

Sprays in Containment: Final results of the SARNET Spray Benchmark

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Summary

The influence of containment sprays on atmosphere behaviour, a sub-task of the Work Package WP12-2 CAM (Containment Atmosphere Mixing), has been investigated through benchmark exercises based on TOSQAN (IRSN) and MISTRA (CEA) experiments. These tests are being simulated with lumped-parameter (LP) and Computational Fluid Dynamics (CFD) codes. Both atmosphere depressurization and mixing are being studied in two phases: a ‘thermalhydraulic part’, which deals with depressurization by sprays (TOSQAN 101 and MISTRA MASPn), and a ‘dynamic part’, dealing with light gas stratification break-up by spray (TOSQAN 113 and MISTRA MARC2b).

In the thermalhydraulic part of the benchmark, participants have found the appropriate modelling to obtain good global results in terms of experimental pressure and mean gas temperature, for both TOSQAN and MISTRA tests. It can thus be considered that code users have a good knowledge of their spray modelling parameters. On a local level, for the TOSQAN test, single droplet behaviour is found to be well estimated by some calculations, but the global modelling of multiple droplets, i.e. of the spray, specifically for the spray dilution, is questionable in some CFD calculations. It can lead to some discrepancies localized in the spray region and can thus have a high impact on the global results, since most of the heat and mass transfers occur inside this region. In the MISTRA tests, wall condensation mass flow rates and local temperatures were used for code-experiment comparison and show that improvement of the local modelling, including initial conditions determination, is needed.

In this dynamic part, a general result, in both tests, is that calculations do not recover the same kinetics of the mixing. Furthermore, concerning global mixing, LP contributions seem not suitable here. For the TOSQAN benchmark, the one-phase CFD calculations recover partially the phenomena involved during the mixing, whereas the two-phase flow CFD contributions generally recover the phenomena. Moreover, one important result is also that none of the contributions finds the exact amount of helium remaining in the dome above the spray nozzle in the TOSQAN 113. Discrepancies are rather high (above 5%vol of helium). Results are thus encouraging, but the level of validation should be improved. The same kind of conclusions can be drawn for the MISTRA MARC2B tests.

As a conclusion of this SARNET spray benchmark, the level of validation obtained here is encouraging for the use of spray modelling for risk analysis. However, some more detailed investigations are needed to improve model parameters and decrease the uncertainty for containment applications as well as to increase the predictability of the phenomena within the containment analyses. Further activities are well encouraged on this topic, such as numerical benchmarks on analytical separate-effect experiments.

A. INTRODUCTION

During the course of a hypothetical severe accident in a Pressurized Water Reactor (PWR), spray systems are used in the containment in order to prevent overpressure in case of a steam line break, and to enhance the gas mixing in case of the presence of hydrogen. Spray models are thus part of thermalhydraulic containment codes. The two major phenomena involved in spray behaviour are the thermodynamical effect of a spray (steam condensation on droplets, evaporation, ...) and the dynamical effect (entrainment and mixing of gases).

In the past, validation of spray modeling has been performed on large-scale facilities (CVTR, NUPEC, CSE, [1]) using several spray nozzles. The present benchmark proposes the use of two recent facilities, TOSQAN (IRSN) and MISTRA (CEA), for a combined spray benchmark. The advantages of these facilities and the proposed tests in regard to previous studies are:

- the 'reduced' size of the facility, allowing a high density of instrumentation for a better analysis of the involved phenomena,
- the use of non-intrusive instrumentation, especially in the TOSQAN facility, making the characterization of the spray droplets possible,
- a 'separate-effect' approach by the use of a single spray nozzle, avoiding interaction of sprays, and the possible resulting deviation in the analysis.

This benchmark is proposed in the frame of the European network of excellence, SARNET (Severe Accident Research NETwork), under the CAM (Containment) group activities. As a result, this benchmark is based on several tests. A first part, called the THERMALHYDRAULIC part, relates to the thermodynamics of sprays, i.e. the droplet heat and mass transfers and the gas thermodynamical modeling. A second part, called the DYNAMIC part, relates to the gas entrainment and atmosphere mixing induced by a spray, avoiding heat and mass transfer exchanges (Figure 1).

In this paper, all tests of this SARNET spray benchmark and the associated numerical results are presented. Experimental data were open for these calculations. Most of the participants have performed several calculations during the period 2005 to 2008, but only the more representative ones were kept here.

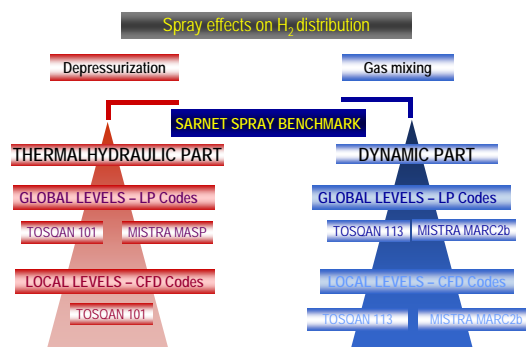


Figure 1: Scheme of the SARNET spray benchmark and the associated tests

B. EXPERIMENTAL FACILITIES

Experiments were performed in the TOSQAN and MISTRA facilities. The TOSQAN facility is located at the Institut de Radioprotection et de Sureté Nucléaire (IRSN) and the MISTRA one at the Commissariat à l'Énergie Atomique (CEA), both in France.

The TOSQAN facility and the associated measurement levels are presented in Figure 2. It is a closed cylindrical vessel (7 m³ volume, 4 m high, 1.5 m internal diameter). The vessel walls are thermostatically controlled by heated oil circulation. The inner spray system is located 65 cm from the top of the enclosure on the vertical axis. It is composed of a single nozzle producing a full-cone water spray. This nozzle can be moved along the vertical axis in order to perform measurements at different distances from the spray nozzles under steady-state conditions. In the lower part of the vessel, the water impacting the sump is removed to avoid water accumulation and to limit evaporation.

The available instrumentation on TOSQAN concerns mass flow-rate, temperature and pressure of the water spray injected, mass flow-rate and temperature of the water removed (or drained) to the sump, mass flow-rate of injected steam and helium, gas measurements, temperature measured by protected thermocouples, volume fraction measured by mass spectrometry [2] and Raman spectroscopy [9] and vessel total pressure. Gas temperature and volume fraction are also measured in the spray zone. For droplet measurements, available techniques are droplet velocity measured by PIV [9], droplet size measured by out-of-focus visualization [15] and droplet temperature [7]. Detailed description of the instrumentation position is given in [3].

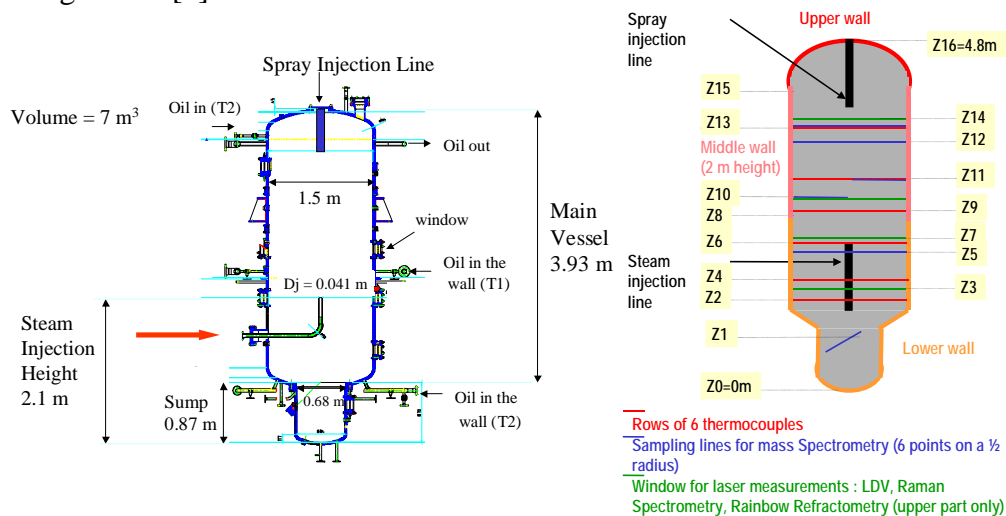


Figure 2: TOSQAN facility

The MISTRA facility is a stainless steel cylindrical vessel of about 99.5 m³, 4.25 m internal diameter and 7.38 m height (Figure 3). It is constituted of 2 shells, a flat cap and a curved bottom, fixed together with twin flanges. The vessel is thermally insulated with 20 cm of rock wool.

Three cylinders (called 'condensers' even if no condensation occurs on them in the present tests) are inserted inside the vessel, close to the walls in order to keep them at constant temperature. A so-called 'dead volume' behind these condensers exists, and during long term experiments, spurious steam condensation can occur on the vessel and bottom walls. Each

condenser has its own regulation circuit designed to provide the circulating water with a most stable and uniform temperature (a wall temperature difference less than 1°C is achieved).

Gutters are installed to collect and quantify the steam condensate or droplet streams. The external parts of the condensers are insulated with synthetic foam. Spurious steam condensation or water droplets are also quantified by collecting water at different locations: along the vertical side walls, along the external part of the condensers and in the bottom. To avoid interaction of droplets with the condensers, the spray is generated by a full jet nozzle with an angle of 30°. The nozzle is fixed near the center of the flat cap at less than a few centimeters from this center (quasi-centered), the bottom of the nozzle is at few centimeters from the roof.

The measurements performed are total pressure, temperature (gas and wall), gas composition and condensed mass flow rate. They are all simultaneously and continuously recorded over the whole test period, except for gas concentration measurements that mainly proceed with successive samplings out of the spray region.

The instrumentation mesh is located on four vertical half-planes: 105°, 165°, 225° and 345° in the main gas volume, but also in the so-called "dead volumes". The instrumental mesh grid on the half plane at 345° combines 10 vertical levels and 5 radial positions. The maximum distance between two sensors is less than 1 meter axially and 0.5 m radially. Three other half-planes are lightly instrumented to check the flow symmetry. For the off-centered injection test, the half plane at 165° allows characterization of the injection area. During the spray activation, instrumentation out of the spray jet is reliable.

Previous benchmarks associated with the MISTRA tests are presented in [18, 19, 20].

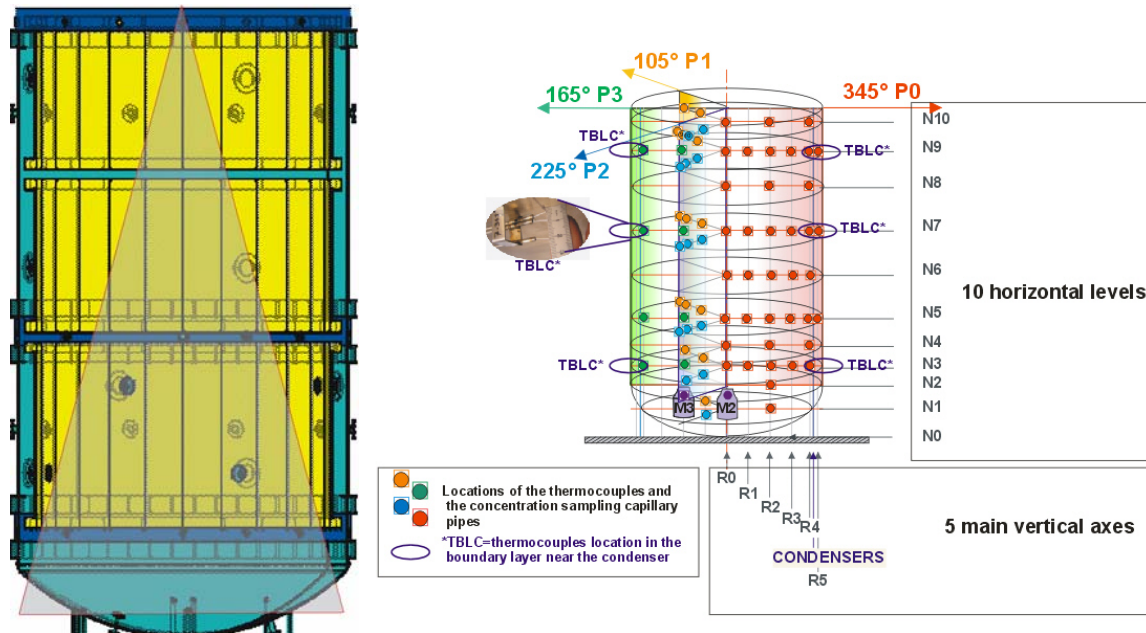


Figure 3: View of MISTRA facility and its main location for instrumentation

C. BENCHMARK SPECIFICATIONS

C.1 Thermalhydraulic part

TOSQAN 101

The night before test 101, compressed air is injected into the open TOSQAN vessel in order to remove steam from former tests. On the morning of the spray test, the air injection is stopped. When a thermal steady state is reached, the vessel is closed (the vessel relative pressure is then 0 bar). An initial pressurization in the vessel is performed with superheated steam up to 2.5 bar. Then, steam injection is stopped and spraying starts simultaneously at a given water temperature (around 25°C) and water mass flow-rate (around 30 g/s). The transient state of depressurization starts and continues until an equilibrium phase, which corresponds to the stabilization of the average temperature and pressure of the gaseous mixture inside the vessel.

The test conditions are given in Table 1 for the gas initial conditions, Table 2 for the mean wall temperatures, and Table 3 for the spray characteristics. More information on the detailed experimental results can be found in [5] and on the benchmark specifications in [9, 13].

Table 1: Experimental gas initial conditions before spray injection ($t = 0$ s) in TOSQAN 101

Mean gas temperature outside the spray zone	131.1°C
Mean gas temperature inside the spray zone	131.0°C
Total absolute pressure	2.5 bar
Initial gas composition (from mass balance)	213 air moles + 308 steam moles

Table 2: Measured mean wall temperatures in TOSQAN 101 (in °C)

Temperatures	Mean wall [°C]	Upper wall [°C] Z: 4.4 – 4.8 m	Middle wall [°C] Z: 2.4 – 4.4 m	Lower wall [°C] Z: 0-2.4 m
Just before spray start	122.1	121.8	122.3	121.7
0-102 s	121.5	121.4	121.6	121.3
107 s - 300 s	120.4	120.8	120.4	120.3
306 s – 601 s	119.9	120.3	120.0	119.4
End of the test	118.9	119.3	120.1	115.4

Table 3: Experimental spray characteristics in TOSQAN 101

Spray flow-rate	29.96 g/s
Spray angle	55°
Water injection temperature (°C)	
At $t=0$ s	119.1°C
At $t=311$ s	22.1°C
At $t=1000$ s	27.7°C
Nozzle position	65 cm from the top on the TOSQAN axis
Droplet velocity 5 cm below the nozzle	10 m/s flat profile
Spray half-width 5 cm below the nozzle	27.1 mm
Droplet size	$D_{10}=145 \mu\text{m}$

MISTRA MASP_n

The M5 test is a test sequence performed before MASP_n test: during this M5 test, a centred steam release is performed in the containment, with a high thermal gradient on condensers in order to create thermal stratification. The bottom condenser is cold and the two other condensers are hot. During the steady-state of M5 test, injection of a hot steam jet is balanced by the condensation on the bottom condenser. The data of the three M5 tests are reproducible [21].

The spray tests MASP1 and MASP2 concern the depressurization of the containment atmosphere by spray. MASP0 is the reference case without spray [21, 9]. The MASP1 and MASP2 tests start after the permanent state of the M5 test and follow the scenario: stop of the injection of steam and injection of a cold spray in an air-steam mixture under pressure with two thermal zones created by the two different temperatures of the condensers.

MASP1 and MASP2 are two similar tests with different spray temperatures (40 or 60°C). The droplets mass flow-rate is 0.87 kg/s, the water temperature in the nozzle is 40°C in MASP1 and 60°C in MASP2. More detailed spray characteristics are given in [21, 9]. During the MASP tests, the condensers are kept at the same temperature as in the M5 test: 80°C for the bottom condenser and 140°C for the top and medium condensers.

The tests MASP1 and MASP2 are composed of two phases:

- I. Depressurization by heat and mass losses (0->2100 s) for MASP1 and 2,
- II. Spray activation during 1800 s (2100 ->3900 s) for MASP1 and 2.

The test MASP0 is composed of a single phase: depressurization by heat and mass losses (0->3900 s).

In order to simulate the MASP_n tests, three methods are used to consider the initial conditions which constitute three parts of this benchmark.

- Part A: Homogeneous initial conditions based on the M5 steady-state [21, Table 4]
- Part B: Initial conditions for gas temperature and steam concentration taken from the experimental data of the M5 steady-state [21]
- Part C: Initial conditions of the M5 test [20, Table 5]

Table 4: Initial conditions of the MISTRA MASP_n tests in Part A [9]

	MASP0	MASP1	MASP2
Pressure (bar)	2.4	2.4	2.4
Mean Gas Temperature (°C)	124	124	124
Steam Volume fraction (from mass balance)	0.45	0.45	0.45

Table 5: Initial conditions of the M5 test for the M5-MISTRA MASP_n tests in Part C

Pressure (bar)	Fluid temperature (°C)	Mass of air (kg)	Initial Humidity (%)
1.007	24	115	50

C.2 Dynamic part

TOSQAN 113

The night before test 113, compressed air is injected into the open TOSQAN vessel in order to remove helium and steam that remain from former tests. On the morning of the spray test, the air injection is stopped. When a thermal steady-state is reached (with atmosphere at ambient temperature), the vessel is closed (the vessel relative pressure is then 0 bar) and helium is injected at a given flow-rate (around 1 g/s). The helium injection nozzle is composed of one main tube of 13 mm i.d. bored with 6 holes of 9 mm i.d. The helium injection is thus exclusively radial. Both nozzles are situated on the top of the dome (4.773 m from the bottom of the facility). When the vessel relative pressure reaches 1 bar, helium injection is stopped. A delay of 400 s is applied before spray activation. During this time, mass spectrometry measurements are performed in order to characterize initial stratification of helium and to check the repeatability of this stratification. Spray is activated (time reference $t = 0$ s) during about 7000 s at 30°C and with an injection mass flow-rate of 30 g/s. Walls are insulated but the wall temperatures are not regulated. The initial stratification of helium is given in Table 6. Symmetry has been checked experimentally so that the given values can be used constant over the entire radius. The main spray characteristics are given in Table 7. More information on this test can be found in [4, 9].

Table 6: Initial conditions before spray injection in TOSQAN Test 113

Z (from the bottom)	Helium concentration (vol%)	Mean gas temperature (°C)
Z13 = 3.93 m	99.0 +/- 0.5	31.8
Z11 = 3.13 m	85.8 +/- 0.5	36.9
Z10 = 2.80 m	47.6 +/- 1.0	At Z9 = 2.67 m : 34.7
Z5 = 1.90 m	2.3 +/- 0.5	At Z6 = 2.04 m : 30.1
Z1 = 0.87 m	1.9 +/- 0.5	At Z2 = 1.2 m : 28.7

Table 7: Experimental spray characteristics for Test 113

Spray flow-rate	30 g/s
Spray angle	55°
Spray injection height	0.65 m from the top on TOSQAN axis
Initial droplet size	about 130 µm
Initial droplet velocity	Around 10 m/s
Droplet injection temperature	30°C

MISTRA MARC2B

Spray is injected in a stratified mixture of helium, nitrogen and air, created during the test MARC2 [17]. The stratification of helium is created by injection of helium followed by injection of nitrogen in containment initially full of air at 24.3°C (1.01 bar). This means that in the calculations, oxygen and nitrogen have to be modelled separately.

The initial conditions of MARC2B test are the final conditions of the MARC2 test:

- Pressure: $P = 1.829$ bar;
- Mass of Air: $m_{\text{air}} = 115.6$ kg;
- Mass of Helium injected: $m_{\text{He inj}} = 6.5$ kg;
- Mass of Nitrogen injected: $m_{\text{N}_2 \text{ inj}} = 46.2$ kg.

The initial stratification before spraying is given in Table 8.

Table 8: Initial conditions before spray injection in MISTRA MARC2b test

Z (from the bottom) mm	Nitrogen concentration (%)	Helium concentration (%)	Gas temperature (°C)
N1 = 614	78.5	14.5	24.7
N2 = 1160	78.0	15.0	24.7
N3 = 1586	77.5	15.2	24.7
N5 = 2634	72.0	19.0	24.7
N7 = 4623			24.7
N9 = 6409	55.0	32.0	24.7
N10 = 7059	54.0	33.0	24.7

The measurements of helium concentration show a 2D axisymmetric symmetry [17].

The spray conditions for this test are:

- Water flow rate:
 - 0.86 kg/s \pm 0.01 kg/s (without the 25 first seconds);
 - 0.91 kg/s \pm 0.03 kg/s (during all spray flow);
- Temperature: 40°C;
- Duration: 300 s;
- Spray injection height to be considered: 7180 mm (different from the exact nozzle position);
- Spray angle at the nozzle: 30°.

The velocity of the mixture at the outlet of the nozzle is of the order of magnitude of 25 m/s considering that the diameter of the nozzle outlet is 6.4 mm. According to the nozzle constructor's brochure, the droplets formed by a 'full cone' spray are large (minimum mean volume diameter of droplets equal to 1 mm).

D. PARTICIPANTS AND SPRAY MODELS

For this spray benchmark, 12 models and their numerical implementation involving 9 codes are presented by 11 institutions. The list of participants is given in Table 9.

Table 9: List of participants to the spray benchmark of SARNET

Institution	Full name	Country	Code
AREVA	AREVA NP GmbH Offenbach	Germany	GASFLOW
CEA	Commissariat à l'Énergie Atomique	France	TONUS
EDF	Electricité De France	France	NEPTUNE
FZK	Forschungszentrum Karlsruhe	Germany	GASFLOW
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	Germany	ASTEC, COCOSYS
IRSN	Institut de Radioprotection et de Sûreté Nucléaire	France	ASTEC-CPA, TONUS
JSI	Institut Jožef Stefan	Slovenia	ASTEC-CPA, CFX
LEI	Lietuvos Energetikos Institutas	Lithuania	COCOSYS
UJV	Ústav Jaderného Výzkumu	Czech Republic	MELCOR
UNIPI	Università di Pisa	Italy	FUMO
VEIKI	Villamosenergiaipari Kutató Intézet	Hungary	GASFLOW

Synthesis of the main phenomena calculated by the codes is given in Table 10. All models take into account heat and mass transfers between spray droplets and containment atmosphere. Mixing phenomenon is calculated by CFD codes but is not modelled in LP codes. However, droplet dynamic on the vertical axis is generally considered in most of the LP models. Half of the codes mentions droplet wall interaction in their respective models. More information on the spray modelling involved in this benchmark can be found in [12].

Table 10: Main phenomena

Phenomenon CODE	Droplet relaxation	Droplet-gas heat and mass transfer	Droplet-gas momentum transfer	Droplet collision	Droplet-walls heat transfer	Droplet-walls mass transfer
ASTEC	yes	yes	no	yes	yes indirect	yes
COCOSYS IVO	yes	yes	no	no		yes
COCOSYS MARCH	yes	yes	no	no		yes
CFX	yes	yes	yes	no	no	no
FUMO	no	yes	no	no	no	yes
GASFLOW	no	yes	no	no	yes	yes
MELCOR	no	yes	no	no	yes indirect	
NEPTUNE CFD	yes	yes	yes	no	yes	yes
TONUS CFD	yes	yes	yes	no	no	no
TONUS LP	no	yes	no	no	yes	yes

BENCHMARK RESULTS

D.1 Thermalhydraulic part

TOSQAN 101

The phenomenology of the TOSQAN 101 test is described in [6, 15, 16]. The time evolution of the gas mole number is a good parameter to represent the pressure and mean temperature evolution. It has been given by the participants or post-processed from pressure and mean gas temperature results assuming perfect gas law. It can be seen on Figure 4 that the gas mole number is generally well recovered by most of the codes. The calculations which overestimate the gas mole number during the transient phase are the ones that have slightly overestimated the initial vaporization phase.

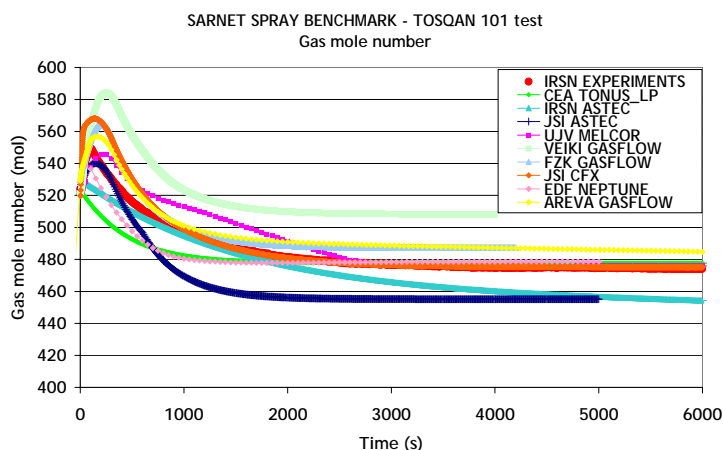


Figure 4: Gas mole number time evolution

Since the specificity of the TOSQAN facility is to produce detailed local measurements, in this paper, only results with local experimental data will be presented; code-to-code comparisons are given in [10].

The droplet/gas velocity results are presented on Figure 5. Results show that most of the calculations recover the equilibrium velocity below approximately 1 m from the nozzle. Differences are mainly observed in the zone between the spray nozzle and the height of the dynamic equilibrium. They are mainly due to the droplet velocity initialisation that is different in each code: codes having a low initial value of the droplet velocity calculate an acceleration of the droplet between Z14 and Z11 up to its final equilibrium value, whereas codes (NEPTUNE and CFX) having a high initial value of this velocity calculate a deceleration of the droplet.

The simulated temperature radial profiles are compared to the experimental data on Figure 6. In the spray zone, the agreement between calculations and experiments is not good for several calculations. One reason for that could be the entrainment and gas mixing that are underestimated in these calculations, which then fail to get the right gas heating. Outside of the spray zone (Figure 6), the average gas temperature is well calculated by most of the calculations, except for the one which does not include a steam/heat source in the lower part of the vessel (TONUS-CFD).

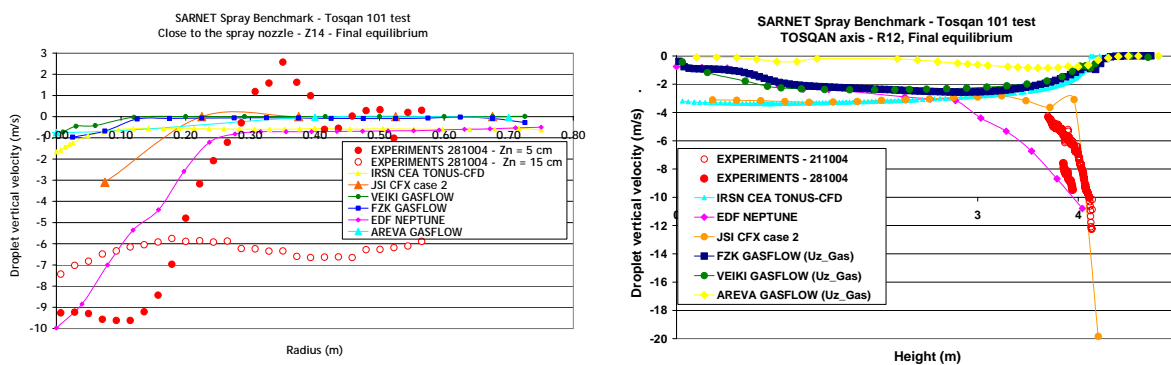


Figure 5: Vertical component of the droplet velocity, radial profile at final equilibrium, Z14 (left) and vertical profile at final equilibrium on R12 central TOSQAN axis (right)

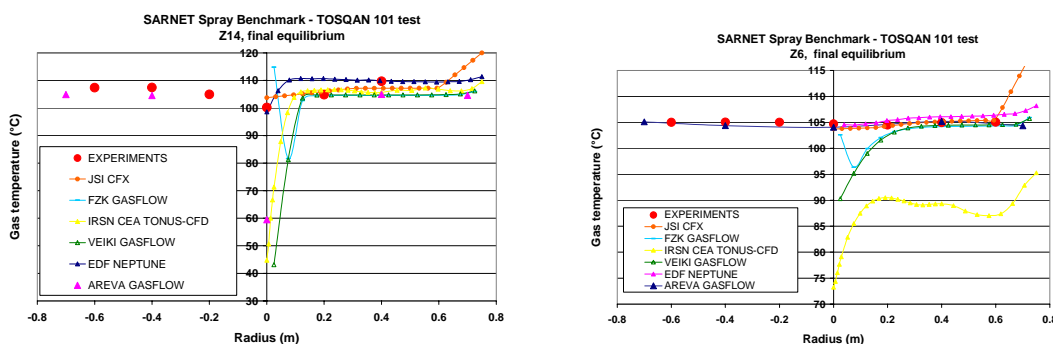


Figure 6: Gas temperature, radial profile during final equilibrium, Z14 and Z6

Steam volume fraction (SVF) radial profiles are presented on Figure 7. It can be seen that most of the participants find a steam radial profile homogeneous, with a constant value about 55% vol, which corresponds to the mean steam volume fraction expected if the concentration field is assumed to be homogeneous. Experimental data obtained by Raman spectroscopy are presented on Figure 7 and should be considered as indicative since the steam concentration values are probably shifted due to calibration error.

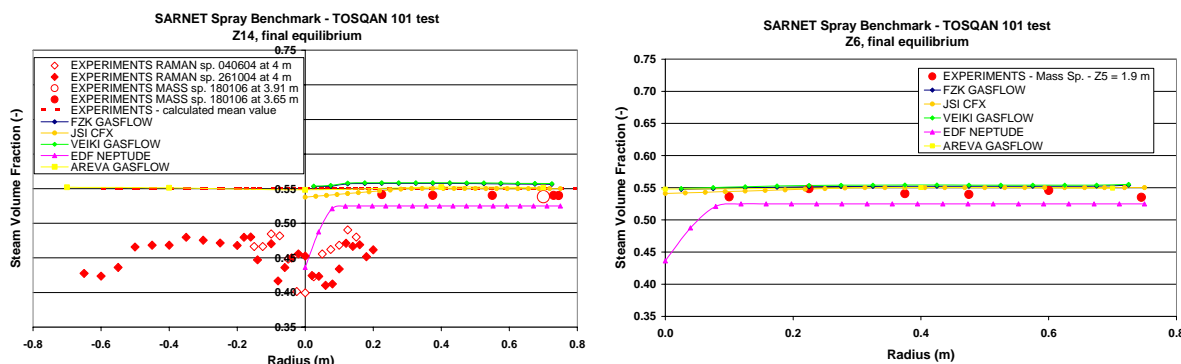


Figure 7: Steam volume fraction, radial profile during final equilibrium, Z14 and Z6

MISTRA MASPn

In MASPO and beginning of MASP1 and MASP2 tests before spray activation, the main physical phenomenon is the depressurization by condensation on cold surfaces. In the experiment (Figure 8), during the M5 steady-state, 95% of the condensation on walls occurs on the bottom cold condensers. Figure 9 presents the results of the calculations of energy ratio associated to condensation on bottom condenser (for partC condensation on bottom condenser (90%) and vertical walls (10%)) by the total energy associated to heat, mass and radiation transfer on walls and sump. These calculations show that energy lost by condensation on the bottom wall until 1000 s varies from 85% to 50%.

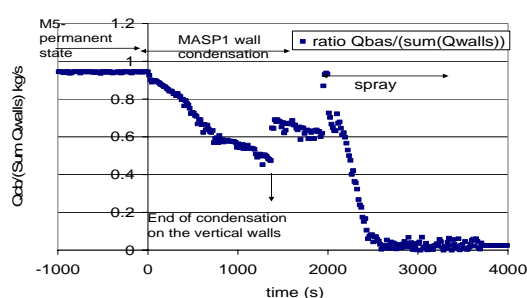


Figure 8: Ratio of condensation mass flow rate on bottom condenser Q_{cb} by condensation on all walls Q_{walls}

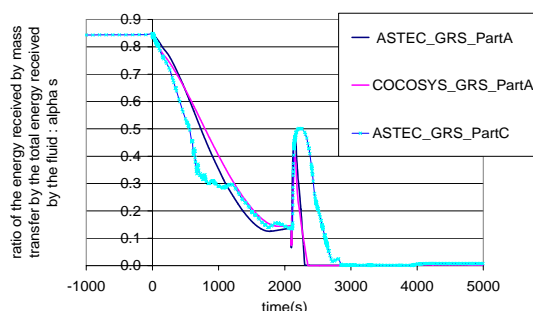


Figure 9 : Ratio of energy associated to condensation on bottom condenser and vertical vessel walls by energy associated to heat, mass and radiation transfer on walls and sump

When the spray is activated, condensation mass flow rate on bottom condenser (Q_{cb}) slightly increases (Figure 10): it is related to cold spray impact on walls but also probably to wall condensation. The numerical simulations reproduce this increase (Figure 10). Furthermore, after spray injection, the increase of the bottom wall condensation energy to the total energy increases slightly up to 60% in the simulations (Figure 9).

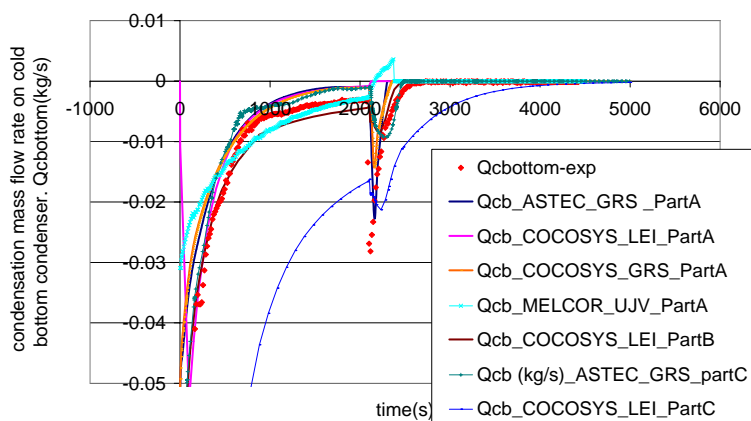


Figure 10: Condensation mass flow rate - calculations-experiment comparison

Spray activation has also a strong influence on pressure drop with time. When the spray is activated (Figure 11), experiments show a depressurisation rate of 0.33 bar during 180 s (0.018 bar/s). In the calculations, the durations needed to reach a 0.33 bar depressurisation are between 120 to 200 s.

These differences can be due to different condensation rates on the cold wall (Figure 10) but also probably on spray droplets exchanges: condensation and evaporation on droplets as well as evaporation and condensation on sump water (if a not drained sump is modelled) are possible.

In order to evaluate which phenomenon (condensation on walls or droplet exchanges with gas) is the most important when spray is activated, the initial phase of MASPn tests and the spray activation phase are analysed: depressurization rates at the beginning of the test is equal to 0.008 bar/s at 180 s in the experiment and to 0.006 to 0.008 bar/s at 180 s for most of the calculations. After spray injection, the depressurization rate is much higher (0.018 bar/s). However, condensation on wall (Figure 10) is lower when spray is activated. As a result, it can be concluded that the main physical phenomenon when the spray is activated is the depressurization related to the interaction of droplet with gas, especially with mass and heat transfer exchanges.

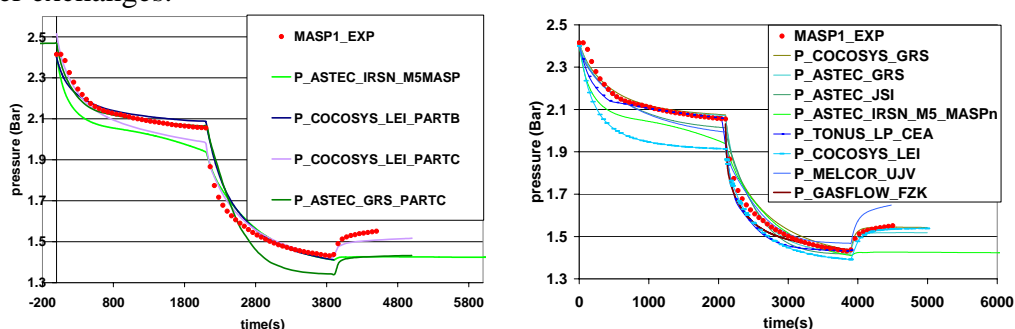


Figure 11: Experimental and simulated time evolution of the pressure for MASP1 for part A (right), part B and C (left)

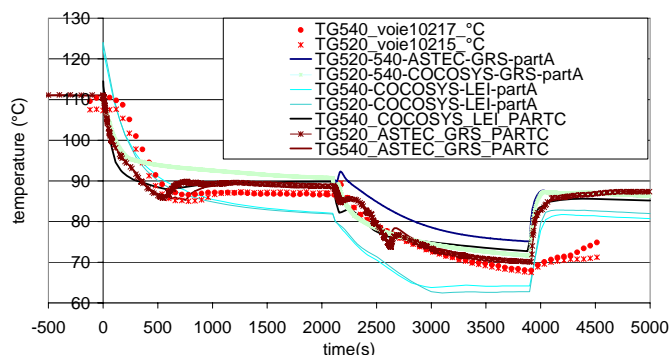


Figure 12: Temperature (°C) at level N5 radius R2-R4 MASP1- simulations-experiment comparison
 Figure 12 presents the evolution of experimental and simulated gas temperature on bulk vertical axis R2 and R4 at level N5 in front of the cold condenser. The experimental evolutions show a temperature decrease during the first 200 s and a quasi-thermal equilibrium between 200 and 2100 s. When spray is activated, gas temperature evolution presents a small increase that is maximal 70 s after the spray activation. The reason for that can be related to convection of hot gas in this zone. This small temperature increase is reproduced by three participants (ASTEC_GRS_PartA, ASTEC_GRS_PartC and COCOSYS_GRS_PartC). After this increase, the experimental temperature decreases till 3900 s. This transient is simulated by most of the participants and maybe due to wall effects. The M5-MASPn tests and benchmark comparisons are presented in details in [21, 13].

D.2 Dynamic part

TOSQAN 113

The phenomenology of the TOSQAN 113 test can be found in [11]. In order to have an estimation of the global stratification break-up time, a 90% mixing time at a chosen location is defined: it is the time at which helium volume fraction at one location (in the bottom of the vessel) has reached 90% of the mean helium volume fraction. Results are presented on Figure 13. In the experiments, a mixing time of about 200 s is found. It can be seen that the mixing time in ASTEC is much higher than in the experiments (around 7000 s): it shows that this calculation finds completely different phenomena of mixing, as expected since the ASTEC code is not devoted to such simulations. Other calculations find a mixing time in the same order of magnitude than in the experiments (between less than 100 s up to over 600 s).

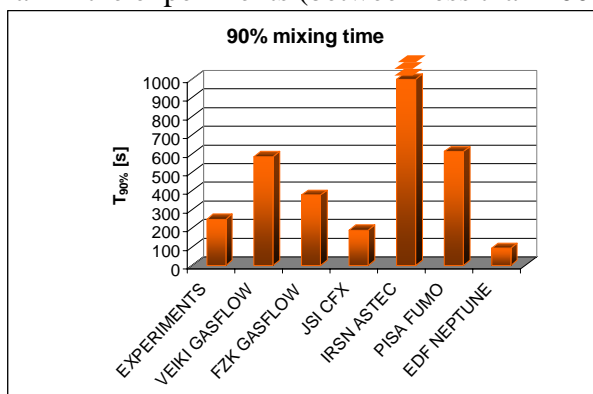


Figure 13: 90% mixing time at Z1R8

In order to complete this quantitative description of the mixing, moments distribution analysis is used [11]. The normalized HVF time derivative can be considered as this mixing time distribution (Figure 14).

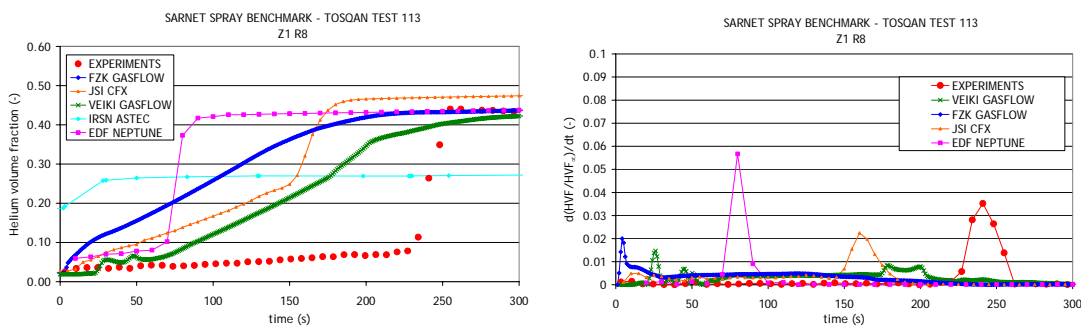


Figure 14: Time evolution of helium volume fraction at Z1R8 during 300 s and associated time evolution of the derivative of normalized helium volume fraction as a function of time at Z1R8

The median mixing time is defined as the ratio of the 1st-order to the 0th-order moment. The standard deviation (mean deviation relative to the median mixing time) is defined by the square root of the 2nd-order central moment. Results are given in Table 11. The median time is longer in the experiment than in the calculations: it confirms that calculations overestimate the mixing. The standard deviation results show that the helium arrival at the bottom of TOSQAN is more dispersed in the experiments than in the calculations.

Table 11: Moments results on the HVF time derivative distribution function

	EXPERIMENT	GASFLOW		New JSI CFX	EDF NEPTUNE
		VEIKI	FZK		
Median time [s]	211	136	86	123	70
Standard deviation σ [s]	104	69	56	55	14

Figure 15 presents the vertical and radial profiles of helium volume fraction obtained by all calculations and measured in TOSQAN. It can be seen that the gas mixture is homogeneous below the spray nozzle and that a helium pocket can be found in the dome. The differences observed between all codes and experiments on the mean values of the HVF outside the spray zone are mostly due to initial conditions and to the amount of helium remaining in the dome.

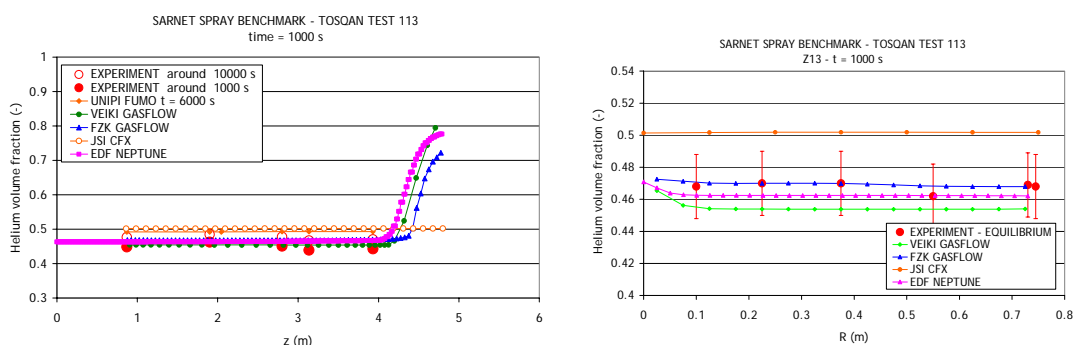


Figure 15: Vertical (left) and radial (right) evolution of helium volume fraction at t=1000 s

An interesting value to determine is the average helium fraction in the dome region above the spray nozzle, at a given time. The TOSQAN vessel can be divided into two theoretical volumes: V_h , situated above the spray nozzle with a HVF α_h ($V_h = 0.9 \text{ m}^3$), and the rest of the volume, located below the spray nozzle ($V_b = 6.1 \text{ m}^3$), with a HVF α_b . Considering the total HVF α_t in the total volume V_t (7 m^3), i.e. the mean value if the flow is completely mixed, it can be written:

$$\alpha_h = \frac{\alpha_t \cdot V_t - \alpha_b \cdot V_b}{V_h}$$

Results are presented in Table 12. It can be seen that all calculations (except the VEIKI GASFLOW ones) overestimate slightly the mixing of the dome area of 5 to 15 % vol.

Table 12: Helium volume fraction post-calculated in the different TOSQAN volumes at a given time

	EXPERIMENTS	GASFLOW		JSI CFX	UNIPI FUMO	EDF NEPTUNE
		VEIKI	FZK			
Time [s]	1000 (300)	1000	1000	300	6000	1000
HVF α_b [-]	0.449 (0.433)	0.454	0.468	0.493	0.492	0.464
HVF α_t [-]	0.478	0.492	0.488	0.515	0.497	0.487
HVF α_h [-]	0.675 (0.803)	0.746	0.620	0.664	0.531	0.637

MISTRA MARC2B

A warm spray of droplets is injected during 300 s in a stratified dry gas mixing of air-helium and nitrogen. Walls and condensers are maintained at atmosphere conditions. Figure 17 shows the helium concentration vs time. Experimental data show the stratification before spray activation and the destratification after spray activation. The helium stratification (33% in the top and 15% in the bottom) is completely destroyed 300 s after the end of spray activation (Figure 16). A molecular diffusion characteristic time can be defined as the ratio H^2/D

(H: height of the MISTRA vessel and D: molecular diffusion coefficient of helium): a value of 400000 s is obtained, so that it can be said that de-stratification is mainly due to dynamic exchange between droplets and gas:

Within the benchmark dynamic part, the test MARC2B was simulated with one LP code by JSI, and with CFD codes by FZK and CEA. The destratification is calculated by the CFD codes and converges to a unique concentration of helium close to experimental data. The typical time to obtain the destratification changes with the modeling.

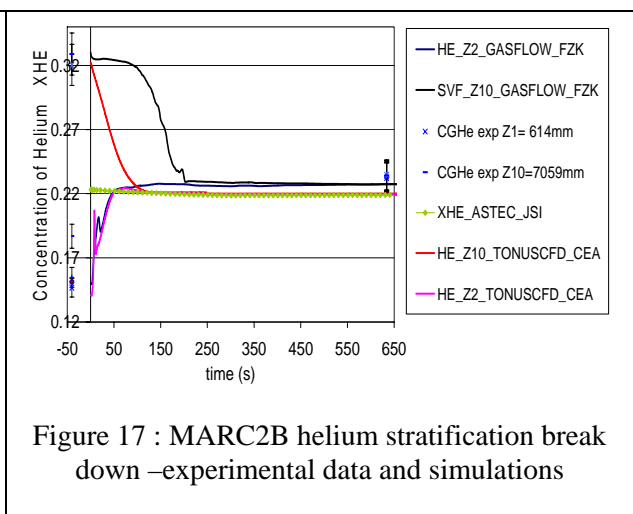
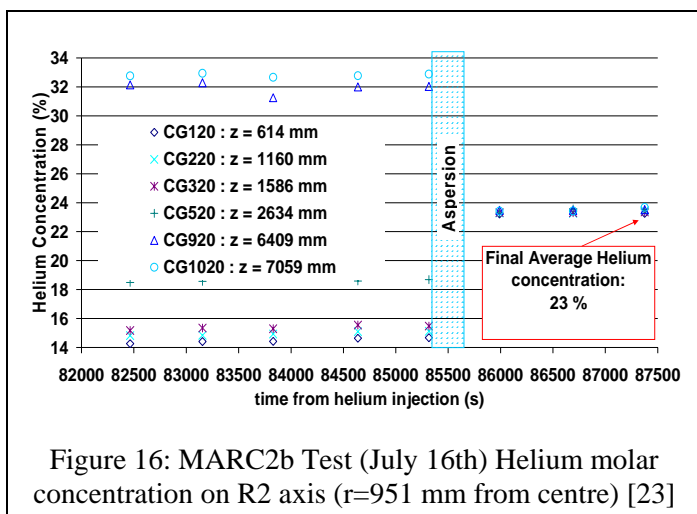


Table 13: Calculated value of the 90% stratification break down time

Time (s)	CG120	CG220	CG320	CG520	CG920	CG1020
GASFLOW_CFD	20	44	65	135	110	192
TONUS_CFD	30	51	48	60	70	90

A stratification break-down time is defined as the time at which a local concentration has decreased by 90% of the decrease between its initial and difference final value. The calculated stratification break-down time increases with height (Table 13 and Figure 17). Stratification break-down time is smaller in TONUS_CFD compared to GASFLOW-CFD results. Mixing is related to turbulence in the gas and also to drag force. The drag force depends of the relative velocity droplet-gas. In GASFLOW mechanical equilibrium between the phases is assumed and relative velocity droplet-gas can be smaller compared to TONUS_CFD model where equation of momentum is solved for both phases.

E. CONCLUSIONS

As a conclusion of the thermallyhydraulic part of the spray benchmark, the level of validation obtained is encouraging for the use of spray modelling for safety analyses. However, it is still not sufficient and more investigations are needed in order to reach the level of validation that has been reached on wall condensation in containment applications during the OECD International Standard Problem No.47 (ISP-47) [12]. Further activities on this topic are encouraged: numerical benchmarks (for example, with simple test cases), in order to evaluate the influence of different parameters in the modelling, as well as benchmarks based on new experimental data with more detailed local measurements inside the spray region.

As a conclusion of the dynamic part of the spray benchmark, recommendations are mainly to perform some numerical benchmarks on different modelling parameters that modify the light gas mixing process by spray activation. This point is probably connected with a more general work on mixing of buoyant flows in closed vessels under turbulent conditions. ISP-47 as well as the benchmark on TOSQAN 113 and MISTRA MARC2b tests shows a lack of capability of CFD calculations to recover the transient characteristics of light gas mixing.

As a conclusion of the spray modelling report that has been performed during this spray benchmark, special topics are integrated in some codes or have been studied by some participants, and should be regarded with more details: interaction between droplets, interaction between aerosol/fission products and droplets and turbulence enhancement by sprays.

As a general perspectives of this whole SARNET work on spray in containment applications, it can be said that benchmarks on simple test cases should be encouraged, in order:

- to evaluate the influence of several parameters (mixture diffusion coefficient, reference temperature, droplet-wall interaction, initial droplet size, etc.),
- to perform separate-effect studies,
- and to get more detailed code-experiment comparison especially in the spray region.

Furthermore, the importance of a more complete modelling of the droplet size distribution should be investigated and a better estimation of the real droplet size in the containment should be obtained in the future.

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