WATER SPRAY INTERACTION WITH AIR-STEAM MIXTURES UNDER CONTAINMENT SPRAY CONDITIONS: COMPARISON OF HEAT AND MASS TRANSFER MODEL WITH THE TOSQAN SPRAY TESTS

Jeanne Malet, Pascal Lemaitre, Emmanuel Porcheron, Jacques Vendel
Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Direction de la Sûreté des Usines, des laboratoires, des transports et des déchets, Saclay, BP 68 - 91192 Gif-sur-Yvette cedex, France
jeanne.malet@irsn.fr

ABSTRACT

A numerical and experimental study of spray effect in a large containment vessel has been performed. The main phenomena occurring when water spray is used are the mixing induced by spray entrainment and the heat and mass transfer on droplets and walls. In order to improve the latter phenomena, different levels of model can be used. The objective of this paper is to evaluate heat and mass transfer models for the gas and the droplet phases on the basis of experimental results obtained for water spray interaction with air-steam mixtures. It is shown that the vessel depressurization (and the decrease of the connected variables, such as gas temperature and humidity) during the spray injection is lower than the one obtained with the numerical results using the gas phase model. This could be due do droplet vaporization that is not taken into account in this model. Concerning the droplet phase model, droplet temperature vertical profiles downward the nozzle are presented. It is shown that the numerical and experimental profiles are qualitatively the same, indicating a good behaviour of the droplet heat and mass transfer model.

KEYWORDS

spray, droplet, heat and mass transfer, condensation, evaporation, containment, hydrogen risk.

1. 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 wall condensation. In order to prevent the overpressures in the event of a steam break, spray systems are used in the containment. However, the effect of a spray could even increases the risk of hydrogen explosion by condensing steam and therefore locally enriches gaseous mixtures in hydrogen. The TOSQAN project has been created to simulate separate-effect tests representative of typical accidental thermal-hydraulic flow conditions in the reactor containment. The idea of the TOSQAN spray programme is to perform an intermediate study between separate-effect tests and integral tests, considering one phenomenom (gas-spray interaction), with a high density of instrumentation.

The present work concerns the interaction of an internal water spray used at the top of the containment in order to reduce the steam partial pressure, under air-steam mixtures conditions. The main phenomena occurring when water spray is used are the mixing induced by spray entrainment and the heat and mass transfer on droplets and walls. In order to improve the latter phenomena, different levels of model can be used. The objective of this paper is to evaluate heat and mass transfer models for the gas and the droplet phases on the basis of experimental results obtained for water spray interaction with air-steam mixtures.
2. DESCRIPTION OF THE TOSQAN FACILITY AND THE SPRAY TESTS

The TOSQAN experiment (Figure 1) is a closed cylindrical vessel (7 m$^3$, i.d. 1.5 m, total height of 4.8 m) into which steam or non-condensable gases can be injected through a vertical pipe located on the vessel axis. The spray is injected on the vessel axis 70 cm from the top of the facility. Over 150 thermocouples are located in the vessel (in the main flow and near the walls). 54 sampling points for mass spectrometry are used for steam volume fraction measurements (Auban et al., 2003). Optical accesses are provided by 14 overpressure resistant viewing windows permitting non-intrusive optical measurements along an enclosure diameter at 4 different levels (LDV and PIV for the gas velocities, Raman spectrometry for steam volume fractions, Porcheron et al., 2002). Measurements are mainly located at the different positions presented in Figure 1. The TOSQAN vessel has thermostatically controlled walls so that the wall temperatures can be kept constant.

![Figure 1: schematic view of the TOSQAN facility and positions of the measurements profiles available in the TOSQAN facility.](image)

Spray tests presented here consist of a water spray injection into the enclosure which is initially filled with an air-steam or an air-steam-helium mixture, the walls having already reached their nominal temperature. A vessel depressurization is observed and a final equilibrium is reached. Measurements are performed during the depressurization and during this final equilibrium.

The TOSQAN spray test matrix is presented on Table 1. Test 101 is the reference test with air-steam mixture, whereas test 102 is the reference test with air-steam-helium mixture. The other tests are performed by changing the spray injection mass-flow rate $Q_{\text{inj}}$ (#103 and #104), the spray injection temperature (#107), the superheating ($T_g-T_{\text{sat}}$) (#105 and #106), the initial gas temperature $T_g$ (#108), the difference between saturation temperature and injection temperature ($T_{\text{sat}}-T_{\text{inj}}$), (#107 and #108), the gas composition (#109 and #110, $X_s$ for steam volume fraction, $X_h$ for helium volume fraction and RH for relative humidity), and the droplet diameter D (#111 and #112). As a result, they have different final pressures P, temperatures and gas compositions. The design of these tests has been performed in the frame of an European Concerted Action SCACEX (Fischer et al. 2002) and details on this spray test matrix can be found in Malet 2003 and Malet et al., 2003.
### Table 1: nominal spray tests matrix in TOSQAN

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mixture</th>
<th>$T_g$ (°C)</th>
<th>P (bar)</th>
<th>$X_s$ (%)</th>
<th>RH (%)</th>
<th>$X_h$ (%)</th>
<th>$T_{sat}$ (°C)</th>
<th>$T_{inj}$ (°C)</th>
<th>$Q_{inj}$ (g/s)</th>
<th>$T_{sat}-T_{inj}$ (°C)</th>
<th>$T_{inj}$ (°C)</th>
<th>D (µm)</th>
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<tbody>
<tr>
<td>101</td>
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<td>120</td>
<td>2.5</td>
<td>0.6</td>
<td>75</td>
<td>0</td>
<td>112.6</td>
<td>7.4</td>
<td>30</td>
<td>92.6</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>102</td>
<td>A-S-H</td>
<td>120</td>
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<td>0.4</td>
<td>50</td>
<td>0.2</td>
<td>100.7</td>
<td>19.3</td>
<td>30</td>
<td>80.7</td>
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<td>200</td>
</tr>
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<td>0.6</td>
<td>75</td>
<td>0</td>
<td>112.6</td>
<td>7.4</td>
<td>10</td>
<td>92.6</td>
<td>20</td>
<td>200</td>
</tr>
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<td>0.6</td>
<td>75</td>
<td>0</td>
<td>112.6</td>
<td>7.4</td>
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<td>200</td>
</tr>
<tr>
<td>105</td>
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<td>0.3</td>
<td>34</td>
<td>0</td>
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<td>28.4</td>
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<td>71.5</td>
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<td>200</td>
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<tr>
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<td>109</td>
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<tr>
<td>112</td>
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<td>0.6</td>
<td>75</td>
<td>0</td>
<td>112.6</td>
<td>7.4</td>
<td>30</td>
<td>92.6</td>
<td>20</td>
<td>500</td>
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</tbody>
</table>

#### 3. PRESENTATION OF THE MODELS

The model approach is performed in two steps: the first one consists of calculating the time evolution of the gas phase, assuming a spray having a given injection temperature and spray mass flow-rate. This approach is performed using the lumped-parameter code TONUS-0D 2003.2 (Dabenne 2004, Galon and Dabene 1998).

The second approach consists of calculation of the spray droplet evolutions at different times of the test, using the gas phase characteristics obtained from the TONUS-0D calculation. This is performed using a single droplet momentum–heat and mass transfer model approach.

It is emphasized that these both models are not coupled: the input of the droplet phase calculation are the output of the gas phase calculation, but the output of the droplet phase calculation does not interact with the gas phase calculation. Both models are described in the next section.

#### 3.1 Model for the gas phase

In the multi-compartment code TONUS-0D, a single compartment has been used for the TOSQAN spray calculation. The non condensable gases are supposed to follow the perfect gas law hypothesis and the steam is modelled as a real gas. The solved equations are the following:

- Mass balance for non condensable gases;
- Water mass balance in the sump of the compartment;
- Energy balance in the compartment;
- Energy balance for the sump;
- Energy balance for the structures.

The equations are presented below for the case of spray injection in one compartment, in a case where no wall condensation occurs.

The water condensed mass flow-rate on the droplet, $Q_{cond}^d$, is given by the following relation:

$$ Q_{cond}^d = C \frac{\dot{E}_{spray}}{L_{Lat}} $$

where $\dot{E}_{spray}$ is the energy rate transfered from the gas to the droplet in order to enhance the droplet temperature at the saturation temperature, $L_{Lat}$ is the latent heat of condensation and C is a “superheating” function given by the following relation:
\[ C = \alpha \beta + \alpha (1-\beta) e^{\gamma (T_{sat} - T_i)} \]  \tag{2} 

with \( \alpha = 1, \beta = 0.92, \gamma = 0.5 \).

The energy rate transferred from the gas to the droplet, \( \dot{E}_{\text{spray}} \), is given by the following relation:

\[ \dot{E}_{\text{spray}} = Q_{inj} (h_{inj} - h_{sat}) \]  \tag{3} 

where \( h_{inj} \) is the specific heat of the injected water, \( h_{sat} \) the specific heat of the water at the saturation temperature, and \( Q_{inj} \), the spray injection mass flow-rate.

Mass balance of the total water (liquid and steam) of density \( \rho \) in a volume \( V \) (here in the TOSQAN volume) is written as:

\[ V \frac{d\rho}{dt} = Q_{\text{vap}} - Q_{\text{cond}} \]  \tag{4} 

The left side of the equation is the time evolution of the water mass in the volume \( V \), the first term of the right handside is the source of steam due to vaporization of the water in the sump, and the last term is the loss term of water due to condensation of the steam on the droplets.

Mass balance of the liquid water in the sump \( m_{\text{liq}} \) is written as follow:

\[ \frac{dm_{\text{liq}}}{dt} = Q_{inj} + Q_{\text{cond}} - Q_{\text{vap}} \]  \tag{5} 

The two first terms of the right handside are the water source terms (by spray injection and condensation on the droplets), the last one is the loss of water due to vaporization of the sump.

The energy balance of the gas mixture \( E_{\text{gas}} \), is written by:

\[ \frac{dE_{\text{gas}}}{dt} = - \dot{E}_{\text{spray}} + h_s Q_{\text{vap}} \]  \tag{6} 

The first term of the right handside is the energy lost due to steam condensation on droplets, and the second one is the energy gained from sump vaporization (but the sump is here taken as a very small volume to simulate the water evacuation of the real TOSQAN case).

### 3.2 Model of the spray droplet

The spray droplets characteristics are calculated using the ACACIA code (Ducret and Vendel 1998) which is a basic program for the calculations of droplets characteristics in an air-steam-helium mixture. In the ACACIA code, the vessel is not modelled, i.e. a unique compartment is considered. Gas thermodynamical conditions are fixed (either obtained from calculations with TONUS, or used on the basis of experimental results): ACACIA computed only the droplets characteristics. The spray is modelled as a single droplet falling under gravity and drag forces. Equations solved are the following:

- Motion equation for the droplet, including gravity and drag forces;
- Heat and mass transfer at the droplet interface;
- Heat transfer to the droplet.

The equation of motion is the standard equation with the density variation term and the drag force:

\[ m_d \frac{dU_d}{dt} = \pi \frac{d_d^3}{6} \rho d (\rho_d - \rho_s) - C_d \rho_s \pi \frac{d_d^2}{8} U_d^2 \]  \tag{7} 

where \( m_d \) is the droplet mass, \( d_d \) is the droplet diameter, \( C_d \) the drag coefficient, \( U_d \) the droplet velocity, \( g \) the gravity, \( \rho \) is the density (subscript \( d \) for droplet and \( g \) for the gas mixture).

The total heat flux \( \Phi_{\text{tot}} \) from the gas to the interface is given by the following expression:

\[ \Phi_{\text{tot}} = \Phi_{\text{mass}} + \Phi_{\text{conv}} \]  \tag{8} 

The phase change mass flux \( \Phi_{\text{mass}} \) is given by:

\[ \Phi_{\text{mass}} = k M_s (Y_s^o - Y_s^i) \Delta H \]  \tag{9}
where \( M \) is the steam molar mass, \( Y \) are the mass fractions (subscript \( s \) for steam, \( o \) for the bulk flow and \( i \) for the interface) and the mass transfer rate \( k \) is defined classically from the Sherwood number \( Sh \):

\[
Sh = \frac{k d_d}{D_m}
\]  

(10)

where \( D_m \) is the diffusion coefficient of the gas mixture, and where \( \Delta H \) is the variation of energy due to heat and mass transfer at the droplet interface:

\[
\Delta H = L_{lat} + C_p \left( T_{g}^o - T_{d}^i \right)
\]

(11)

where \( C_p \) is the specific heat and \( L_{lat} \) the latent heat of condensation, \( T_{g} \) the gas mixture temperature. The Sherwood number is obtained by heat and mass transfer analogy using the Pruppacher (1971) correlation from the gas Schmidt number \( Sc \) and the droplet Reynolds number \( Re_d \):

\[
Sh = 1.61 + 0.718 \frac{Re_d^{1/2} Sc^{1/3}}{}
\]

(12)

Assuming that the steam is saturated at the interface, \( Y_s^i \) can be determined using the saturation pressure at the interface temperature.

The convective flux \( \Phi_{conv} \) is defined as follow:

\[
\Phi_{conv} = h_{conv}^g \left( T_{g}^o - T_{d}^i \right)
\]

(13)

Furthermore, the total heat flux \( \Phi_{tot} \) from the gas to the interface is equal to the total heat flux from the interface into the droplet, which can be written as follow:

\[
\Phi_{tot} = h_{conv}^d \left( T_{g}^d - T_{d}^i \right)
\]

(14)

Using all these equations, and combining them together, a system of equations is obtained, and solved using a Newton-Raphson method. The so-called ‘film temperature’ \( T_{g}^f \), for the calculations of all gas thermodynamic characteristics, is defined by:

\[
T_{g}^f = \frac{2}{3} T_{d} + \frac{1}{3} T_{g}
\]

(15)

4. RESULTS

The TOSQAN vessel is nodalized by a 7 m³ single volume, with stainless steel wall of a surface of 21.915 m², having the characteristics given in Table 2.

| Specific heat | \( c_p = 500 \text{ J/kg/K} \) |
| Thermal conductivity | \( \lambda = 15 \text{ W/m/K} \) |
| Density | \( \rho = 7800 \text{ kg/m}^3 \) |

Table 2: thermal characteristics of the TOSQAN wall in TONUS-0D.

Initial and boundary conditions are the ones of test 101 given in Table 1. For the injection, the injected enthalpy has to be specified and is taken as \( 8.2 \times 10^4 \text{ J/kg} \).

4.1 Steam pressurization

Before the spray is injected, the vessel is pressurized with steam in order to reach a given air steam mixture. Two-dimensional numerical calculations are performed in order to verify whether the mixture is homogeneous. The latter is performed with the TONUS-3D code, which has already been validated on 2D TOSQAN tests (Malet et al. 2004). This calculation is thus performed using the following conditions:

- dry air at initial atmospheric pressure and 102°C;
- injection during 600 s at 10 g/s and 120°C;
- the walls temperatures are kept constant at 120°C.
Results are presented on Figure 2. It can be seen that the thermal and mass stratification in the spray injection zone is about 2°C and 3vol%. The results show also that the flow in the whole vessel is separated in two zones:
- the first zone is below the injection, where higher temperatures are obtained because the pressurization leads to a compression effect below the injection, even if the walls cool down the gas close to them;
- the second zone above the injection where the compression does not lead to the same effects because the increase of temperature is counterbalanced by the heat, mass and momentum exchanges between the forced steam injection and the walls on the one side, and the gas on the other side.

This heating of the lower part of the vessel should be reduced as soon as the spray is activated because of the forced mixing that is then generated. However, it could lead to strong droplet vaporization at the beginning of the depressurization. It should be emphasized also that the end of this pressurization phase seems not to be a steady-state: since a large pocket of hot gases exists at the bottom of the facility, it should rise due to buoyancy effects once the steam injection is stopped. However, the entrainment of gas by the spray injected just after the end of the steam injection should counterbalance this effect. Further calculations and experiments could be done to investigate this initial stage. Despite this, homogeneous temperature and concentration fields can be considered here for the 0D calculations presented in the next sections: this assumption seems to be acceptable in the spray region, close to the nozzle, where most of the heat and mass transfer phenomena occurs.

![Figure 2: gas temperature (left), velocity field (center) and steam volume fraction (right) at the end of the pressurization phase.](image)

4.2 Numerical results on a reference test (101)

Figure 3 shows the pressure time evolution and the condensation mass flow-rate on droplets and the total condensed mass on droplets are presented on Figure 4. It can be seen that the pressure decreases down to 1 bar (approximately), which is the partial pressure of air. All the steam is thus condensed by the spray. This can be also seen on Figure 3 since the steam volume fraction and the humidity decrease to 0. In the real case, several points that could be important are not considered in the TONUS-0D model:

- The mono-compartment discretization does not take into account spatial variation of steam distribution, and accumulation of steam could occur in the top of the vessel;
- Droplet vaporization in the gas or on the structure when the droplets impinging the walls, could be a steam source, which could change the final pressure level;
- Convective heat transfer between droplets and gas is neglected here and could play a role on the gas temperature value, modifying the phase-to-phase change rate.

Figure 3: time evolution of the total pressure, the steam volume fraction and the relative humidity calculated by the TONUS-0D code.

Figure 4: time evolution of the total pressure, condensation mass flow-rate and the total condensed mass on droplets calculated by the TONUS-0D code.

The droplet diameter and the droplet temperature at spray injection start (t = 0 s) calculated with ACACIA are given in Figure 5. An increase of the droplet diameter is observed in the first 30 cm from the injection, showing the condensation zone. The decrease of the diameter shows that the vaporization zone of the droplet is on a major part of the vessel height.
Figure 5: droplet diameter and temperature versus axial distance from the injection at injection start, calculated with ACACIA.

Figure 6 and Figure 7 show the same kind of curve as for the former figure, i.e. droplet size and temperature on the vessel height, but for different times during the depressurization. On the lower part of the vessel, the droplet diameter decreases slightly up to the vanishing of the droplet around 2 m at the final equilibrium (> 2500 s). This is probably due to the way the gas characteristics are computed in TONUS-0D, without any steam source from the evaporation of the droplets in the gas or on the walls. The droplet temperature at the final equilibrium is thus quite low.

Figure 6: droplet diameter versus axial distance from the injection at different times, calculated with ACACIA.
4.3 Influent parameters

The influence of the spray injection mass flow-rate on the depressurization and on droplet diameter gradient is presented on Figure 8 and Figure 9. As expected from the spray model used in the TONUS-0D code, the condensed mass flow-rate on water is proportional to the spray mass flow-rate, so that the depressurization, which is due to the steam condensation on droplets, is much lower for lower spray injection mass flow-rate.

The influence of the spray mass flow-rate (i.e. the droplet initial velocity in ACACIA) on the droplet diameter gradient leads to two effects:

- on the one part, if the droplet is injected at higher velocity, at a given time, the droplet has reached a higher distance from the nozzle, so that it increases the condensation zone;
- on the other part, since heat and mass transfer on the droplets depend on the droplet Reynolds number, at higher velocity, these transfers are more important;
Figure 9: influence of spray injection mass flow-rate on droplet spray gradient calculated by ACACIA.

The influence of the helium volume fraction on the depressurization is given on Figure 10. If tests 101, 102, 109 and 110 are considered, depressurization is lower for higher helium concentration. A more detailed analysis shows that it is not directly an effect of helium, but an effect relative to the temperature difference ($T_{\text{sat}} - T_{\text{inj}}$). For lower temperature differences ($T_{\text{sat}} - T_{\text{inj}}$), the depressurization is lower. This is confirmed if test 105 is added to the above considered tests (101, 102, 109, 110): test 105 has approximately the same ($T_{\text{sat}} - T_{\text{inj}}$) as test 110, but not the same helium volume fraction: it leads to a very similar depressurization rate as the one of test 110.

Figure 10: influence of helium volume fraction and ($T_{\text{sat}} - T_{\text{inj}}$) temperature difference on the depressurization, calculated by TONUS-0D.

It can be seen on Figure 11 that the temperature difference ($T_{\text{sat}} - T_{\text{inj}}$) is the important factor for depressurization (in the TONUS-0D model) and the gas superheating does not play a significant role.
Influence of initial droplet diameter is presented on Figure 12. It can be seen that in the zone close to the nozzle, the droplet diameter gradients are higher for the smaller particle sizes (200 µm), so that variation of droplet size is easier to measure for smaller droplets. At a higher distance from the nozzle, the droplet diameter gradients become higher for larger particle size.

4.4 Comparison with experiments

Two kinds of experimental results are compared to the numerical ones: the first one concerns the gas phase, and allows the evaluation of our gas phase model (TONUS-0D code), and the second one concerns the droplet phase, and is used for the evaluation of our droplet model (ACACIA code). More experimental results and the measurement technics are presented in companion papers (Porcheron et al., 2005, Lemaitre et al. 2005).
Concerning the gas phase, the first experimental results obtained on the total pressure time evolution are compared to numerical calculations on Figure 13. It can be clearly seen on this figure that the pressure is underestimated in the calculation. This result shows clearly that if the only considered heat and mass transfer between the gas and the droplet is steam condensation, the pressure evolution is underestimated; two main phenomena may change the theoretical results: droplet evaporation, since the ACACIA code shows that the droplet diameter is decreasing in the vessel, and droplet interaction with walls (especially the lower walls where droplet can impact) which both could lead to an increase of steam in the vessel. Competition between this increase of steam concentration and the steam condensation on droplets leads to higher experimental pressure level. In order to see the impact of spray-wall interaction, some tests were conducted having a spray injection which was not situated on the vertical axis: in such a configuration, the spray droplets were impacting the vertical walls, where, for the ‘centered’ configuration, the spray droplets impact the walls fast only on the lower horizontal part of the vessel. Results show a pressure of 0.2 bar higher with the non-centered configuration, which could be due to the spray-wall interaction (Figure 14). More investigations are planned to be done in order to see the influence of this phenomenon on the results.

Figure 13: comparison of the experimental total pressure measured in TOSQAN and the numerical calculation taking into account only steam condensation on droplets.

Figure 14: comparison of the vessel depressurization between axial and non axial spray injection conditions.
Concerning the droplet phase, an optical diagnostic is used to determine the droplet temperature vertical evolution: the rainbow interferometry (Lemaitre, 2004, Lemaitre et al. 2005). The results, compared to the ACACIA results, are presented on Figure 15. For the ACACIA calculations, the values of the gas phase are taken from the experimental results, in order to be sure to compare only the droplet model: mean gas temperature of 380.65 K, total pressure of 2.23 bar and relative humidity of 100%. Furthermore, since the droplet characteristics (initial diameter and velocity) are not well-known, results are presented for different droplet sizes and velocities. A good agreement is obtained if a size of 130 µm and an initial velocity of 22.5 m/s is considered (Figure 15); a droplet temperature vertical profile has been obtained and is a good basis for code validation.

The values of the initial droplet size and velocity chosen for Figure 15 at the nozzle exit are difficult to estimate. Measurements have been performed below the nozzle exit:
- the droplet size distribution measured at 1.35 m from the injection (by Interferometrics Laser Imaging for Droplet Sizing, Porcheron et al. 2004), shows an arithmetic mean diameter of 145 µm and a mode between 90 µm and 110 µm (see Figure 16);
- the droplet initial velocity at the nozzle exit can be estimated between 38 m/s and 3 m/s (a divergent inside the nozzle has a 1 mm inlet internal diameter and expands to a 3.5 mm outlet diameter); furthermore, measurements (Particle Image Velocimetry) have been performed 50 mm from the nozzle exit and show a droplet velocity of 10 m/s (Figure 17); the velocity at the nozzle exit should be higher than this value (deceleration of the droplets), and lower than 38 m/s; a velocity around 20 m/s seems thus to be a good approximation.

![Figure 15: droplet vertical temperature profile calculated by ACACIA and compared to the experimental result.](image)

![Figure 16: droplet size distribution measured during final equilibrium at 1.35 m from the nozzle, on the TOSQAN axis.](image)
5. CONCLUSIONS

This paper presents two approaches for the model of the spray under conditions representative for a hypothetical nuclear reactor accident.

The first one is used to compute the gas phase. A simple spray model is used, that takes into account steam condensation on droplets. The second one is used for the droplet phase.

Numerical results show the main sensitive parameters of the gas model: influence fo the spray injection and of the temperature difference ($T_{\text{sat}}-T_{\text{inj}}$). Helium concentration and gas superheating do not play a significant role on depressurization in this gas model. Comparison between experiments and calculations shows that the depressurization in TOSQAN is underestimated by the calculation; this could mainly be due to the droplets vaporization in the gas and on the walls.

The droplet phase model is dependant on parameters, such as droplet sizes and velocity at the nozzle exit. Comparison between experiments and calculations shows that the droplet model follows the experimental results for given values of two parameters (droplet initial diameter and velocity); measurements of these two parameters show that the choosen value are realistic.

Concerning the model approaches, the next step will be the use of another model for the gas phase, which takes into account a complete heat and mass transfer model of the droplets, including, not only the steam condensation on droplets, but also the steam production due to droplet vaporization in the gas and/or on the walls.
NOMENCLATURE

Most of the mathematical terms are defined in the text.

D: diameter
E: energy
g: gravity
h: heat transfer coefficient
h_v_s: steam specific enthalpy
M: molar mass
Q: flow-rate
Q_inj: injection mass flow-rate
Q_cond: condensation mass flow-rate
R_s: steam injection radius
ρ: density
t: time
T: temperature
V: velocity

Subscripts:
Cond: condensation
conv: thermal convection
d: droplet
g: non condensable gases
i: interface
inj: injection
m: mean value
mass: mass
o: bulk flow
s: steam
sat: saturation
spray: spray
sump: sump
vap: vaporization

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