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MISTRA Facility for Containment Lumped Parameter and CFD Codes Validation: Example of the International Standard Problem ISP47

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ABSTRACT

During a severe accident in a Pressurized Water Reactor (PWR), the formation of a combustible gas mixture in the complex geometry of the reactor depends on the understanding of hydrogen production, the complex 3D thermal-hydraulics flow due to gas/steam injection, natural convection, heat transfer by condensation on walls and effect of mitigation devices. Numerical simulation of such flows may be performed either by Lumped Parameter (LP) or by Computational Fluid Dynamics (CFD) codes. Advantages and drawbacks of LP and CFD codes are well-known. LP codes are mainly developed for full size containment analysis but they need improvements, especially since they are not able to accurately predict the local gas mixing within the containment. CFD codes require a process of validation on well-instrumented experimental data before they can be used with a high degree of confidence. The MISTRA coupled effect test facility has been built at CEA to fulfil this validation objective: with numerous measurement points in the gaseous volume – temperature, gas concentration, velocity and turbulence - and with well controlled boundary conditions. As illustration of both experimental and simulation areas of this topic, a recent example in the use of MISTRA test data is presented for the case of the International Standard Problem ISP47. The proposed experimental work in the MISTRA facility provides essential data to fill the gaps in the modelling/validation of computational tools.

1 INTRODUCTION

The MISTRA experimental programme is part of CEA's programme on severe accidents occurring in Pressurized Water Reactors (PWR) or naval nuclear reactors and is focused on containment thermal hydraulics and the hydrogen risk ([1],[2], [3]). It is associated with the development and validation programme of the TONUS code [2], performed in collaboration with *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN).
The MISTRA coupled effect test facility was built at CEA to fulfil two objectives:

- understanding the physics of hydrogen (simulated by helium) mixing and distribution in confined geometries

- and producing high quality data for validation of CFD codes under thermal hydraulics conditions representative of PWR.

The scale of the facility (7 m, high, 4 m, diameter and 100 m^3, volume) makes it well suited to the study of turbulent convective flow with condensation and generally, gas mixing in large free or compartmented volumes. Numerous measurement points near the wall and in the containment gas volume are simultaneously recorded to set up spatial mappings, leading to a fine analysis of the physical phenomena: temperature, gas composition (mass spectrometer), velocity/turbulence (LDV) and condensed mass flow rate. The instrumentation and the experience drawn from the use of different types of sensors and probes will be detailed in paragraph 2.

Due to the complexity of containment thermal-hydraulics, the phenomena are first studied separately, and then progressively coupled.

The experimental test series are as follows:

- Elementary convective flows, studies of jet and plume flows: effect of injection conditions with different air/helium gas mixtures composition
- Steam condensation on temperature regulated walls: effect of the gas mixture composition (air, steam and helium), steam overheating, pressure, variation of the heat and mass exchanges with the wall and their modelling, then influence between the total exchanged flux, turbulence and the injection conditions (including centred and off-centred injection localization) on the flow pattern and the stratification.
- Water spray as a mitigation device: effect of the temperature and the size of the droplets on the mass and energy exchanges, and depressurisation rate, and also study of stratification break-up through the use of sprays.
- Nitrogen or other gas inerting mitigation efficiency
- Finally, the use of compartments provides flow data for more complex geometries and representative accident scenarios.

The experimental programme over the period 2001-2005 followed this progressive approach in terms of test specification (separate effect and coupled effects), in step with the model and validation matrices of codes [1].

2 MISTRA FACILITY [1]

2.1 Objectives

The MISTRA facility is designed to support the development of the thermal-hydraulic modelling of PWR containments, in particular for hydrogen distribution, in different situations. To achieve this goal, the experimental programme needs to fulfil the following criteria:

- allow the study of physical phenomena and their interactions
- allow the study of mitigation techniques, specific to hydrogen risk
- be at a representative scale to study the couplings between the different phenomena and to facilitate extrapolation to the reactor scale
- allow the simulation, in a single experimental device, of different scenarios and different types of containments
- to control the experimental conditions, especially the boundary conditions such as injection conditions and wall temperatures.

To fulfil the first two criteria, MISTRA is able to simulate:
- hydrogen release in time and for different locations
- three-dimensional flows of air, steam and hydrogen, due to natural convection, heat transfer by condensation to internal structures and containment walls, local hydrogen enrichment by wall condensation or condensation on droplets (when using spray systems to control the pressurization due to steam release),
- effect of mitigation devices such as H_2 recombiners (simulated electric heaters), or inerting for small-scale containments.

The third criterion is related to the scaling issue. MISTRA is an intermediate size facility which allows studying coupled effect phenomena. The scaling reduction is close to 10 versus actual reactor containment, the 'operating' ranges of temperature and pressure being the same.

The flow due to steam and hydrogen release into the reactor containment in the event of a severe accident is characterized by three dimensionless parameters (calculated here for steady state). The Richardson[1] number, related to injection conditions, expresses the buoyancy to inertia ratio. It ranges for MISTRA between 10^{-4} (jet configuration) to 10^{3} (plume configuration) and for a typical PWR, it is included between 10^{-4} to 10^{2}. The Reynolds [1] number expressing the inertia to viscosity ratio: It ranges between: 10^{3} to 10^{5} for MISTRA facility and 10^{3} to 10^{5} for a PWR. For areas located close to the condensation wall, the Grashof number which characterises the natural convection near the wall is dependent on the variation of density along the wall. The MISTRA values range between 10^{10} to 10^{13} (turbulent condition) and for a PWR between 10^{11} to 10^{16}.

The last two criteria are achieved by controlling directly the wall temperatures. This avoids the problems related to thermal inertia of walls and on the condensing surfaces to the surface/volume ratio. It is then possible to simulate, in a single experimental device, different scenarios and different types of containments (concrete walls, with or without gaps, liners, ...).

2.2 Description of the facility

The MISTRA facility is a stainless steel containment of 97.6 m^3. The internal diameter of 4.25m and the height of 7.3m were chosen to correspond to a linear length scale ratio of 0.1 with a typical French PWR containment (figure 1). It comprises: 2 shells, a flat cap and a bottom, which are fixed together with twin flanges. The vessel itself is not temperature-regulated but thermally insulated with 20 cm of rock wool. Prior to the experiments; the facility is usually preheated through steam injection and condensation.

Three condensers are inserted inside the containment, close to the vessel walls. A so-called "dead volume" behind the condensers exists, and during long experiments, spurious condensation can occur but is always measured. The condensers consist of vertical pipes, fitted together into 24 elementary cells. Each condenser has its own regulation circuit: internal and external collectors are specially designed to provide the circulating water with a most stable and uniform temperature (wall temperature differences less than 1°C is achieved). Gutters are installed to collect and quantify the condensate. The external parts of the condensers are insulated with synthetic foam and viewing windows are installed for laser measurements. Spurious condensation is also quantified by condensate collecting at different

[1] dimensionless parameters definition :

Richardson number	Reynolds number	Grashof number
$Ri_{inj} = \frac{(\rho_c - \rho_{inj}) g D_{inj}}{\rho_{inj} V_{inj}^2}$	$\mathrm{Re}_{inj} = \frac{\rho_{inj} V_{inj} D_{inj}}{\mu_{inj}}$	$Gr = \frac{h^3 g \Delta\rho}{\rho_c v_g^2}$ with $\Delta\rho = \rho_g - \rho_w$

locations: along the side walls of the containment, along the external part of the condensers and in the bottom. It should be noticed that the collected water in the bottom of the containment is continuously measured and evacuated, though a sump can be created if necessary. Figure 2 shows internal view, of the 3 condensers, the bottom and the four instrumented half-planes for the main gaseous free volume.

Figure 1: View of MISTRA facility

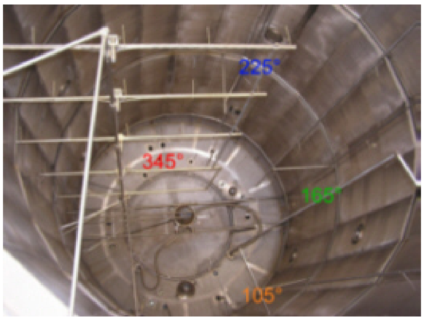

Figure 2: Internal views of MISTRA facility

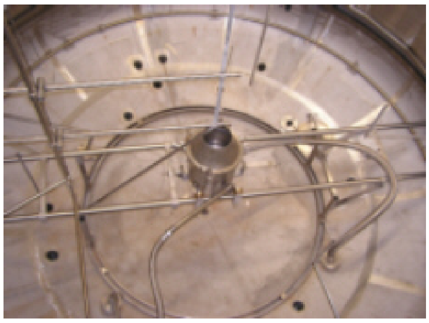

Figure 3 : View of 200mm injection nozzle, here positioned at the centre (ie. for ISP-47 test)

A diffusion cone including a porous media and fitted with a removable cap is designed for gas injection and steam/gas (helium simulating hydrogen or other gases) mixing. Different injection diameters (75, 150, 200mm) can be used to cover a large range of Richardson numbers (jet and plume regimes). The diffusion nozzles can be set up in the central position (figure 3) or at an off-centred position. The injection velocity profiles are flat. Injection gas flow rates are controlled and measured with sonic nozzles that ensure a constant value independently of the downward operating conditions. The different gases can be heated up to 220° C which is the design temperature of the facility. An additional steam line is also present in the bottom of the containment, but it is only used for the wall containment heating prior to tests: a ring with four nozzles directed towards the so-called “dead volume” comprised between the containment wall and the external condensers walls, and four nozzles directed towards the containment bottom. Table 1 summarizes the MISTRA facility operating conditions range. Until 2004, the test series was based on a free gaseous volume configuration (figure 2).

Table 1: The MISTRA facility operating conditions range

Containment		Height : 7.38m
		Inside diameter : 3.8m
		$P \leq 0.6$ MPa
		$T \leq 200°C$
Injection	Steam injection	0.015 kg/s $\leq Q_{inj,steam} \leq 0.14$ kg/s
		$T \leq 240°C$
	Helium injection	5 10-3 $\leq Q_{inj,gas} \leq$ 5 10-2 kg/s
		$T \leq 200°C$
	Variable Nozzle diameter	75E-3 m $\leq D_{inj} \leq$ 200E-3 m
Wall temperature	Temperature controlled wall:	$40°C \leq T \leq 145°C$
		$T_{reg} \pm 1°C$ (condensers)
	Maximal thermal flux	5kW/m^2 (3 condnensers) to 15kW/m2 (1 condensers)
Spray circuit		$0.5 \leq Q \leq 4$ kg/s
		$20°C \leq T \leq 140°C$
		0.5 MPa $\leq P \leq 1.5$ MPa
Flow characteristics	*injection Richardson number*	*1E-4 {jet configuration} to*
		1E3 {plume configuration}
	injection Reynolds number	*1E3 to 1E5*
	Grashof number along the condenser wall	*1E10 to 1E13*

2.3 Instrumentation

The experiment should provide data for modelling and the size of MISTRA facility allows having a consistent instrumentation with a fine spatial mapping. The measurements performed in MISTRA are related to pressure, temperature (gas and wall), gas composition (steam, air, helium...), velocity and condensed mass flow rate. They are all simultaneously and continuously recorded over the whole test period, except for gas concentration measurement that mainly proceeds with successive samplings [4]. Gas concentration transient measurements at a higher sampling frequency rate are also possible but only with a limited number of sampling points (typically 8 or 9 points). The measurements are applied first to set up mass and energy balances, with a particular attention to heat and mass exchanges to the wall.

Then, the second objective is to set up spatial mappings (temperature and gas concentration) to locate the different physical phenomena taking place in the gaseous volume. Finally, the use of laser diagnostics such as Laser Doppler Velocimetry or Particle Image Velocimetry allows to measure instantaneous velocity profiles and turbulence characteristics. Measurements are also located on the wall for boundary conditions control.

In 2003-2004, for the free volume configuration tests, the instrumentation mesh was located on four vertical half-planes: 105°, 165°, 225° and 345° in the main gas volume, but also in the so-called "dead volumes" behind the condensers. The instrumental mesh grid on the half plane at 345° combines 10 vertical levels and 5 radial positions (Figure 4). Special attention was paid to setting up instrumentation near the condensers and axially near the injection device. Everywhere else, the sensors are equally distributed. Table 2 summarizes the technology, the location and the number of sensors available for free volume configuration tests.

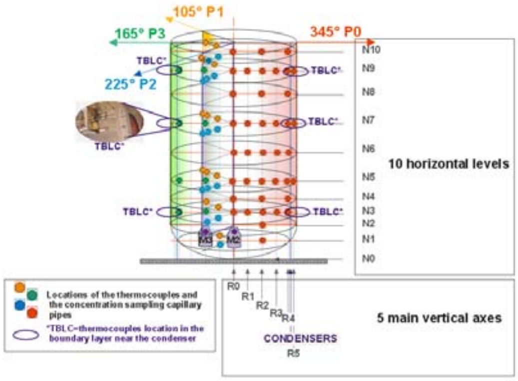

Figure 4: Sketch of MISTRA's instrumental mesh grid for free volume configuration

Table 2: Summary of MISTRA instrumentation available since 2003

measurement type *(for free volume configuration [<2005])*			Gas volume (included dead-volume)	Injection	Condenser	Sump	Containement (external and internal walls)
pressure	*1*	*absolute*	1				
temperature	*309*	*thermocouple (chromel-alumel type)*	102	1 (steam) 2 (gas)	107	5	92
heat flow	*1*				1		
gas concentration	*78*	*simultaneous sampling and analysis by mass spectrometry*	77+1				
velocity	*1 by test/12*	*LDV and PIV*	12 viewing windows				
condensed steam flow rate	*6*	*continuous mass flow rate measurement*			3 (internal face of the condenser)	1	
		differential pressure measurement			1 (external isolated face of the condenser =>spurious condensation)		1

Therefore, the maximum distance between two sensors is less than 1 meter axially and 0.5 m radially. Three other half-planes are lightly instrumented, mainly to check the flow symmetry (centred configuration). In off-centred configuration, the half plane at 165° is used to characterize the injection area.

2.4 Quality of data

Besides the control of the experimental conditions (initial and boundary conditions), the quality of the experimental data relies on the application of "Good Laboratory Practices". Our practice is based on a quality assurance programme in three steps. The first step before the test is:

- regularly control the integrity of the facility with periodic inspection (integrity of a pressure apparatus) and periodic maintenance,
- the apparatus used for instrumentation should be periodically inspected, cleaned, maintained, and calibrated according to Standard Operating Procedures,
- the records of these activities should be maintained,
- the calibration should, where appropriate, be traceable to national or international standards of measurement.

The second step during the test is :

- to define an experimental protocol used for all the test runs
- to run several times the same test and to compare these different results to assess the reproducibility errors and in some case to evaluate the data by comparison to pre-calculations.

The last step is data processing for primary data (appropriate data presentation ie. curves, table for specific location in the facility, evaluation of uncertainties with estimation of error bars ...) and storage for further use.

2.5 MISTRA experimental programme: example of coupled effect test for International code benchmarking ISP47 step 1

MISTRA is a Coupled Effect Test (CET) facility, and as such, enables both SET (Separate Effect Tests) and CET to be performed. A progressive approach to the definition of tests corresponding to a progressive approach in the validation of physical and numerical models in the associated codes has therefore been adopted. For free volume configuration approximately a hundred tests since the beginning have been performed in the MISTRA facility.

Some MISTRA experiments have already been proposed to the international community for code benchmarking and the data is available on request. The first is the MICOCO benchmark organized by CEA in which partially blind calculations of an air/steam mixture steady state (injection and condensation) have been performed [5].

A second experiment for benchmarking is the international standard problem (ISP47) proposed for the OECD-CSNI [6]. ISP-47 benchmark is a computer code exercise based on three experimental facilities in order to assess the actual capability of CFD and Lumped-parameter codes to predict local gas distributions under Loss Of Coolant Accident (LOCA) and Severe Accident (SA) conditions in PWR. ISP 47 is performed in two main steps. The Step 1 has been dedicated to the validation of CFD and lumped parameter codes simulating the processes that take place in the separate effect facility TOSQAN,V=7 m3, of IRSN of Saclay (France). Wall condensation and buoyancy are addressed under well-controlled initial conditions in a simple geometry. Simultaneously, the validation of the interactions of phenomena such as condensation/stratification, turbulence/buoyancy, including the effect of scale-up allowed by the large scale facility such as MISTRA - V = 97.6 m3 - has been addressed with the flow patterns in a rather simple geometry. The Step 2 concerns the

validation of codes in a complex and more realistic compartmented geometry. Stratification in a multi-compartment geometry with asymmetric injection was studied in the ThAI, V= 60 m^3 facility of the Becker Technologies GmBH, Eschborn (Germany). The ISP47 MISTRA test is included in the OECD test matrix (Containment Code Validation Matrix).
This Step 1 of the ISP-47 deals with a steam and helium injection in air performed in the TOSQAN and MISTRA experimental facilities; the code benchmark was open for the TOSQAN part and blind for the MISTRA part. For lumped parameter codes, comparisons focus on pressure, mean temperature and mean steam concentrations. For CFD codes, they also include local data like temperature, steam concentrations and radial profiles of the 3D velocity fields. Twenty-one participants are engaged in the ISP-47 and the calculations are performed by fifteen codes (lumped-parameter and CFD codes) ([7]), [8]).

Table 3: Summary of ISP47 benchmark participants [8]

Identification	Organisation	Country	Computer code	Version	Category
A	AECL	Canada	GOTHIC	6.1bp2	CFD
B	UJV	Czeck Republic	MELCOR	1.8.5(A)QZ(+Patch002)	LP
C	IRSN	France	TONUS	V2002.2	LP
D	IRSN	France	ASTEC	V0.4	LP
G	FZK	Germany	GASFLOW II	V2.2.4.21	CFD
H	GRS	Germany	COCOSYS	V2.0	LP
I	VEIKI	Hungary	ASTEC	V1.0	LP
K	University of Pisa	Italy	FUMO	Vdev	LP
L	NUPEC	Japan	DEFINE	Vdev	CFD
M	NRG	Netherlands	CFX	4.4	CFD
O	IJS	Slovenia	CONTAIN	2.0	LP
Q	STUDVISK	Sweden	MELCOR	1.8.5	LP
R	PSI	Switzerland	CFX	4.3	CFD
S	NAI	U.S.A.	GOTHIC	7.2dev	LP and CFD
T	LEI	Lithuania	COCOSYS	2.0	LP
U	IPPE	Russia	KUPOL-M	1.10	LP and CFD
V	GRS	Germany	ASTEC	V1.0	LP
W	CEA	France	TONUS	Vdev	LP and CFD

(Vdev: under development version)

The simplified MISTRA test sequence related to the ISP47 exercise is decomposed into four successive phases:

- Preheating phase: superheated steam injection into the facility initially at room temperature and pressure. This is a process phase mainly used to heat up the steel structures and results of this phase are not reported and discussed in the present document.
- Air/Steam steady-state (Phase A) defined from the equilibrium between the injected and condensed mass flow rates (130 g/s) insuring the stability of all the parameters: pressure, temperature and gas concentrations.
- Air/Steam/Helium transient and helium (simulating hydrogen) mass flow rate (about 10 g/s) is added to the main steam mass flow rate for half an hour.
- Air/Steam/Helium steady-state (Phase B) with the same definition and boundary conditions as for Phase A.

The test has been run ten times (6 times in 2002 and 4 times in 2004 due to the dismantling phase in 2003) for reproducibility and also to allow gas concentration measurements.

The main experimental results of the MISTRA ISP47 tests are summarised bellow.
Initial conditions are only relevant to specify the air density which is constant during the test (a mean value of 1.195 kg/m^3 with an uncertainty of about 0.02 kg/m^3). The injected superheated steam mass flow rate is constant during the test: 130.1 g/s with an estimated uncertainty of 3 g/s. The injected helium mass flow rate is 10.16 g/s (with an estimated uncertainty of 0.35 g/s) for duration of 1826 seconds and this leads to about 18.6 kg of helium

inside the facility. The injection temperature at the steady state is about 198.1°C for Phase A and 201.6°C for Phase B with an uncertainty of about 2.3°C.
Transient behaviour of the injected temperature is measured during the transient helium injection phase (HTI). The helium injection pipe is not (2002 tests series) or only partially heated during the tests and before helium injection water plugs are present inside the pipe (condensation during the Phase A steady-state). So, the flowing hot helium heats up the line and evaporates the water plug (lower bound of the injection temperature corresponds to the saturation temperature at the vessel pressure) (figure 5).

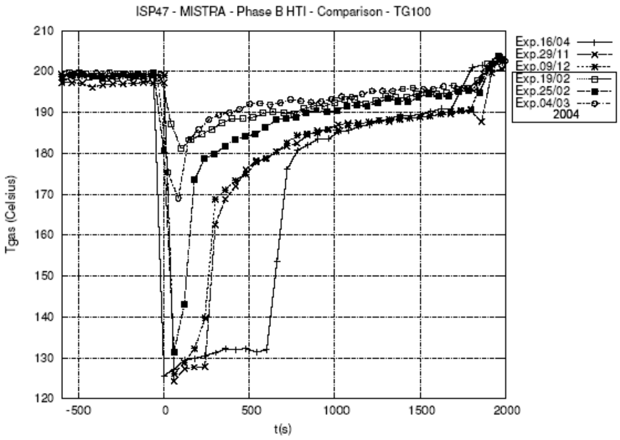

Figure 5: ISP47: injection temperature of the gaseous mixture (Steam and Helium) during the transient addition of helium (2002 tests series: 16/04, 29/11 and 09/12 - 2004 tests series 19/02, 25/02 and 04/03) [8]

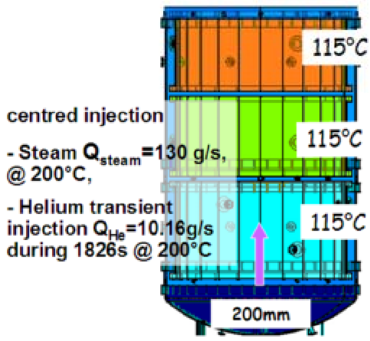

Figure 6: Sketch of MISTRA specification boundary conditions for ISP47 test.

Improvements during the 2003 instrumental reconfiguration phase (purge of the water plug prior helium injection and additional electrical heating of the main injection line) have reduced this temperature decrease. Finally, it has been measured that these different transients' conditions have no impact on the transient behaviour of the condensation described below. For the condensers, the specified temperature is 115°C for each condenser (figure 6) and the achieved conditions are 115.2°C for the lower condenser, 114.6°C for the middle condenser and 115.3°C for the upper condenser with a thermocouple uncertainty of about +/-0.8°C. This gives an idea of the controlled boundary conditions in the MISTRA experiments (Table 4).

Table 4: Reproducibility of the experimental condensers temperature for 6 ISP47 total tests (Phases A and B)

		Steady State Phase A			Steady State Phase B		
date	test n°	Lower condenser	Middle condenser	Upper condenser	Lower condenser	Middle condenser	Upper condenser
16/04/2002	1	115.0 +/- 0.8°C	114.5 +/- 0.8°C	115.2 +/- 0.8°C	115.1 +/- 0.4°C	114.8+/- 0.4°C	115.3+/- 0.6°C
29/11/2002	5				115.2+/- 0.4°C	114.7+/- 0.3°C	115.1+/- 0.5°C
09/12/2002	6				115.8+/- 1.9°C	114.7+/- 0.3°C	115.4+/- 0.5°C
19/02/2004	8	115.1+/- 0.2°C	114.7+/- 0.1°C	115.1+/- 0.2°C	115.1+/- 0.2°C	114.4+/- 0.1°C	115.4+/- 0.2°C
25/02/2004	9	115.1+/- 0.2°C	114.7+/- 0.1°C	114.7+/- 0.2°C	115+/- 0.2°C	114.4+/- 0.1°C	115.3+/- 0.2°C
04/03/2004	10	115.1+/- 0.1°C	115+/- 0.1°C	115+/- 0.1°C	115+/- 0.2°C	114.4+/- 0.1°C	115.3+/- 0.1°C

Spurious condensation along the external steel walls has been specified for the benchmark exercise (12% of the injected mass flow rate ie. 15.6 g/s) and the measured values corresponds to 17.9 g/s for Phase B and between 15.2 to 17.5 g/s for Phase A (distributed as follow: 40% on the containment walls, 40% on the sump and 20% on the insulated material on the external side of the condensers). This spurious condensation represents the heat losses of the facility and for the benchmark different strategies were proposed depending on the code capabilities: to remove the spurious condensation mass flow rate from the injected mass flow rate or to compute the thermal behaviour of the steel structure using an external heat exchange coefficient of 3-4 W/m^2/K with 20°C constant external temperature.

Improvement of the mass balance (injection/condensation) has been performed during the instrumental reconfiguration phase in 2003. The 2002 tests series lead to about 1 to 7 % difference and this reduces to less than 1 % for the 2004 tests series (Table 5).

Table 5: Reproducibility of the experimental results: injection and condensation mass flow rates, mass balance for 6 ISP47 total tests (Phases A and B)

date	test n°	injected mean value	Lower condenser	Middle condenser	Upper condenser	spurious condensation	condensed mean value	mass balance (%)
Steady State Phase A								
16/04/2002	1	131.39	39.1	34.2	43.3	16.7	133.3	-1.5
29/11/2002	5	130.6	35.3	30.1	40.4	18.0	123.8	5.2
09/12/2002	6	130.39	35.7	31.5	41.4	17.7	126.3	3.1
19/02/2004	8	130.4	39.0	39.2	47.7	15.3	131.2	-0.6
25/02/2004	9	130.38	29.3	39.5	47.7	15.4	131.9	-1.2
04/03/2004	10	130.38	27.8	39.2	48.0	15.0	130.0	0.3
Steady State Phase B								
16/04/2002	1	129.7	32.0	26.2	53.0	17.0	128.2	1.2
29/11/2002	5	128.7	31.6	20.5	48.1	19.6	119.8	6.9
09/12/2002	6	128.7	32.6	23.5	50.0	18.1	124.3	3.4
19/02/2004	8	130.4	29.5	27.1	56.4	17.5	130.5	-0.1
25/02/2004	9	130.38	30.1	27.4	56.4	17.3	131.2	-0.6
04/03/2004	10	130.38	29.6	26.7	57.1	17.7	131.1	-0.6

The MISTRA blind exercise is not discussed in detail in this paper but a set of significant results are chosen to illustrate the main conclusions of the benchmark. A synthesis of MISTRA exercise is given by STUDER et al. in [8].

The first example is the case of the total pressure (global variable). Accurate prediction of the total pressure during severe accident scenario may be considered as the first requirement for a severe accident computer code. For phases A and B steady state the results are given on figure 7. For LP and CFD it is observed for phase B, 0.2 bar of underestimation and for phase A, 0.1 bar overestimation. This deviation can be associated to the evaluation of steam mass content in relation with the modelling of wall condensation [8].

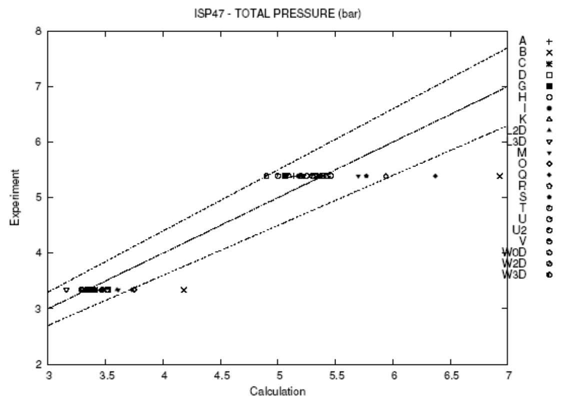

Figure 7: Total pressure for the two steady-states A and B (lines correspond to 10% deviation)

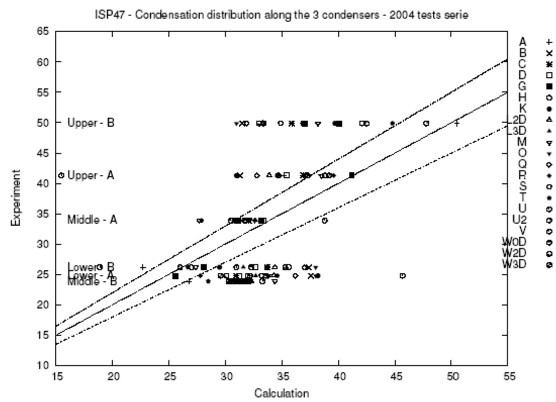

Figure 8 : Condensation distribution for the two steady-states A and B - 2004 tests series (lines correspond to 10% deviation)

Another interesting estimation is the condensation mass flow rates (level and distribution in MISTRA facility). Figure 8 shows the total condensed mass flow rate along the three condensers (about 88% of the injected mass flow rate). It is observed that none of the participants really match the condensation distribution along the 3 condensers. The spreading of the computed values is the highest for the upper condenser and at this location; the flow has to turn before the development of the boundary layers (observed for 2002 and 2004 tests). Models are not relevant for such situations because they address diffusion of steam through non-condensable gases in a fully developed boundary layer. This mainly leads to an underestimation of the condensation mass flow rate.

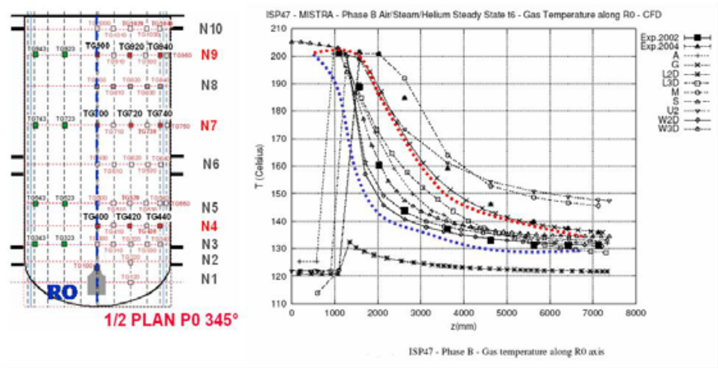

Figure 9 : ISP47 - Phase B - Gas temperature along R0 axis

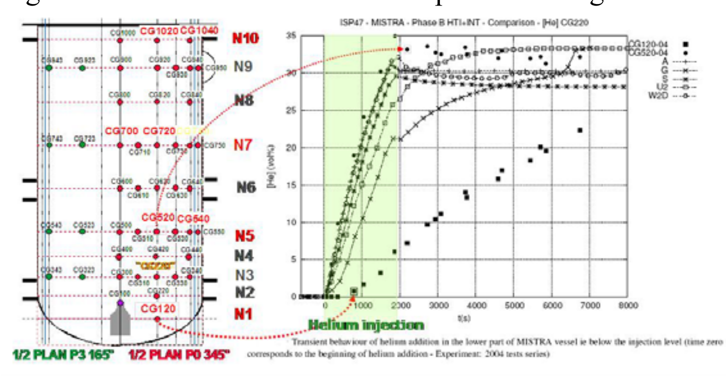

Figure 10 : Transient behaviour of helium addition in the lower part of MISTRA vessel ie below the injection level (time zero corresponds to the beginning of helium addition - Experiment: 2004 tests series)

The estimation of local variables such as temperature and gas concentration profiles shows some large spreading of the computed values.

Vertical and radial gas temperature and gas concentration profiles are recovered from the experimental measurements. The first active zone in this simple flow pattern is the rising buoyant jet (injection Richardson number is 0.09). Typical gas temperature profile is plotted in figure 9. The difference in the two test series corresponds to the presence of the potential zone above the injection device (5 diameters extend) and the main effect is that a hotter gaseous mixture reaches the top of the facility when the potential zone is present (about 5°C difference).

The difference between the two test series is due to a leakage in the main seal of the injection device, which was discovered when opening the facility in 2003. The porous media was welded for the 2004 tests. The main observation for the computations are that the simulation of the potential zone is out of the scope of LP codes and CFD codes need fine grids and adequate turbulence models to capture the phenomena. The consequences are the 5°C difference in the upper zone (upper condenser) and a large spreading of the computed values (up to 30°C).

Transients were not the first objectives of this MISTRA exercise. Nevertheless, some interesting phenomena are observed. For example in the experiments, the phase B steady-state is reached after 4 hours of transients and this relative long time scale is related to the mixing process in the lower head of the MISTRA facility (Figure 10). In this area out of the main convective loop, the time scale for helium enrichment (by convection/diffusion processes) corresponds to these 4 hours. The accurate behaviour of the lower head of the facility is not simulated by the participants mainly because attention has not been paid to model this region apart from the main gaseous volume. Post-test calculations regarding this specific point may be interesting and helium enrichment in the lower part of a vessel is investigated in the Thai facility using upper injection with low momentum.

Conclusions for ISP-47 MISTRA exercise:

The MISTRA experimental results are relevant to provide reproducible measurements of interaction between injection and wall condensation, saturation behaviour, gas concentration gradients along vertical condensers and transient effects due to helium addition. For the ISP47 blind exercise we have noted that:

- Due to interacting phenomena, explanations of the experimental results are sometimes difficult and additional post-test calculations may be interesting to enhance the current knowledge
- Global variables (total pressure) are quite well predicted
- Improvements is still needed in steam condensation models (steady-state condensation distribution and during helium addition)
- Despite relative simple flow pattern in the MISTRA facility, large deviations are obtained in gas temperature and concentration profiles (compatibility with the narrow gas concentration bandwidths related to combustion processes) to enhance the current knowledge.

The detailed analysis of the results performed by STUDER [8] shows that some improvements in code modelling and validation are still necessary. Regarding CFD contributions, some capabilities have been demonstrated and experienced code/user is another important fact. Nevertheless, some open questions remain such as the transient behaviour of the vessel lower head during helium mixing, the effect of helium addition on condensation transients, the simulation of the rising jet with a coarse grid or an algebraic model of turbulence (and the impact of the thermal boundary conditions instead of computing the thermal behaviour of the steel vessel). Implementation of condensation models in commercial CFD codes was performed by some contributors and this can lead to some differences (Phase A results) involving additional verification work. Modelling saturation is another key point and only some CFD codes incorporate such modelling. Additional improvements and verification are also needed in this field.

For LP codes, it can be concluded that they give reasonable results if the nodalisation is sufficient to capture the main findings of the flow pattern. The nodalisation or models used to describe the rising jet are clearly not sufficient to simulate the impact of the mixing process especially for Phase A steady-state. Some user effect has also been observed with some large deviations for the same code and this can lead to wrong flow pattern and large pressure over estimation. LP codes usually incorporate fog modelling and this is an important point for Phase B steady-state where some fog is present. Nevertheless, it is not a sufficient condition to recover the experimental distribution of the condensation mass flow rate along the condensers. Establishment of the boundary layer along the upper condenser may be an important aspect out of the main capabilities of current LP codes.

2.6 General Conclusions for MISTRA facility

In conclusion, the MISTRA facility is well designed to support the further development and validation of the thermal-hydraulic modelling of the containment, in particular for hydrogen distribution in PWR containments. We are able to simulate in a single experimental device different situations and phenomena related to the hydrogen risk. Flows with Richardson and Grashof numbers representative of the reactor case may be simulated. A major issue for the validation of codes is the control of the experimental conditions, especially the boundary conditions with injection conditions and wall temperature control, and these are all well controlled in MISTRA. The example of ISP-47 shows the capability of MISTRA to produce high quality data with a good reproducibility.

After a first experimental campaign with free gaseous volume, the use of compartments will provide flow data for more complex geometries and be representative of accident scenarios. Our next test series to be discussed with OECD experts, will address the issue of validating codes (especially CFD) for transient flows with different injection points.

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