rainbow Thermometry measurements in order to characterize droplet temperature (Lemaitre et al., 2003).

ACKNOWLEDGEMENT

We want to thank P. Gicquel from ONERA, for ours discussions about velocity two-phase flow measurements using LDV technique and Dr G. Grehan from CNRS for ILIDS software development.
7. REFERENCES