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European Research on Issues Concerning Hydrogen Behaviour in Containment within the SARNET Network of Excellence

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Abstract – *The paper describes European research on issues concerning hydrogen behaviour in containment within the SARNET network of excellence. The hydrogen combustion and associated risk mitigation have been studied, concentrating on the formation of combustible gas mixtures in containments, its local gas composition and potential combustion modes, including the reaction kinetics inside catalytic recombiners. The potential hydrogen distribution in different parts of the containment has been investigated, with the objective of assessing the formation of combustible gas mixtures taking into account the effect of mitigation systems such as sprays or recombiners. Due to its influence on hydrogen distribution, steam condensation is also being investigated.*

I. INTRODUCTION

In the hypothetical case of a severe accident in a nuclear reactor with core meltdown, the interaction of the hot core with the cooling water can generate large amounts of hydrogen. The most relevant property of hydrogen related to safety is its flammability, as a hydrogen explosion can generate high overpressures with the potential to endanger the integrity of the containment. Therefore, the prediction of the consequences of hydrogen explosions is a crucial stage of the safety analysis of a nuclear power plant.

Within the Severe Accident Research Network of Excellence (SARNET), which is part of the 6th European Union Framework Programme, the following topics concerning hydrogen behaviour in the containment are being investigated:

— influence of containment sprays on containment atmosphere behaviour,
— reaction kinetics and heat transfer in autocatalytic recombiners,
— interaction between passive autocatalytic recombiners (PAR) and containment atmosphere,
— steam condensation,
— hydrogen combustion with concentration gradients involved.

The influence of containment sprays on atmosphere behaviour is being investigated both experimentally and theoretically. Experiments are being performed on the TOSQAN and MISTRA experimental facilities. These experiments are being simulated with lumped-parameter (LP) and Computational Fluid Dynamics (CFD) codes within benchmark exercises. Both atmosphere depressurization and atmosphere mixing are being studied.

Processes in autocatalytic recombiners are being investigated experimentally in the REK0-3 facility, which represents a box-type recombiner section. Experiments have been performed under forced flow conditions to

reduce the number of parameters for model development. The influences of steam and oxygen depletion on the reaction kinetics were studied. Hydrogen recombination was modelled with the REKO-DIREKT computer code.

Investigations on the interaction between PARs and containment atmosphere have been started with a benchmark exercise, which involved two-dimensional CFD simulation of PARs in a simplified domain that represents the containment.

Steam condensation influences the flow circulation in the containment at severe accident conditions and thus atmosphere mixing. The flow of a mixture containing steam in a simple conduit was simulated using CFD codes within a benchmark exercise to compare different condensation models used in simulations of containment thermal-hydraulics.

Hydrogen combustion was studied experimentally in the ENACCEF facility, which allows, due to its vertical design, to study the effect of concentration gradients on flame acceleration and deceleration. Tests with a homogeneous initial mixture as well as with positive and negative hydrogen concentration gradients were performed. The results were also used in a benchmark, which showed the limitations of the combustion models used in many CFD codes.

In the present paper, the status of these research activities is presented.

II. INTERACTION BETWEEN CONTAINMENT ATMOSPHERE AND CONTAINMENT SPRAYS

Both experimental and theoretical investigations of the interaction between the containment atmosphere and containment sprays are being carried out. Experiments were performed in the TOSQAN and MISTRA facilities [1, 2]. The TOSQAN facility (Fig. 1) is located at the Institut de Radioprotection et de Sureté Nucléaire (IRSN) in Saclay (France). It is a closed cylindrical vessel with an internal volume of 7.0 m^3. The total height of the facility is 4.8 m, and the diameter of the main cylindrical part is 1.5 m. The temperature of the vessel walls may be controlled, with the possibility of adjusting a different temperature in different regions.

The MISTRA facility (Fig. 2) is located at the Commissariat à l'Energie Atomique (CEA) in Saclay (France). It is a steel cylindrical vessel with a top flat cap and a curved bottom. The internal volume is 99.5 m^3, the internal diameter is 4.25 m and the height is 7.4 m. The vessel is thermally insulated on the outside, but the wall temperature is not controlled. Three cylindrical condensers are inserted inside the vessel, close to the wall and one above the other (so that they span over most of the vessel height). The facility is designed in such a way that almost all steam condensation is supposed to occur on the interior side of the condensers.

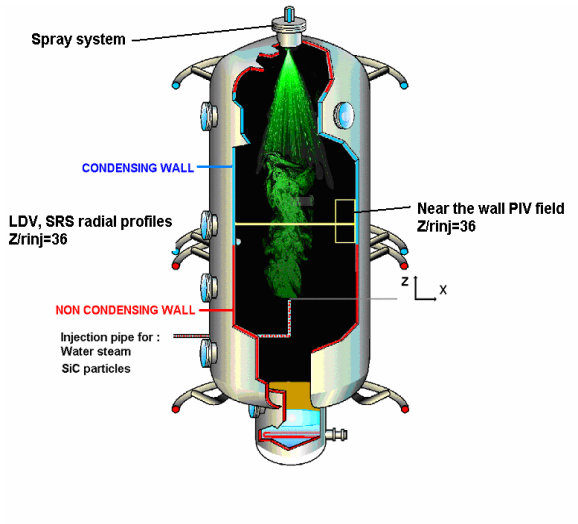

Figure 1. Schematic view of TOSQAN experimental facility.

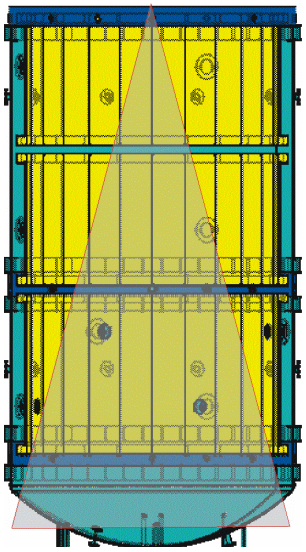

Figure 2. Schematic view of MISTRA experimental facility.

Both facilities were additionally equipped with sprays located below the vessel ceiling. The following experiments were carried out and studied within SARNET: tests 101 and 113, performed in the TOSQAN facility, and tests MASP1, MASP2 and MARC2b, performed in the MISTRA facility. The main purpose of the TOSQAN 101 and MISTRA MASP1 and MASP2 tests was to investigate

the depressurization of the containment atmosphere due to heat and mass transfer between the atmosphere and the cold spray droplets, whereas the main purpose of tests TOSQAN 113 and MISTRA MARC2b was to investigate the mixing (i.e., stratification breakup) of the containment atmosphere induced by the motion of the droplets.

All the tests followed the same basic pattern. First, a well-defined (in terms of pressure, temperature and atmosphere composition) initial state was obtained, with a quiescent atmosphere. Then, sprays were activated with all boundary conditions remaining constant. The tests lasted typically less than two hours.

The theoretical investigations within SARNET consisted in simulations of experiments. Both CFD and LP codes were used. To allow a systematic and orderly comparison between experimental and simulation results, a "spray benchmark" was organized by IRSN and CEA [1-4]. The benchmark is divided into two phases: a "thermal-hydraulic part", which deals with the simulation of tests TOSQAN 101 and MISTRA MASP1 and MASP2, and a "dynamic part", which deals with the simulation of tests TOSQAN 113 and MISTRA MARC2b.

Within the benchmark thermal-hydraulic part, the test TOSQAN 101 was simulated with LP codes by IRSN, CEA, UNIPI, JSI and UJV, and with CFD codes by IRSN, EDF, FZK, JSI and VEIKI. The tests MISTRA MASP1 and MASP2 were simulated with LP codes by IRSN, CEA, GRS, JSI, LEI and UJV, and with CFD codes by CEA and FZK. In the simulations with LP codes, spatial profiles of physical parameters were obtained if the vessels were subdivided into several control volumes. Otherwise, the results were limited to the time-dependent pressure and average temperature.

Concerning the test TOSQAN 101, calculated pressure and average atmosphere temperature were qualitatively similar to the experimental measurements. Moreover, some results also showed a good qualitative agreement. As an illustration, Fig. 3 shows the experimental and calculated pressure. Nevertheless, none of the participants obtained a good qualitative and quantitative agreement for both variables (pressure and average temperature). Furthermore, participants have found the parameters that allow to recover the experimental values of pressure and mean gas temperature, so that it may be considered that code users have a good knowledge of the use of spray models implemented in the codes. A further step is needed to justify the modelling parameters, but this could not be done presently due to lack of experimental data. The main conclusion from the simulations of the TOSQAN test 101, reached so far, is that the interaction between the spray droplets and the vessel walls (that is, the evaporation of the liquid film formed by droplet deposition) should definitely be taken into account in the modelling.

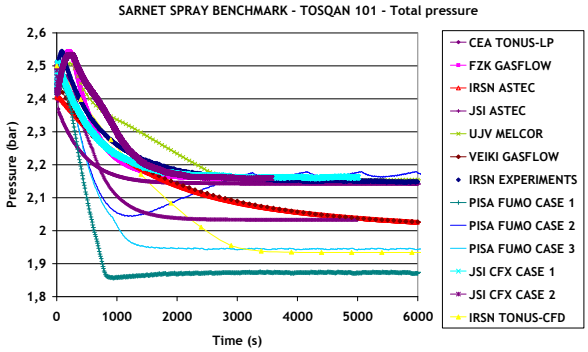

Figure 3. Test TOSQAN 101: experimental and calculated pressure.

As the TOSQAN facility is devoted to local measurements, code-experiment comparisons of local variables have been performed as well. Single droplet behaviour is found to be well estimated by the 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 major impact on the global results, since most of the heat and mass transfer occurs inside this region.

Concerning the tests MISTRA MASP1 and MASP2, the depressurization was mostly well simulated, in agreement with experimental data, by most benchmark participants. As an illustration, Fig. 4 shows the experimental and calculated pressure for test MASP2. However, a better agreement between experimental and simulation results was obtained for the pressure than for the average atmosphere temperature. So far, the main conclusion is that a better experimental interpretation of the tests should be performed, as the simulation results are very sensitive to initial and boundary conditions.

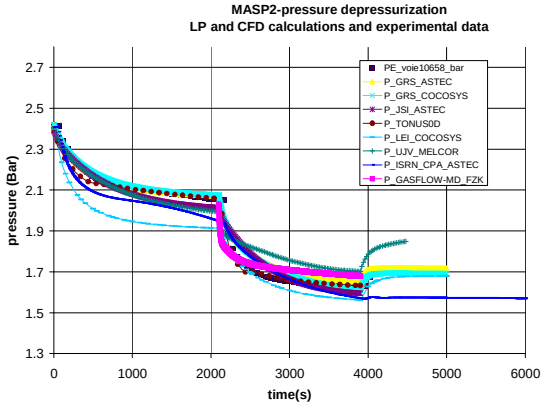

Figure 4. Test MISTRA MASP2: experimental and calculated pressure.

Within the benchmark dynamic part, the test TOSQAN 113 was simulated with LP codes by IRSN, UNIPI and JSI, and with CFD codes by EDF, FZK, JSI and VEIKI. In this test, experimental results show that the helium-air interface moves slowly down to the bottom of the facility (much slower than the residence time of a fluid particle moving by gas entrainment by the spray due to the buoyancy forces of the helium layer at the top of the facility). As a result, the helium mixing inside the vessel occurs in three steps:

— the first step corresponds probably to the transport of helium inside the spray, so that a small amount is continuously entrained by the spray, showing a slow increase of helium concentration in the lower part of the vessel;

— the second step corresponds to the arrival of the helium front at the bottom of the facility, i.e. to an increase of helium concentration, due to gas recirculation loops induced by the spray;

— the third step corresponds to the increase of concentration up to its mean value (obtained considering that the light gas concentration is homogeneous in the entire vessel); this step depends mainly on the mixing of the zone above the spray nozzle.

Most of the CFD calculations are able to recover these three steps, showing that the phenomena involved in the light gas mixing in test 113 were qualitatively well reproduced by different participants (Figure 5). Only some LP calculations (ASTEC and FUMO) do not recover these qualitative results.

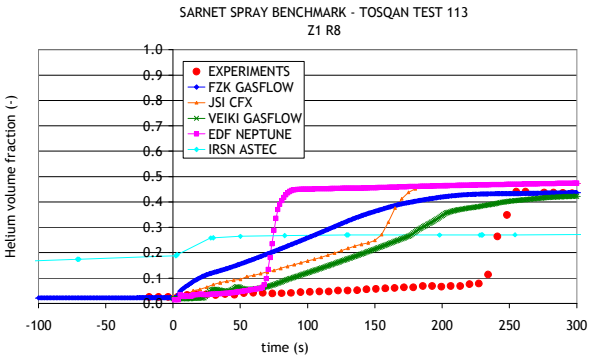

Figure 5. Test TOSQAN 113: experimental and calculated helium volume fraction *vs* time at vessel bottom.

However, the calculations encounter some difficulties to recover the quantitative variables relative to the mixing process in the test TOSQAN 113. Generally, this mixing occurs much faster than in the experiment. Furthermore, if the arrival of the helium-air interface is not well calculated, a peak of light gas concentration can be underestimated by the calculations, as can be seen on Fig. 6. This point is not acceptable for safety analyses.

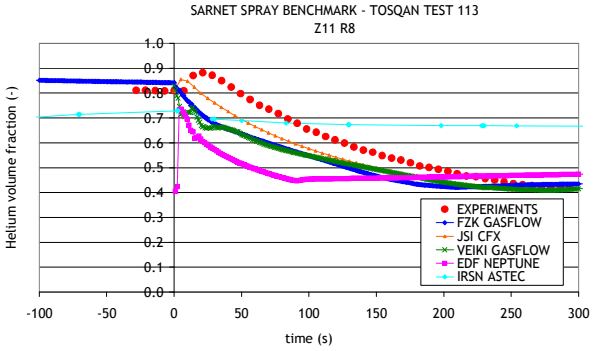

Figure 6. Test TOSQAN 113: exp. and calc. helium volume fraction 1m below spray nozzle, at half radius.

Thus, mixing of light gas by sprays is not accurately modelled by numerical tools used in this benchmark and work has to be performed to find the parameters (turbulence, buoyancy modelling, spray modelling, …) that govern this phenomenon.

The same kind of observations can be made for the MISTRA MARC2b test, which was simulated with a LP code by JSI, and with CFD codes by FZK and CEA. Figure 7 shows the helium concentration *vs* time. Experimental data show the stratification before spray activation and the destratification after spray activation. The final concentration of helium is well calculated by both CFD codes. The typical time to obtain destratification changes with the modelling.

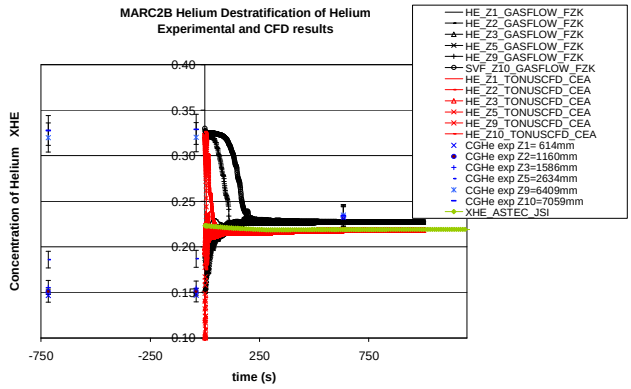

Figure 7. Test MISTRA MARC2b: experimental and calc. helium concentration at different vertical positions at center of the bulk.

III. REACTION KINETICS AND HEAT TRANSFER IN AUTOCATALYTIC RECOMBINERS

FZ-Juelich is operating the REKO-3 test facility, for which a sketch is shown in Fig. 8. REKO-3 allows the investigation of catalyst samples inside a vertical flow channel under well-defined conditions such as gas mixture, flow rate and inlet temperature. More details about the facility might be found in [5]. Recent achievements were made by studying the following phenomena:

— the influence of steam on the reaction kinetics varied between 20 and 60 vol.%,

— the influence of oxygen depletion on the reaction kinetics varied between 1 and 20 vol.%,

— self-ignition of hydrogen in recombiners.

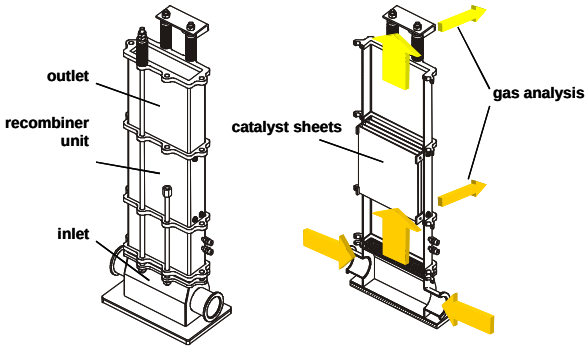

Figure 8. Sketch of FZJ REKO-3 test facility for investigation of recombiner sections under well-defined conditions.

The first two items are relevant as steam is released during many phases of a severe accident into the containment, and oxygen might be depleted due to combustion or autocatalytic reaction of hydrogen. The third item is of importance, as self-ignition could result in a fast flame with a large overpressure.

The experimental results have been used also for model validation during the PARIS benchmark (see next section).

Previous simulations indicated the importance of radiative heat transfer within the recombiner. Therefore, such a model was developed for the REKO-DIREKT code. Figure 9 shows a comparison of stationary temperature profiles within the recombiner for 20 vol.% steam and 1-4 vol.% hydrogen at the inlet. Results compare very well, even at higher inlet hydrogen concentrations when, due to higher temperatures, radiation becomes more important.

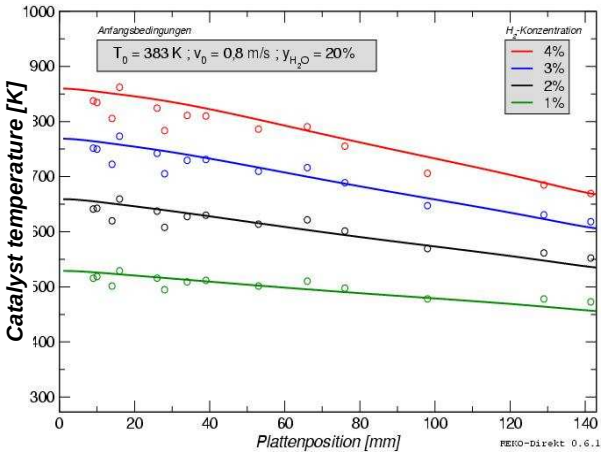

Figure 9. Comparison of REKO-3 experimental results and REKO-DIREKT simulations for 60 vol.% steam and 1-5 vol.% hydrogen (symbols: experiment, lines: simulation).

Newer experiments performed in the REKO-3 facility study the effect of catalytic self-ignition in the recombiner. Figure 10 shows time-history plots with self-ignition when the REKO-3 facility is fed with a hydrogen-air mixture of 7 vol.% hydrogen, which is less than twice the LFL (lower flammability limit). As soon as the catalytic plates get in contact with the hydrogen, it is recombined with oxygen causing the temperature at the catalyst to increase until self-ignition occurs at a temperature of about 600° C. After this self-ignition, backward burning of hydrogen towards the inlet occurs. Later, the hydrogen supply is stopped.

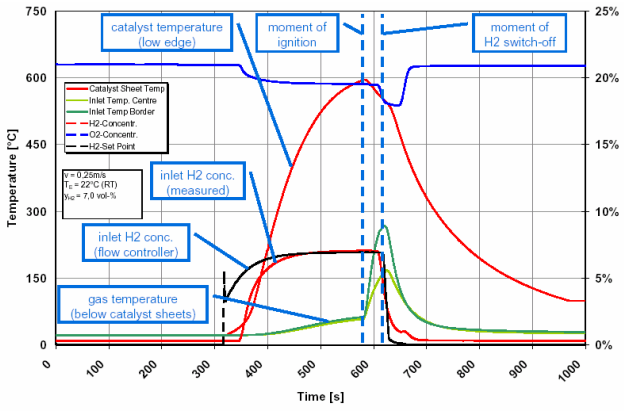

Figure 10. Hydrogen self-ignition in the REKO-3 experiment at inlet hydrogen concentration of 7 vol.%.

IV. INTERACTION BETWEEN HYDROGEN RECOMBINERS AND CONTAINMENT ATMOSPHERE

The interaction between the atmosphere and Passive Autocatalytic Recombiners (PARs) would significantly influence the hydrogen distribution in the containment. As a first step towards the resolution of this issue, CEA organized a numerical benchmark on PAR Interaction Studies (PARIS) [6] in order to:

— check the PAR elevation influence on the hydrogen distribution,

— study natural convection loop interactions when several PARs are present.

The following organizations participated in the benchmark and submitted simulation results: CEA, UNIPI, UPM, FZJ, JSI, VEIKI and FZK.

The simulation of PAR-atmosphere interaction was purely theoretical, as no adequate experimental results are available. To start the investigations of this important topic, it was decided to consider an extremely simplified system: the containment was modeled as a two-dimensional square enclosure, in which two PARs (of type SIEMENS FR90/1-150) are placed symmetrically to the central vertical divide (Fig. 11). Furthermore, no heat transfer between the atmosphere and the containment walls, or steam condensation on containment walls, was considered. However, heat generation due to hydrogen recombination was taken into account.

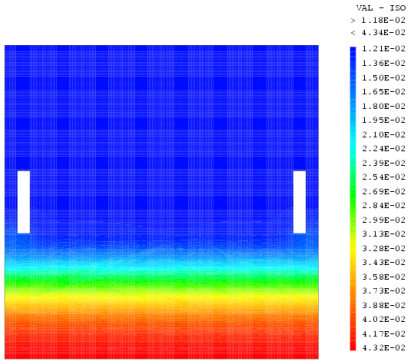

Figure 11. Simulation of PAR-atmosphere interaction: hydrogen concentration after 3000 s (red: high conc., blue: low conc., simulation by CEA).

The performed simulations (using CFD codes) lasted 3000 s. The main general result of the simulations is the low hydrogen depletion rate below the PARs (as shown on Fig. 11). Three separate layers formed in the square »containment«:

— A floor layer with slow mass and thermal mixing processes. There, hydrogen concentration and temperature were not much affected by the PAR efficiency. This floor layer is more stable if the PAR elevation is higher.

— A roof layer with intensive mass and thermal mixing processes. There, hydrogen depletion was very fast and already effective early into the transient. During the transient, inertial phenomena due to the influences of the PAR exit flow may split this layer in two.

— An intermediate buffer layer with high vertical hydrogen concentration and temperature gradients that connects the floor layer and the roof layer.

The stability of the floor layer depends on wall boundary conditions. Thus, it will be necessary to address the stratification stability with scenarii close to real situations.

Three characteristic times also appeared:

— A hydrogen depletion time. This is the earliest time when most of the hydrogen located in the roof layer has been consumed. The flow motion is caused by PAR inlet and exit flows.

— A roof layer time. This is the time when inertial effects decrease and a roof layer with constant temperature and hydrogen mass develops.

— A diffusion process time. If the PAR inlet falls in the buffer layer, this time characterizes the mixing process at the interface between the buffer layer and the roof layer (due to the absence of flow in the PAR). Otherwise, the time characterizes the mixing process between the buffer layer and the floor layer.

The PAR exit interaction with the atmosphere is not clear. When the heated mixture leaves the PAR, buoyant and inertia forces compete in order to define the PAR exit behaviour. If it is clear that the flow will move up due to buoyancy, the lateral extension depends on the turbulence. As hydrogen mobilization depends on the extension of thermal convection loops, this point should be further investigated as code to code comparisons disagree.

Due to the very simplified modelling, no real definitive conclusions concerning the influence of PARs on the containment atmosphere during an actual hypothetical severe accident can be stated. However, the results may be an indication of the possible phenomena that could be expected and an illustration of the influence of PAR actuation on the non-homogeneous structure of the containment atmosphere.

V. STEAM CONDENSATION

Condensation in the presence of non-condensable gases is also among the relevant phenomena that influence containment atmosphere mixing. Many activities have been performed in the past to investigate this phenomenon. However, new possibilities have appeared recently with the opportunity to use CFD codes. This justifies the interest for

additional experimental and theoretical studies of condensation, which are aimed to support the developmental work in the field of CFD.

Within SARNET, a "condensation benchmark" was organized by the University of Pisa (Italy) [7, 8]. In the first phase ("Benchmark-0"), a numerical benchmark based on a simple geometry was proposed, while in a later phase, comparison with experiments will also be considered. These benchmarks are mainly aimed at studying the following phenomena:

— wall condensation for air-steam, air-helium-steam and air-hydrogen-steam mixtures,
— bulk condensation phenomena,
— the effects of different turbulence models.

The initial benchmark exercise was only related to the steady-state simulation of wall condensation phenomena in forced convection conditions in a simple two-dimensional geometry, similar to the University of Pisa CONAN experimental apparatus (Fig. 12).

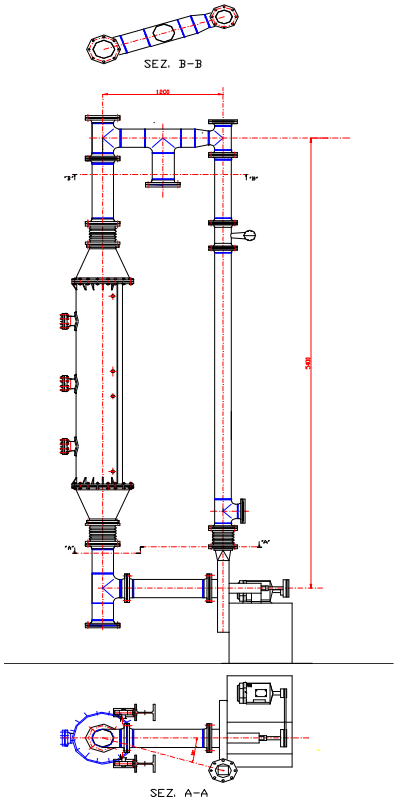

Figure 12. Schematic of CONAN experimental facility.

The test section is a vertical rectangular channel 2.0 m high and 0.34 m wide. Condensation occurs only on a single cooled vertical plate (0.34 m wide in the third dimension). The aim is to highlight code capabilities in simulating heat transfer phenomena in pure forced convection conditions and the corresponding analogous mass transfer that occurs during condensation. A well-known engineering correlation for heat transfer on a flat plate was taken as reference for this exercise in order to compare computed local Nusselt and Sherwood numbers.

Four simulation cases with different boundary conditions were considered, with two steps for each case:

— the evaluation of the purely convective heat transfer, given the wall surface and the bulk temperature, the inlet air velocity and turbulence intensity,
— the evaluation of the corresponding mass transfer by condensation given the wall surface and the bulk temperatures, mixture velocity and steam mass fraction.

The following organizations have participated in the benchmark and submitted results: CEA, FZJ, FZK, JRC, JSI, NRG, UJV, UNIPI, VEIKI and VTT.

The performed exercise proved very useful for checking the capabilities of available condensation models. In particular, the interactions that occurred in relation to obtained data allowed improving the results of some of the adopted models. In this regard, the benchmark achieved its purpose to discuss and equalize as far as possible the capabilities of different models on the basis of a common understanding.

Figure 13 reports an example of how the condensation rates, computed by different organizations, compare with each other for one of the addressed mass transfer cases. Though discrepancies do appear, it must be considered that their reasons were understood and a feedback action can be taken to improve coherence where needed.

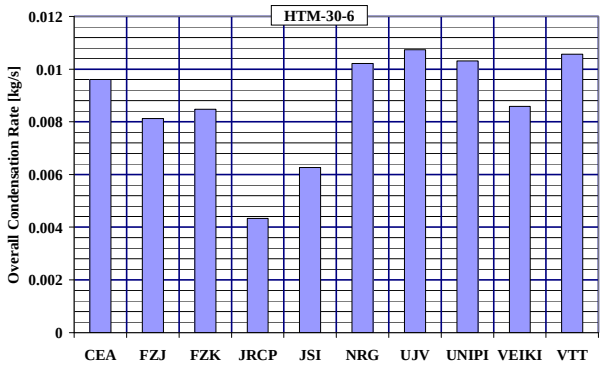

Figure 13. Condensation rate computed by different organizations for one of mass transfer Benchmark-0 tests.

VI. HYDROGEN COMBUSTION

Although previous studies of hydrogen combustion were concentrated most of the time on homogeneous mixtures (e.g. [9]), in case of a severe accident a non-homogeneous hydrogen-air-steam mixture is formed in the reactor containment during the release of hydrogen. Therefore simulation tools have to be also validated at such non-homogeneous conditions. For this reason, the ENACCEF facility is operated at IRSN. ENACCEF allows the study of the influence of hydrogen gradients on flame acceleration and deceleration. The facility is a vertical stainless steel setup with a total length of 4.9 m. It is constituted of two main parts, the acceleration tube and the dome (Fig. 14). In the acceleration tube, annular obstacles are dedicated to the flame acceleration due to turbulence generation. More details about the ENACCEF facility can be found in ref. [10]. Due to the vertical setup of ENACCEF, it is possible to create defined hydrogen gradients inside the test facility before ignition.

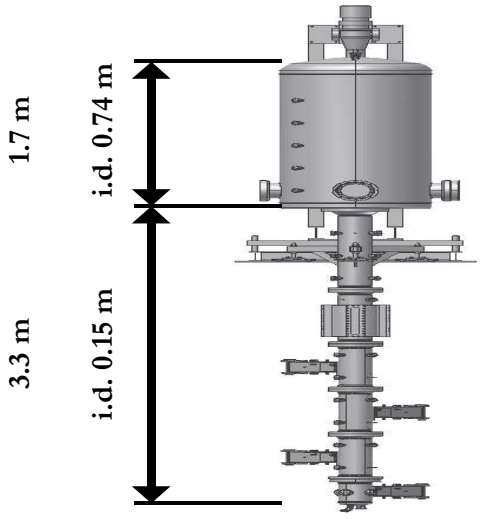

Figure 14. Sketch of the different parts of ENACCEF facility.

In the ENACCEF facility, various experiments with different hydrogen concentrations with positive and negative gradient with varying concentration between 8 and 18 vol.% of hydrogen in air have been performed. For a code benchmark, 3 experiments were selected: a homogeneous 13 vol.% hydrogen in air mixture as a reference mixture, and two non- homogeneous mixtures with positive and negative gradients between 10 and 13 vol.% hydrogen in air. Three different codes were used: REACFLOW by JRC, TONUS-3D by IRSN and VTT, and FLUENT by VTT again. All of them are CFD codes but use partially different approaches, such as grid-type and resolution.

The uniform test is characterized by an expansion factor of 4.21. In this case, the ratio between the maximum speed and sound speed in the burned gas is higher than 0.5 and the flame regime can be considered as choked regime. The experimental results indicate that the flame accelerates strongly in the obstacles field and reaches a maximum flame velocity of 535 $m.s^{-1}$ before dropping to a velocity of about 400 $m.s^{-1}$. Three flame propagation phases can be distinguished within the tube:

— 1st phase: "quasi-turbulent" flame propagation regime between the ignition point and the first obstacle between 0 and 0.638 m,

— 2nd phase: acceleration phase due to turbulence generated by the expanding hot gases over the obstacles between the 1st and the last obstacle from 0.638 m up to 1.87 m,

— 3rd phase: deceleration phase after the last obstacle due to the reduced turbulence levels.

The calculation results shows that the FLUENT and REACFLOW codes predicted reasonably well the first phase. Flame velocity is overestimated for both TONUS runs during this phase.

All codes predicted the deceleration phase in the last part of the tube without turbulence generating obstacles.

Figure 15 shows a comparison of pressure histories between experiment and simulations for 13 vol.% hydrogen in air. The pressure sensor location is about 2.877 m away from the ignition, close to the end of the tube and the junction between tube and dome. Experimental data have not been filtered and therefore contain a lot of noise. For comparison, the simulation results are shifted in time. Due to the fast flame speed (355 m/s in the experiment) there is a strong pressure increase of about 2.5 bar just ahead of the flame. This steep pressure increase is predicted by all codes, but overpredicted by FLUENT (2 bar) and half as much by TONUS (1 bar). This first pressure wave follows a decrease in pressure due to the transition from the tube towards the dome. Afterwards, the pressure increases again but not as fast, due to combustion in the large dome area. Generally, pressures are simulated well for such a homogeneous mixture.

Similar results have been obtained when simulating the burning of a mixture with a positive hydrogen gradient with the hydrogen concentration increasing from 10.5 to 13 vol.%.

Figure 16 shows the results for the negative hydrogen gradient with the hydrogen concentration decreasing from 13 to 10.5 vol.%. Ignition conditions are similar to the homogeneous case. Results are therefore very similar for the first and second phase within the tube until the last obstacle is reached in the tube. Then, a strong deceleration of the flame occurred in the experiment, which is due to the reduced hydrogen concentration in the third phase. Such

strong deceleration cannot be observed in the simulations. Therefore, flame speeds are overpredicted and, as a consequence, overpressures as well.

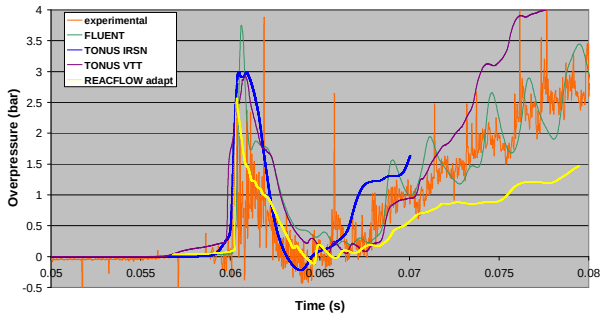

Figure 15. ENACCEF Benchmark: experimental and calculated overpressure histories at 2.877 m from ignition point, with uniform mixture 13 vol.% hydrogen in air.

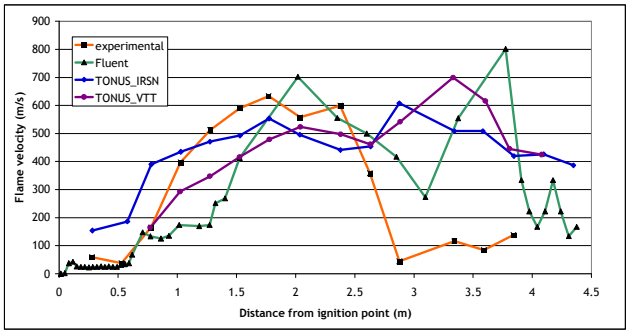

Figure 16. ENACCEF Benchmark: comparison of flame velocity between experiments and negative gradient.

VII. CONCLUSIONS

Within the European network of excellence SARNET, hydrogen distribution and combustion in the containment are being investigated.

As a conclusion of the thermal-hydraulic part of the spray benchmark, the level of qualification 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 qualification that has been reached on wall condensation in containment applications during the OECD International Standard Problem No.47 (ISP-47) [11]. 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, should be performed.

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 mixing process of light gas by spray activation. This point is probably connected with 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 show a lack of capability of CFD calculations to recover the transient characteristics of light gas mixing.

Results of REKO-3 experiments can be used during the development and validation of recombiner models. Due to the forced flow conditions, effects of natural convection can be separated from the models and the importance of other physical effects such as radiation can be evaluated.

Furthermore, the importance to study hydrogen self-ignition within the recombiner was demonstrated.

The results of the PAR-atmosphere interaction simulations have revealed the persistence of a layer with high hydrogen concentration at elevations below the PARs.

Simulations of steam condensation in a simple conduit have confirmed that the condensation issue, despite the knowledge accumulated up to the present time, deserves additional efforts for assuring a coherent model implementation in CFD codes.

The results of hydrogen combustion benchmark showed that all codes are able to predict flame speed and pressure for a homogeneous hydrogen air mixture. This is not surprising, as all codes and models have been already validated before and tested for similar conditions. This also applies to the case, when the hydrogen gradient is positive. Nevertheless, when the hydrogen gradient becomes negative, the flame speed is generally overpredicted. This indicates that there are still limitations and weaknesses in the combustion models used in the different codes. Up to now it is not clear, whether the limitations are in the chemistry part or in the turbulent combustion model, or in the coupling between the two. Therefore further investigations are needed, also because scaling remains an open issue.

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ABBREVIATIONS

CEA Commissariat à l' Energie Atomique (France)
CFD Computational Fluid Dynamics
EDF Electricité de France
FZJ Forschungszentrum Jülich (Germany)
FZK Forschungszentrum Karlsruhe (Germany)
GRS Gesellschaft für Anlagen und Reaktorsicherheit (Germany)
IRSN Institut de Radioprotection et de Sureté Nucléaire (France)
JRC EU Joint Research Center (The Netherlands)
JSI Jozef Stefan Institute (Slovenia)
LEI Lithuanian Energy Institute
LP lumped-parameter
NRG Nuclear Research and Consultancy Group (The Netherlands)
UJV Ustav Jaderneho Vyzkumu Rez (Czech Republic)
UNIPI University of Pisa (Italy)
UPM Polytechnic University of Madrid (Spain)
VEIKI Institute for Electric Power Research (Hungary)
VTT Technical Research Center (Finland)

REFERENCES

1. J.MALET, E.Porcheron, J.Vendel, L.Blumenfeld and I.Tkatschenko, *SARNET Spray Benchmark: TOSQAN and MISTRA Specification Report*, Report DSU/ SERAC/LEMAC/06-11, SARNET-CONT-P03, IRSN and CEA , Saclay, France (2007).

2. J.MALET, P.Metier, L.Blumenfeld and I.Tkatschenko, *SARNET Spray Benchmark: Thermal-Hydraulic Part, Subpart A, Comparison report*, Rev.1, SARNET report, rev. 3, Saclay, France (2007).

3. J.MALET and P.Metier, *SARNET Spray Benchmark: Thermal-Hydraulic Part, TOSQAN 101 test, Code-experiment comparison report*, Report DSU/ SERAC/LEMAC/07-03, IRSN and CEA, Saclay, France (2007).

4. P.METIER and J.Malet, SARNET *Spray Benchmark, Spray Models*, rev. 3, IRSN report, IRSN/DSU/ SERAC/LEMAC/07-20 (2007).

5. E.-A.REINECKE, J.Böhm, P.Drinovac, S.Struth and I.M.Tragsdorf, First validation results of the recombiner code REKO-DIREKT, Proc. Ann. Mtg. on Nuclear Technology, Aachen, Germany (2006).

6. F.DABBENE and H.Paillère, *PARIS Benchmark Results*, Report DM2S/SFME/LTMF/RT/07-003/A, SARNET-CONT-P04, CEA, Saclay, France (2007).

7. W.AMBROSINI, M.Bucci, N.Forgione, F.Oriolo and S.Paci, Results of the SARNET Condensation Benchmark No.0, Report DIMNP 006 (2007), University of Pisa, Italy (2007).

8. W.AMBROSINI, N.Forgione, F.Oriolo, C.Dannöhl and H.J.Konle, Experiments and CFD analyses on condensation heat transfer on a flat plate in a square cross section channel, Proc. 11th Int. Topical Meeting on Nuclear Reactor Thermal-Hydraulics, NURETH-11, Avignon, France (2005).

9. H.WILKENING and T.Huld, An adaptive 3-d solver for modeling explosions on large industrial environment scales, Combustion Science and Technology, 149, 361-387 (1999).

10. A.BENTAIB, A.Bleyer, A.Charlet, F.Malet, N.Djebaili-Chaumeix, H.Cheikhvarat and C.E.Paillard, Experimental and numerical study of flame propagation with hydrogen gradient in a vertical facility: ENACCEF, European Review Meeting on Severe Accident Research, Aix-en-Provence, France (2005).

11. H.J.ALLELEIN, K.Fischer, J.Vendel, J.Malet, E.Studer, S.Schwarz, M.Houkema, H.Paillère and A.Bentaib, *International Standard Problem ISP-47 on Containment Thermal Hydraulics*, Final report, NEA/CSNI/R(2007)10 (2007).