COMBINED EFFECTS OF COOLER AND SPRAY ACTIVATION ON THE HYDROGEN DISTRIBUTION IN THE PRESENCE OF A JET FLOW

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ABSTRACT

In this paper we present the experimental results of the PANDA HP4_2_2 test performed within the OECD/NEA HYMERES (HYdrogen Mitigation Experiments for REactor Safety) project. The experiment addresses the combined effect of a cooler in operation and a spray activation on the hydrogen distribution in the presence of a jet, which among other effects, changes the gas mixture composition, density and the containment pressure. The test scenarios included five phases, with the cooler in operation in all five phases and the spray in two phases. The presence of a three gas mixture (steam, air, helium) and of phase change phenomena (e.g. condensation) as well as the multi-compartment features of the facility caused the formation of a stratified atmosphere with a higher helium concentration in the upper region of the compartments. After the first spray phase the gas composition in the entire vessel homogenized over the vessel height. However, the release of steam jet in the following phase, determined the formation of mixture with higher helium content, below the jet elevation and as well in the containment compartment adjacent. The cooler is a heat sink which induces convection, however due to the condensation at the other side of the cooler pipes, the highest helium concentration during the test is reached inside the cooler case. The HP4_2_2 experimental data are currently analyzed within the OECD/HYMERES project with different computational tools.

KEYWORDS
Containment, Cooler, Hydrogen, HYMERES, OECD/NEA, Spray

1. INTRODUCTION

The analysis with Lumped Parameter (LP) or Computational Fluid Dynamics (CFD) codes of the thermal-hydraulic processes in a nuclear plant containment during a postulated accident scenario with the release of hydrogen is complex. It requires the modelling of physical phenomena such as, e.g. jets and plumes interacting with flow obstructions, mixing of gases with different densities, stratification, transport induced by density or pressure differences, condensation induced by the proximity of a cold wall or the activation of safety systems, re-evaporation phenomena, etc. Moreover the overall gas species (e.g. hydrogen, steam, air, etc.) distribution will depend on the design and performance of safety components (e.g. cooler, spray, PAR, igniter, etc.), the accident scenarios and the containment design.
HYMERES is the acronym for an OECD/NEA project (2013-2016) with PSI and CEA Operating Agents [1] performing experiments in PANDA and MISTRA facilities, respectively, and supported by Organizations from 13 Countries, i.e. Canada, China, Czech Republic, Finland, France, Germany, India, Japan, Republic of Korea. Russian Federation, Spain, Sweden and Switzerland. The main objective of the HYMERES Project is to improve the understanding of the hydrogen mixing phenomenology in containment in order to enhance its modelling in the support of safety assessment that will be performed

for current and new nuclear power plants. With respect to previous projects related to hydrogen risk e.g. SETH, SETH-2, etc.), the HYMERES project introduced three new elements. First, realistic flow conditions have been addressed, e.g. diffuse flow resulting from a jet impinging onto walls and inner partitions. This provided information in the evaluation of the basic computational and modelling requirements, i.e. mesh size, turbulence models, etc. needed to analyze a real nuclear plant. Second, the program includes tests addressing the interaction of safety components e.g. two heater sources, spray and cooler. Third, the system behavior for selected cases is going to be addressed.

The HYMERES PANDA cooler and spray tests are generic and aims to advance the understanding gained with the OECD/SETH-2 project [2] and the EURATOM/ROSATOM ERCOSAM-SAMARA project [3], [4] in which tests have been performed in different thermal-hydraulic facilities with the cooler or spray activated as individual component, for generic (SETH-2) and scaled scenarios (ERCOSAM-SAMARA). The previous spray tests showed that the spray activation has a strong effect on atmosphere mixing and containment de-pressurization. Containment cooler acts as a heat sink, which condenses steam and induces convection, however depending by the scenarios and cooler design, the effect is limited to the cooler region and could also lead to local hydrogen concentration increases, e.g. due to steam condensation and hydrogen pocket inside the cooler.

In the present paper the experimental results of the OECD HYMERES PANDA HP4_2_2 test are presented, in which the effect of containment cooler and spray activation on the hydrogen distribution was investigated during a steam and steam/helium jet release scenario in the containment. The HP4_2_2 test belongs to a series (HP4, HYMERES PANDA series 4) of 5 tests performed with cooler and spray operation. The main parameters varied in the HP4 series are the cooler geometry, the spray nozzle type (full cone or hollow cone) and the water temperature injected with the spray.

The organizations participating to the HYMERES project contribute via code (LP and CFD) simulations to the definition and analysis of the tests. To meet the requirements for the validation of the computational tools, an effort has been made by the Operating Agents to refine the measurements (spatial and temporal resolution) in function of each specific HYMERES test series.

The PANDA measurement for the HP4_2_2 test included, e.g. gas mixture composition and temperature in the vessels free volume and also the cooler devices. Flow velocity fields have been measured with PIV in the region between the cooler and the spray.

Some of the axis scales in the figures of the present paper are not shown or are presented in non-dimensional form, because the data of the OECD HYMERES project belongs to the project participants. The full set of HYMERES experimental data will be opened for the public in 2020. Nevertheless, the present overview should allow the reader to follow and understand the main phenomena characterizing the HP4_2_2 test.

2. PANDA FACILITY

PANDA is a large-scale thermal-hydraulic test facility designed for investigating containment system behaviour, related phenomena for different ALWR designs, e.g. SBWR or ESBWR, and for large-scale separate effect tests [5]. The overall height of the PANDA facility is 25 m, the total volume of the vessels is about 460 m^3 and the maximum operating conditions are 10 bar at 200 °C. The facility is equipped with an electrical heater bundle with a maximum power of 1.5 MW, which is used to produce steam for the preconditioning of the facility and to perform the tests. Various auxiliary systems are available to maintain and control the necessary initial and boundary conditions during the tests. The PANDA instrumentation covers the measurement of fluid and wall temperatures, absolute and differential pressures, flow rates, heater power, gas concentrations and flow velocities. The measurement sensors are installed in all facility components, in the system lines and in the auxiliary systems. The PANDA instrumentation has been continuously upgraded over the years to meet the various project requirements. An overview of the PANDA projects has been reported in [5].

2.1. Facility Configuration

Figure 1 depicts the interconnected PANDA vessels (Vessel 1 and Vessel 2) used for the HP4_2_2 test, each with 4 m diameter and 8 m height. The cooler was installed in the central region and the spray in the upper region of Vessel 1. Pure steam and steam mixed with helium was released through a vertically oriented pipe, located in the central axis of Vessel 1 and with its exit in the lower vessel region, i.e. below the cooler. The release of steam and helium jet below the cooler has been made to create a jet/structure (cooler) interaction (as in other HYMERES series), and in particular the interaction with the flow pattern created by the cooler, (which is some previous cooler tests led to helium pockets inside the cooler). The cooler has 8 pipes which are un-finned and located in a case (frame). The external diameter of the pipes is 16 mm and the pipe wall thickness is 2 mm. The cooler casing is made of stainless steel 1.4404 with a thickness of 1.5 mm whereas the cooling tubes are made of stainless steel 1.4571. The water that feeds the cooler is brought into and out of the cooler through two flexible tubes. The length of the flexible tubes, for both inlet and outlet, is approximately 5000 mm inside Vessel 1. The inlet flow enters the cooler line at the top and then is divided into the eight streams corresponding to the eight vertical serpentine tubes. The cooler pipes are concentrated in about half of the cooler case, while the other half is an empty volume [6].

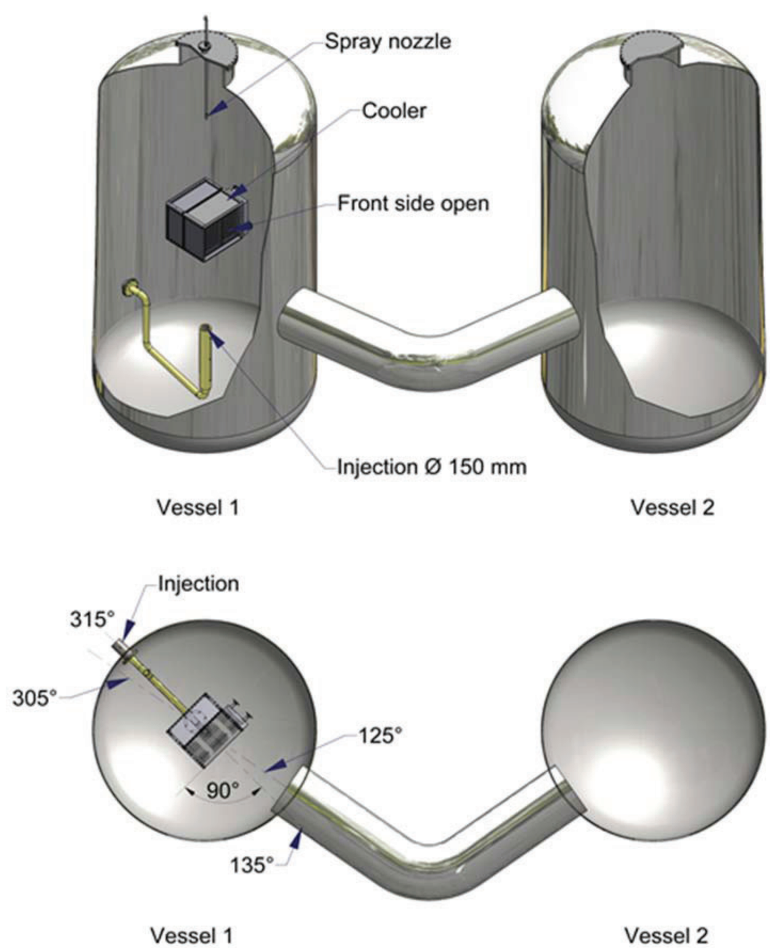


Figure 1. Facility Configuration

Figure 1, indicates the front side of the cooler, which was open for all the tests of the HP4 series. Individual sides of the cooler cases can be removed, and for the HP4_2_2 test also the rear side not visible in Figure 1, was opened. Figure 2 shows the schematic for the cooler of the HP4 series. The cooler reference point (Figure 2c) was corresponding to the central axis of Vessel 1.
The spray nozzle used in test HP4_2_2, was a full cone nozzle, provided by SSCO Spraying System AG under the reference HH-30, which has an opening angle of 30^o. The spray nozzle was mounted in a pipe and the exit of the spray nozzle was 6.9 m above the vessel bottom i.e. about 1.1 m below the vessel dome. Figure 2 shows schematic of Vessels 1-2, with the main component elevations and the test condition (which will be discussed in section 2.3).

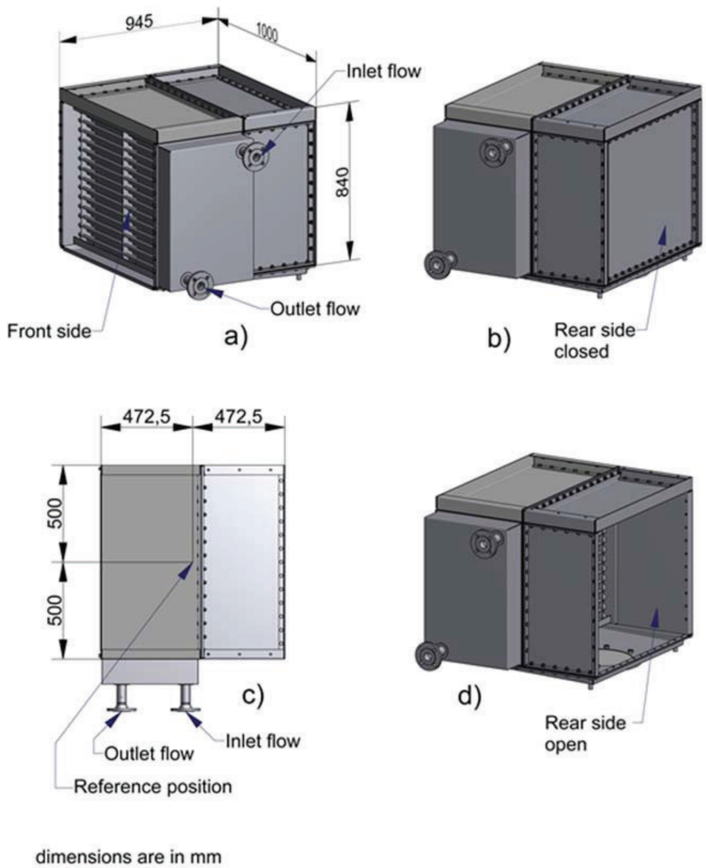


Figure 2. Schematic of Cooler Arrangement. a) View of the Front Side; b) View of the Rear Side Closed; c) Top View; d) View of the Rear Side Open.

2.2. Instrumentation

Spatial and temporal distributions of the gas concentration were measured using sampling capillaries connected to two mass-spectrometers, while the gas temperature was measured using thermocouples at the same positions.
The accuracy associated with all the measurements in PANDA is given in the report [7]. Specifically for the sensor used in this paper, the error for the gas concentration measurement is about 1.5 % and for the fluid and wall temperature measurements is about 0.7 ^{o}C, for the pressure is 3.3 kPa. The local gas velocity field was measured using Particle Image Velocimetry (PIV) at selected field of views in the

region between the spray and the cooler, which highlighted the flow structures near the cooler. The error for the PIV is related to the "rms" (root mean square) and it is test dependent [8]. An average value for the mean axial velocity would typically be of magnitude $v \approx -0.12$ m/s , with a standard deviation of around v rms ≈ 0.072 m/s . Thus, the two-sided uncertainty, with 95% confidence level, is estimated at ε (v)= $\pm$ 0.0026 m/s for the mean vertical velocity. Analogous estimates apply also for the lateral velocities ($u \approx -0.005$ m/s , u rms ≈ 0.08) and result in ε (u)= $\pm$ 0.003 m/s .

3 TEST CONDITIONS

In the HP4_2_2 test, the PANDA Vessels 1-2 were initially filled with air at 1 bar and were preconditioned (wall and fluid) to a temperature of about 112 ^{o}C (Figure 3). The test scenario consisted of five different phases plus a relaxation phase (Table I), needed to configure the PANDA facility to the following Phase 3. With respect to injection conditions, steam was injected during all the five phases as well as in the relaxation phase with a flow rate of 60 g/s. Helium was injected in Phase 2 with a flow rate of 2 g/s. The cooler was kept in operation during all five phases (and relaxation) and the water flow rate circulating in the cooler was 0.5 kg/s. The spray was activated in Phases 3 and 5 and the injection flow rate was 1 kg/s. There was no venting during the HP4_2_2 test, therefore the variation in containment pressure was due solely to the competition between the injection conditions and the cooler and spray operation.

Table I. HP4_2_2 test scenarios

	Injection conditions		**Component operation**	
	Steam 60 g/s	**Helium 2 g/s**	**Cooler 0.5 kg/s**	**Spray 1 kg/s**
Phase 1 (3600 s)	X (150 ^{o}C)		X (30 ^{o}C)	
Phase 2 (3600 s)	X (150 ^{o}C)	X(150 ^{o}C)	X (30 ^{o}C)	
Relaxation (500 s)	X (150 ^{o}C)		X (30 ^{o}C)	
Phase 3 (1200 s)	X (150 ^{o}C)		X (30 ^{o}C)	X (30 ^{o}C)
Phase 4 (3600 s)	X (150 ^{o}C)		X (30 ^{o}C)	
Phase 5 (3600 s)	X (150 ^{o}C)		X (30 ^{o}C)	X (85 ^{o}C)

4 GAS SPECIES DISTRIBUTION DURING THE HP4_2_2 TEST

The test phenomenology is discussed in function of the following parameters. The pressure history and the heat power removed by the cooler are shown in Figures 4 and 5. Temperature contour maps representing flow patterns in Vessels 1-2 and in the interconnecting pipe, for selected times representative of each test phase, are plotted in Figure 6 where red depict higher and blue lower temperatures. The location of capillaries for gas concentration measurements and thermocouples for gas temperature measurements (those sensors used for the figures in the present paper) in the Vessels 1 and 2 are included in the schematics of Figure 7. The gas mixture densities in Vessels 1-2, derived from the gas concentration and temperature measurements are shown in Figure 8. It should be noted that the capillaries for the sensors at the exit of the interconnecting pipe from the Vessel 2 side (TD2_1, TD2_5) are included in both Figures 8a and b. The variation of helium content in Vessels 1 and 2 are plotted in Figure 9. The ratio of helium/air molar fraction in Vessel 1 in the cooler and in Vessel 2 is given in Figures 10, 11, 12.
In Figure 13 are given the PIV field of view (a), the velocity fields at three selected time, i.e. before the spray injection (b), during the spray injection (c) and after the spray injection (d).

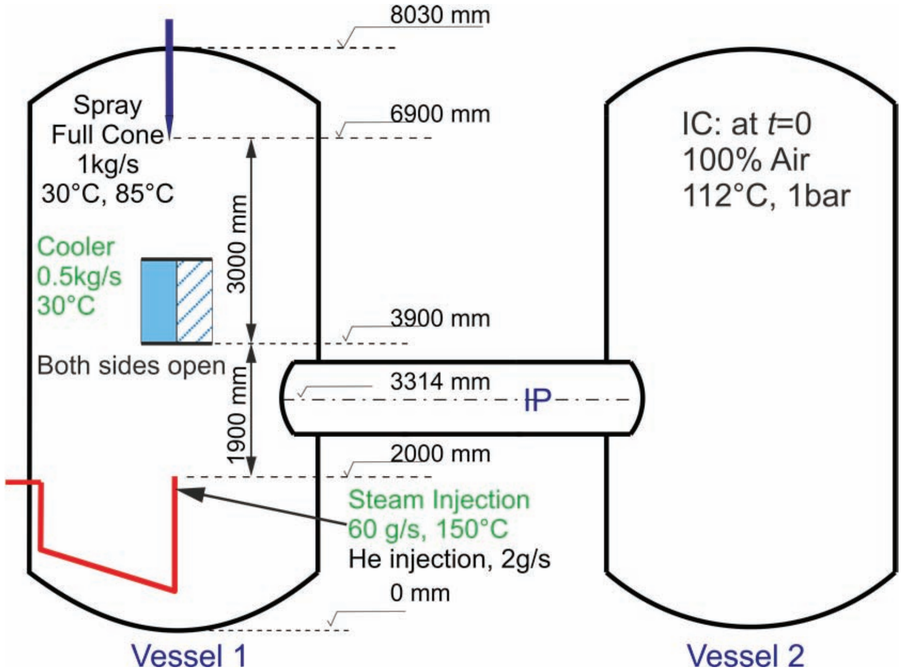


Figure 3. Vessel Configuration and Flow Conditions for the HP4_2_2 test

Phase 1, steam injection:

The steam injection, during Phase 1 causes a pressurization of the containment to 1.8 bar (Figure 4). Since the steam (D1X, Figure 8a) has a lower density than the air atmosphere initially filling the vessel, the steam jet experiences buoyancy forces. Density stratification forms in Vessel 1 and inside the cooler. At the end of Phase 1, the mixture density in the upper region of Vessel 1 (A_20, Figure 8a) is about 1.2 kg/m^3 and in the region below the injection elevation (S_14, Figure 8a) is about 1.4 kg/m^3. The heat power removed by the cooler (Figure 4), increases with the pressurization with steam and the fluid heating and it reaches about 100 kW at the end of Phase 1. However the cooler power is not uniformly extracted but it is mostly removed by the upper part of the cooler. In Figure 6a the temperature contour maps at t=501s is shown, e.g. with the warmer fluid in the injection and in the upper regions until the level of the cooler (upper half). The colder fluid gives an indication on the extension of the region directly affected by the cooler operation.

The evolution of temperature contour maps combined with the mixture densities revealed a warmer and lighter (sensor CO3, Figure 8a) stream entering the cooler from the top part of the cooler open side and a colder and heavier stream (CO5, Figure 8a) leaving the cooler from the lower part of the opened side. Being the air-steam stream leaving the cooler (sensor CO5, Figure 8a) heavier than the surrounding warmer air, flowed downwards and increased the steam content below the injection elevation.

The inter compartment gas species transport, was characterized by a lighter (TD2_1, Figure 8a) and colder mixture flowing from Vessel 1 to Vessel 2 from the upper region of the interconnecting pipe and a heavier (TD2_5, Figure 8a) and warmer mixture flowing from Vessel 2 to Vessel 1 from the lower region of the interconnecting pipe. That mixture from Vessel 2 reaching Vessel 1 has a lower density respect to the mixture abandoning the cooler and therefore the resulting mixture which accumulates in the lower region of Vessel 1 has an intermediate density.

Phase 2, steam and helium injection - cooler operation:

During Phase 2, the containment pressure is further increased to 2.5 bar (Figure 4) by the effect of steam and helium injection. The slightly decreases in cooler power at the beginning of Phase 2 (Figure 5) corresponds to the start of helium injection and the increases at the end of Phase 2 corresponds to the stop

of helium injection. The cooler power stabilizes to about 100 KW and the helium effect on the cooler power deterioration is minor. However a more detailed analysis of the cooler performance in all the five test phases will be reported in a separate document.
As an example, the normalized flow velocity field, at, t=3824.1s is shown in Figure 13b. The curvature and the direction of the streamlines are oriented towards the cooler and as explained in Phase 1, a gas stream enters the cooler from the upper part of the opened face. Due to the pressurization the mixture density in Vessel 1 increased almost everywhere (except at the location CO_5, Figure 8a). Density stratification formed in Vessel 1 and in Vessel 2. Figure 7 shows that at the end of Phase 2, the density in the upper region of Vessel 1 is about 1.4 kg/m^3 while in the lower region we find 1.8 kg/m^3. This is mainly due to the fact that helium accumulates above the injection elevation (Figure 9a). It should be pointed out that the mixture flowing out from the cooler is heavier that the surrounding fluid (sensor CO_5 in comparison with M_26, Figure 8a) but lighter that the mixture below the injection elevation (S14, Figure 8a), therefore accumulated between the cooler and the jet injection. The temperature contour map in Figure 6b revealed that the coldest fluid is in the lower region of Vessel 1 due to the fact that the warmer and lighter fluid cannot mix with the colder and heavier fluid below the injection elevation.
Figures 10 and 11 show that helium/air molar fraction ration increases steadily in the Vessel 1 and in the cooler with the exception of the region below the elevation of injection (sensor S_14, Figure 10). Density stratification forms also in Vessel 2 (Figure 7b). The fluid at the exit of the interconnecting pipe (TD2_1, Figure 8b) has similar density like in the upper region of Vessel 2 (A_20, Figure 8b) which means that the flow is directed through the interconnecting pipe to the upper region of Vessel 2.

Phase 3, steam injection - cooler and spray operation:
The spray is operated with a water flow rate of 1 kg/s and temperature of 30 ^{o}C. The spray operation induces condensation and de-pressurization from 2.5 bar to 1.8 bar (Figure 3) and the cooling of gas mixture (Figure 6d). The cooler heat power decreased from about 105 kW to 50 kW (Figure 5). The spray induced the mixing of the atmosphere, e.g. breaking up the density stratification in Vessel 1. The helium content becomes uniform in Vessel 1 (Figure 9a). As an example of the spray droplet velocity field, the normalized velocities at t=7778 s are shown in Figure 13c. The streamlines velocities are nearly vertical and representative of the spray flow direction. The velocities are two order of magnitude higher that in the previous phase (e.g. ~0.2 m/s versus 20 m/s).
The inter compartment gas species transport through the interconnecting pipe is reversed, e.g. it flows from Vessel 1 to Vessel 2 from the lower region of the interconnecting pipe and from Vessel 2 to Vessel 1 from the upper region. The mixture containing helium, in Vessel 2 in the proximity of the interconnecting pipe (TD2_1, TD2_5, Figure 8b), is lighter than the mixture in the lower region (R_15 and T_20, Figure 8b) and heavier than the mixture in the upper region (A_20, D_20, Figure 8b) therefore accumulates at intermediate elevations (e.g. Figure 9b).

Phase 4, steam injection – cooler operation:
With respect to the cooler operation and injection conditions Phase 4 and Phase 1 are similar. However a three gas mixture with a density of about 1.35 kg/m^3 (Figure 8a) is present in the Vessel 1 instead of pure air as during the start of Phase 1. Phase 4 starts with fluid pressure at about 1.8 bar and the injected steam has a higher density than in Phase 1 (DIX, Figure 8a) the jet buoyancy is lower in Phase 4, compared with Phase 1 (see e.g. the evolution of difference between M_26 and D1X in Figure 8a). As an example, the normalized flow velocity field at t=9016.1s is shown in Figure 13d. The curvature of the streamlines are in the direction of the cooler but the velocity magnitude is lower compared with Phase 2, e.g. this is consistent with the flow induced by the jet which is slower due to the lower buoyancy.
The injected steam fills uniformly the volume above the injection level and determines a dilution in the helium concentration above the injection (Figure 9a). The region below the injection is not affected and therefore there a minor variation in the gas mixture composition below the injection level was observed.

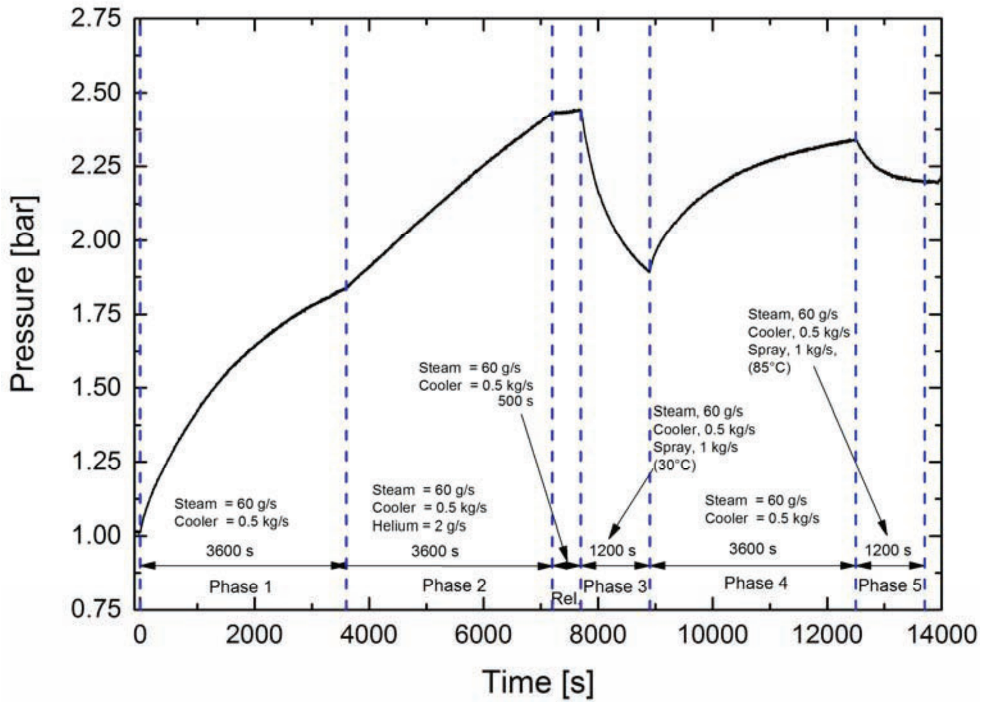


Figure 4. Pressure Curve and Test Conditions

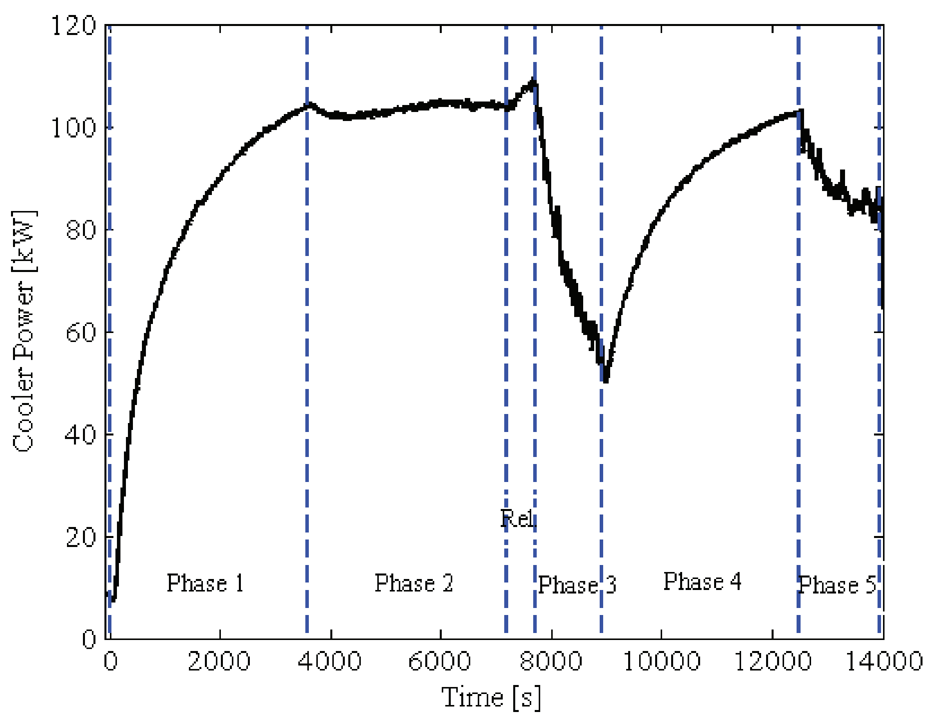


Figure 5. Estimation of Heat Power Removed by the Cooler

The containment pressure increases and reaches about 2.2 bar at the end of Phase 4 (Figure 4). The power removed by the cooler reaches again 100 kW. As an effect of the steam release, the helium concentration at the end of Phase 4, in the lower region of Vessel 1 is higher than in the upper region (Figure 9a). The helium/air molar ratio however remains constant and uniform over the vessel height as shown in Figure 10.

Overall, there is an increase in density in Vessel 2 due to the pressurization, though at the level N (N15, Figure 8b) the increase is milder. In fact, the helium-steam-air mixture, reaching Vessel 2, accumulates at the elevation of the interconnecting pipe and below until the level N (Figure 9).

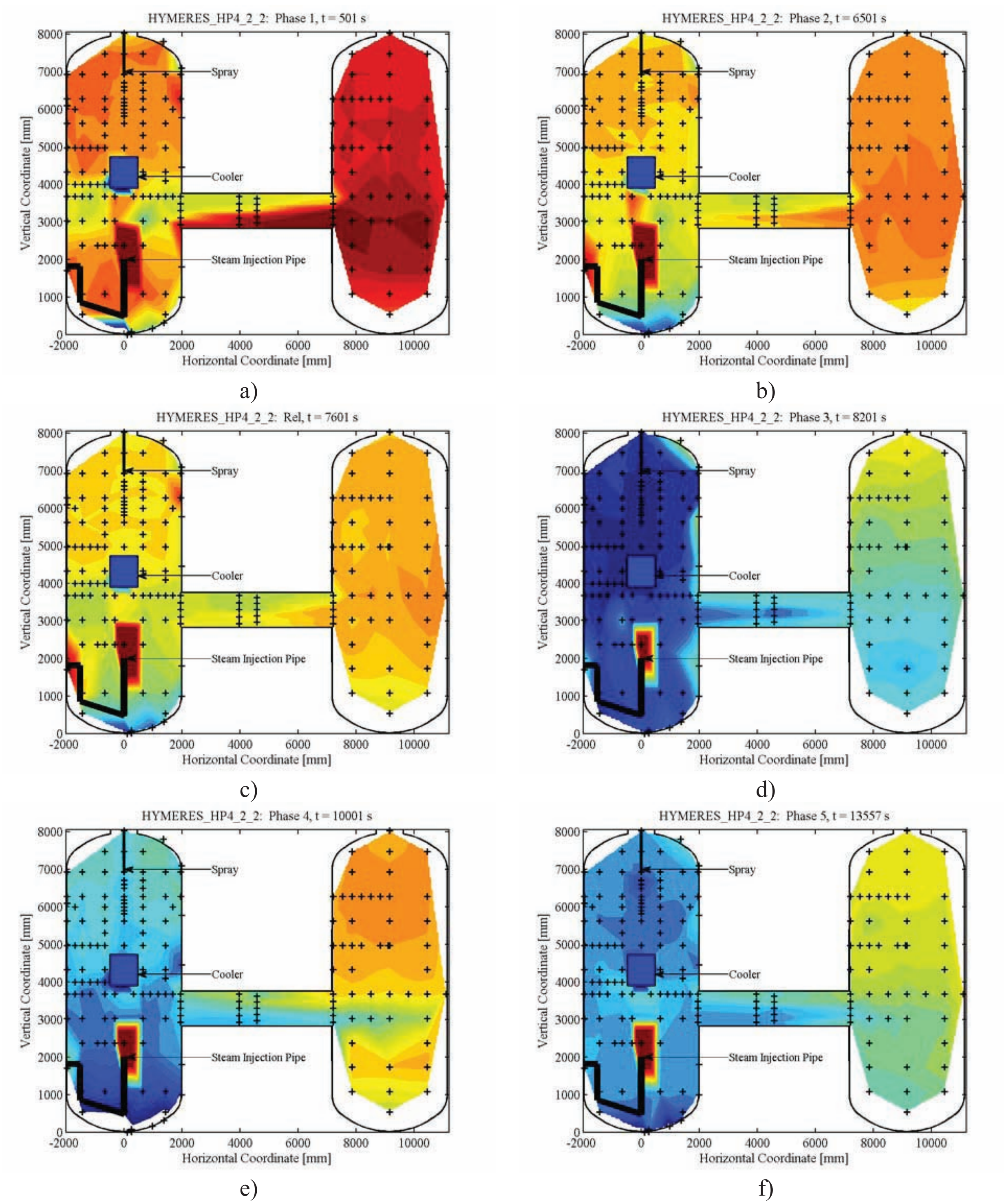
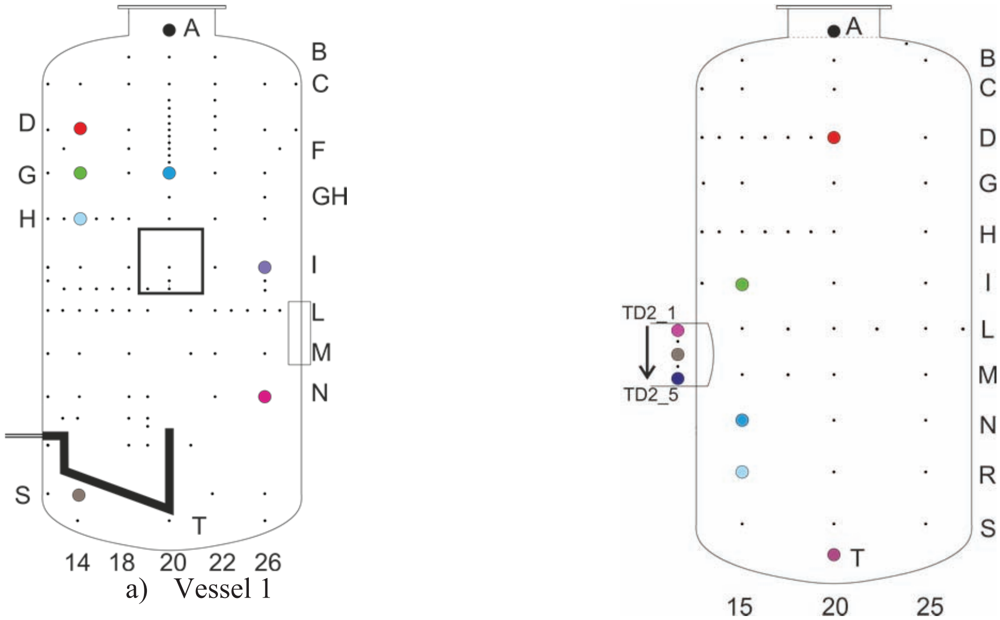
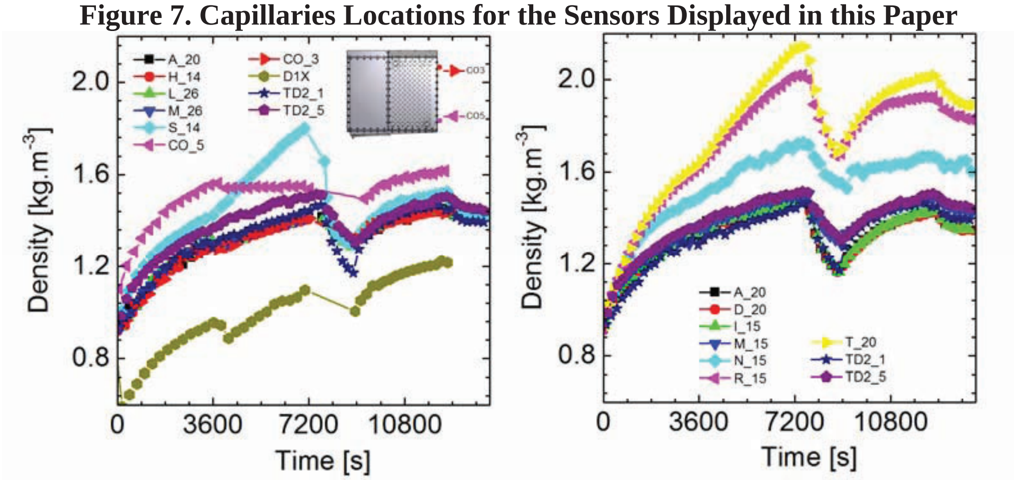


Figure 6. Temperature Contour Maps at Selected Times in the Different Phases



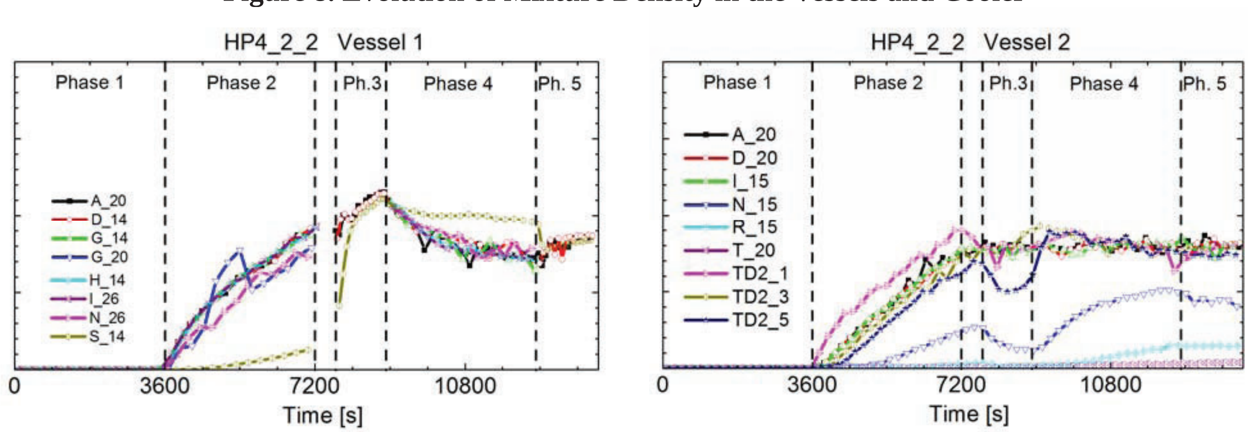
a) Vessel 1 b) Vessel 2

Figure 7. Capillaries Locations for the Sensors Displayed in this Paper



a) Vessel 1 and cooler b) Vessel 2

Figure 8. Evolution of Mixture Density in the Vessels and Cooler



a) Vessel 1 b) Vessel 2

Figure 9. Variation of Helium Content

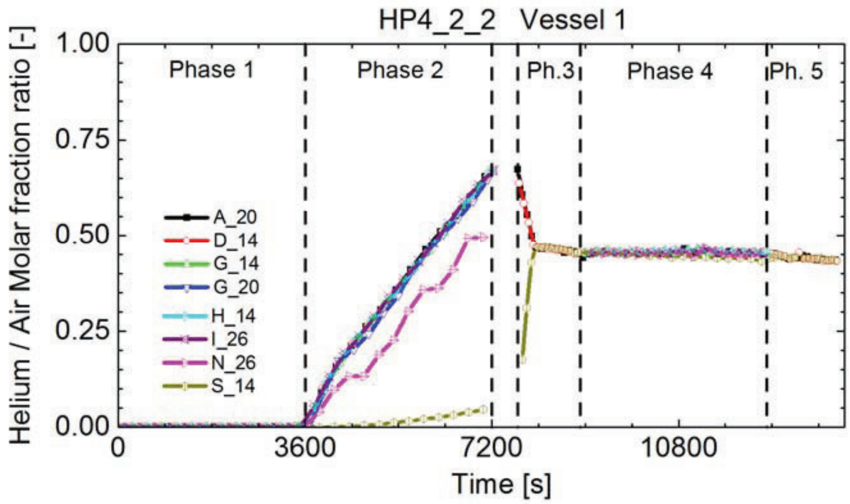


Figure 10. Helium/air Molar Fraction Ratio in Vessel 1

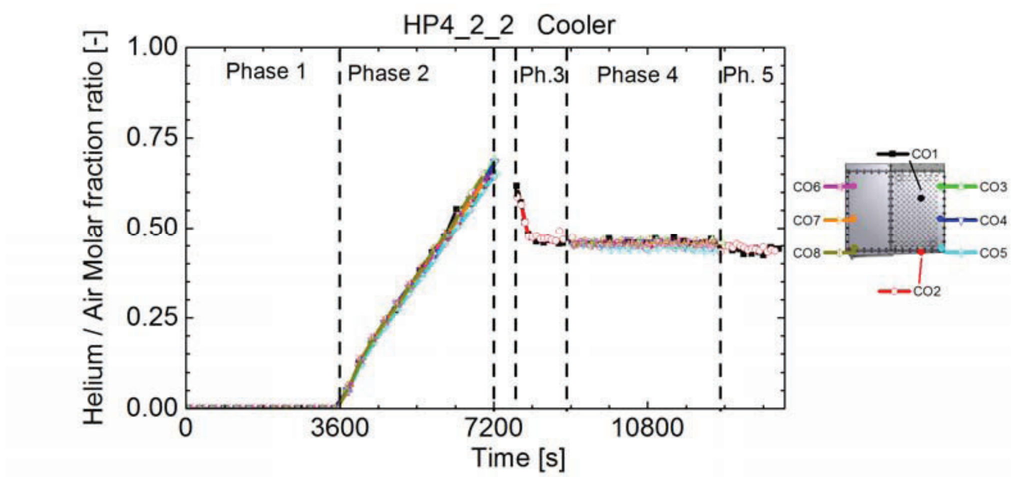


Figure 11. Helium/air Molar Fraction Ratio in the Cooler

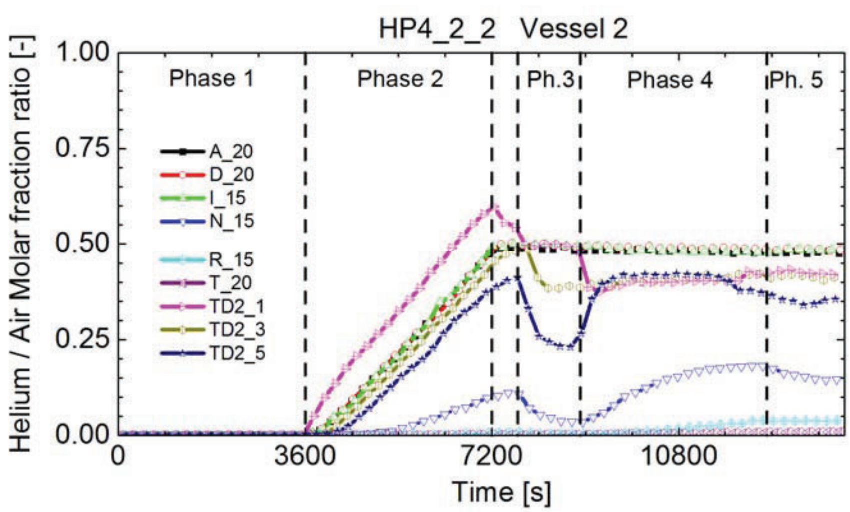
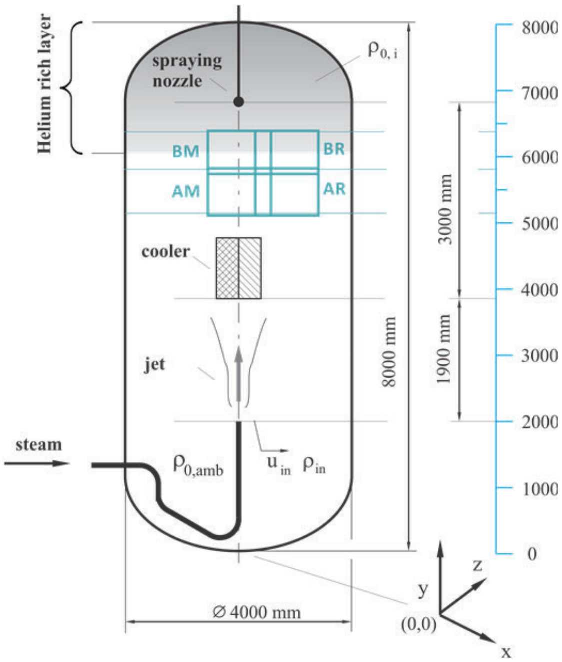
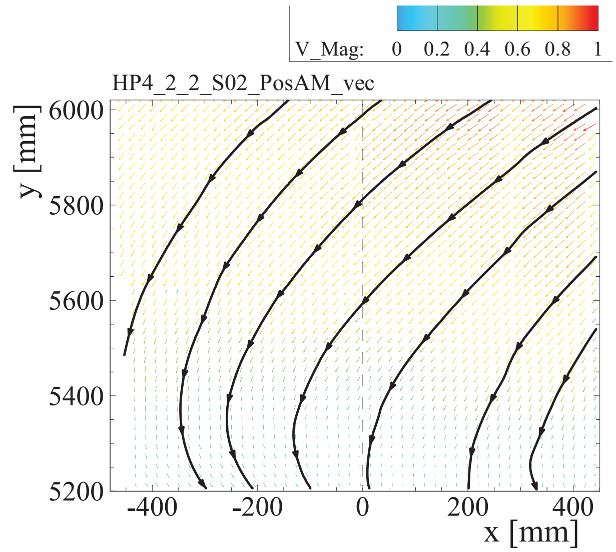


Figure 12. Helium/air Molar Fraction ration in Vessel 2

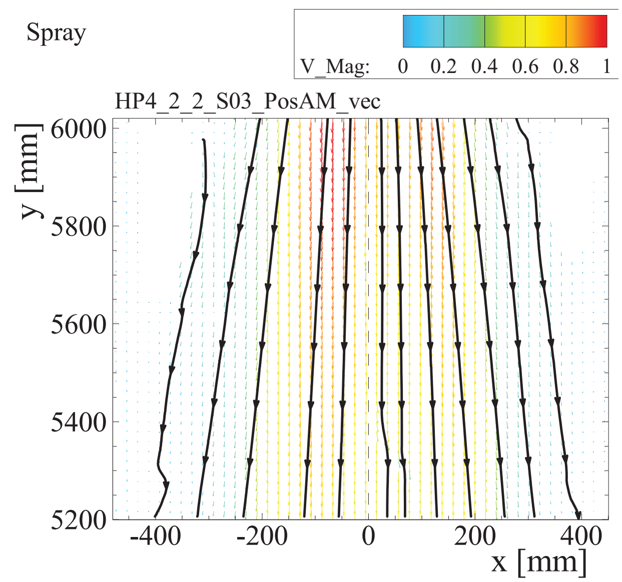


a) Vessel 1 schematic and PIV field of view



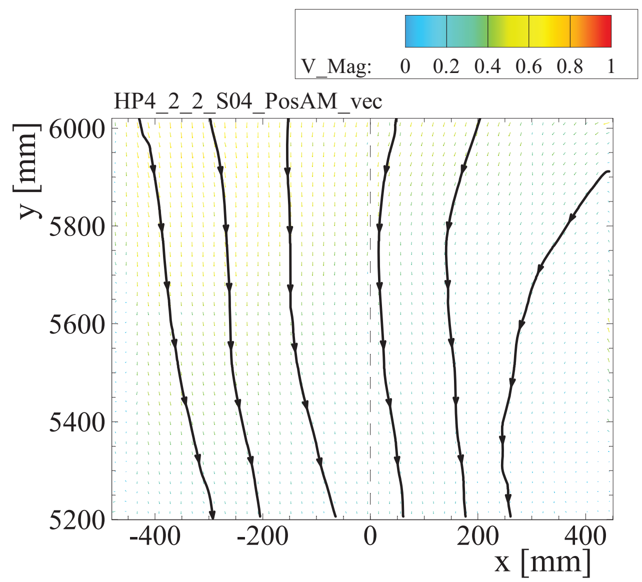
Position AM

b) Phase 2 (before spray injection); t= 3824.1 s



Position AM

c) Phase 3 (during spray injection); t= 7778.1 s



Position AM

c) Phase 4 (after spray activation); t=9016.1 s

Figure 13. Vessel 1 Configuration with PIV Fields of View, Normalized Velocities

Phase 5 (12500s – 13800 s) steam injection – cooler and spray operation:

The spray is activated again with a water flow rate of 1 kg/s but now with a temperature of 85 ^{o}C. The spray induces condensation and consequently, a weak de-pressurization of about 0.13 bar (Figure 4), i.e. the pressure decay is a direct function of the spray water temperature. The gas mixture is cooled by the effect of the spray (Figure 6f). The cooler heat power decreases to about 80 kW, for effect of the lower pressure and fluid temperature. The spray activation enhances the mixing of containment atmosphere in Vessel 1 and the mixture density become uniform (Figure 8a). The gas composition evolution in Vessel 2 remains almost not affected by the activation of spray in Vessel 1, and the stratification which was present at the end of Phase 4 remained in Phase 5.

5 CONCLUSIONS

The OECD HYMERES PANDA HP4_2_2 test was performed to study the effect of cooler and spray activation, on gas species (air, steam, helium) evolution for a scenarios consisting of five phases with a jet of steam or steam/helium release. The scenario is more complex that the previous tests in which the cooler or the spray were activated as individual components.

The jet led to density stratification in Vessels 1 and 2, e.g. steam/air in phase 1 and steam/air/helium in the second phases. The key parameter affecting the stratification in Vessel 1 is the release elevation and in Vessel 2 the elevation of the interconnecting pipe. The jet is always buoyant and the composition above the injection elevation tends to be uniform. The cooler operation in Phase 1 determined the formation of an air-steam mixture colder and heavier than the air in the lower region of Vessel 1, which determines the transport of steam also below the injection elevation. Stratification is built-up in both vessels also in Phase 2 when helium is releases. The spray activation produces several effects including the complete mixing in Vessel 1. Almost no effect on mixing of the gas atmosphere in Vessel 2 was induced by the spray. When the spray is not anymore in operation the stratification is again built-up duo to the jet release. The cooler is a heat sink which induces convection but did not prevent the build-up of a density stratification.

The spray has a strong effect on the system pressure, on the mixing of atmosphere in Vessel 1 and in the inter-compartment Vessels 1-2 gas transport. The inter-compartment flow transport through the interconnecting pipe is before the spray operation from vessel 1 to vessel 2 from the upper region of the interconnecting pipe, and from vessel 2 to vessel 1 from the lower region. When the spray is activated the IP flow is reversed, e.g. is from Vessel 1 to Vessel 2 from the lower region of the interconnecting pipe. In Phase 4, the mixture containing helium flowing from Vessel 1 to Vessel 2 is heavier than the mixture in the upper region and lighter than the mixture in the lower region of Vessel 2, and this determines an accumulation of helium in the central region of Vessel 2. The comparison of test HP4_2_2 with the other tests performed within the same series (HP4) will be illustrated in another paper, and will provide insights on the effect of other parameters, e.g. cooler and spray designs, spray water temperature, etc. on the hydrogen distribution in a multi-compartment containment.

The HP4_2_2 test experimental data are currently analyzed within the OECD/HYMERES project with different computational tools.

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