PLANNING CALCULATIONS OF SPRAY TESTS FOR THE ERCOSAM-SAMARA PROJECT

Z. Liang[1], M. Andreani[2]
[1] Atomic Energy of Canada Limited, Chalk River Laboratories, Ontario, Canada, K0J 1J0
[2] Laboratory for Thermal-Hydraulics, Paul Scherrer Institut, Switzerland, 5232 Villigen, Switzerland

Abstract

Within the framework of the ERCOSAM-SAMARA project, co-funded* by the European Union and the Russian State Atomic Energy Corporation, planning and pre-test calculations are performed to examine sensitivity parameters that can affect the break-up (erosion) of a helium (substitute for hydrogen) layer by mitigation devices (i.e., cooler, spray, or Passive Autocatalytic Recombiner - PAR). This paper reports the GOTHIC analysis results for the spray tests to be performed in the PANDA facility. The effects of spray flow rate, temperature and injection height on depressurization, erosion of helium cloud and gas transport behavior are studied. This analysis is valuable because only a limited number of conditions will be examined in the planned experiments. The study provides a useful understanding of the interaction of spray with a stratified atmosphere.

1. Introduction

During postulated severe accidents with core degradation in nuclear power reactors, a large amount of hydrogen can be produced from oxidation of metallic components of the reactor core and molten core concrete interaction. The hydrogen may migrate into the containment and form explosive mixtures through various physical processes (i.e., mixing, stratification, and condensation). The presence of hydrogen stratification is a safety concern because pockets of high hydrogen concentration could lead to a deflagration or detonation, which might challenge the integrity of containment buildings. Containment spray systems are used in some reactors to provide heat removal following accidents by steam condensation on water droplets, thus reducing the pressure in the containment building. Questions have been raised concerning the use of spray during an accident where hydrogen is produced, because it may lead to higher hydrogen concentrations and more sensitive air/steam/hydrogen mixture compositions after steam condensation; however, it may also mitigate the hydrogen risk by breaking up the stratified hydrogen clouds due to enhanced mixing.

The ERCOSAM-SAMARA project [1] includes various experiments addressing accident scenarios, scaled down from existing severe accident plant calculations to different thermal-hydraulics facilities: TOSQAN (IRSN, France), MISTRA (CEA, France), PANDA (PSI, Switzerland) and SPOT (Afrikantov OKBM, Russia). The tests sequences are designed to investigate hydrogen concentration build-up and stratification under stylized postulated accident scenarios and the effectiveness of accident management systems (i.e., cooler, spray, and PAR) in destabilizing a stratified hydrogen layer. Prior to commencing with the experimental program, planning and pre-test calculations have been performed to determine the optimum experimental conditions.

* Canada is providing in-kind contributions without direct funding through planning, pre- and post-test calculations.

This paper presents the GOTHIC 8.0 (a general purpose thermal-hydraulic code) analysis for one of the spray tests (no wall condensation) to be performed in the PANDA facility.

2. Facility and Description of PANDA Tests

For the ERCOSAM-SAMARA project, the PANDA facility will be configured with two vertical vessels (DW1/DW2, 90 m^3 each, height of 8 m, diameter of 4 m), connected by an interconnecting pipe (IP; length of ~5 m, diameter of 1 m). The facility layout is shown in Figure 1. No venting will occur during testing. The vessels are thermally insulated and will be pre-heated to minimize wall condensation. A more detailed description of the PANDA facility is given in [2]-[3]. Steam and helium will be injected from a vertical pipe aligned with the axis of the vessel DW1 with the exit at 4 m above the vessel bottom.

For the spray tests, water will be injected through a spray nozzle, located in the vertical axis and oriented downward in the upper region of DW1 (see Figure 1). The nozzle produces a full-cone spray with an included angle of 30°. The system allows water injection at a specified flow rate and the droplet diameter distribution changes with the flow rate, which has been determined in previous experimental programs.

The ERCOSAM-SAMARA tests will generally include the following phases:

1) Phase I: steam injection to simulate the late stage of a loss of coolant accident (LOCA) blow-down
2) Phase II: helium (substitute for hydrogen) injection to simulate core damage
3) Phase III: no injection (stabilization of helium distribution) to simulate post-core damage
4) Phase IV: activation of one of the severe accident management devices (spray, cooler, or PAR)

The above test sequence represents a stylized LOCA in a light water reactor, chosen from existing plant calculations. The planning calculations presented in this paper assume that stable nominal conditions are achieved in Phase III and focus on the behaviour during Phase IV. The goal is to examine the helium erosion process by activating a containment spray under pre-defined initial conditions, representing the foreseen conditions at the end of Phase III, where steam is ~70% above the elevation of the IP and ~50% below the IP in both vessels with 10% helium in the top of the DW1. Note the gas concentrations shown in this paper are referred to the volume percentage.

3. GOTHIC Model Description

The PANDA vessels (DW1, DW2 and IP) are represented in GOTHIC by three control volumes, each of which is subdivided into a three-dimensional grid in Cartesian coordinates (see Figure 2). The bend of the IP is neglected and it is modelled as a straight pipe. The three volumes are inter-connected by 3-D connectors. Symmetry is assumed and only half of the volumes along the middle plane of the vessels are modelled. Features that define the perimeter of the vessel (including the lower and upper heads, cylindrical wall, and lid area cylinder) are modelled by blockages. The vertical subdivisions are maintained throughout all three volumes (except for the bottom of DW1). The control volumes are subdivided by 21×10×38 grids along the x, y and z directions for DW1, 14×10×40 grids for DW2, and 11×3×5 grids for IP. The total number of active (non-blocked) cells is 10970. The first z-grid in the lower header of DW1 is larger due to numerical difficulty (small time steps) in dealing with water when filling a cell. Overall, the mesh size is similar to the GOTHIC model of [4], which is proven to be sufficient to capture gas stratification.

Heat transfer between the fluid and the internal structures and the vessel walls is simulated. The metallic walls and the insulation layers of the vessels are fully represented. The default GOTHIC models have been used for mass and heat transfer (including condensation), and the standard two equation κ-ε model is used to model turbulence. The spray is modelled with a flow boundary (to define the flow rate and initial droplet diameter) and a flow path instead of a built-in spray component, which was proven to be of limited use [5]. The area of the flow path is set equal to the area of the spray nozzle (I.D. 6.4 mm) before the discharge. It has been found in [5] that GOTHIC tended to over-predict the depressurization of spray tests partially because the convective heat transfer from the wall to the fluid was under-predicted. An enhancement factor of 5 is thus applied for the convective heat transfer coefficient as used in [5]. Preliminary model testing was performed by simulating the past PANDA gas mixing tests (without spray) published in [4]. The results obtained with the current model captured the trends of the measurement well.

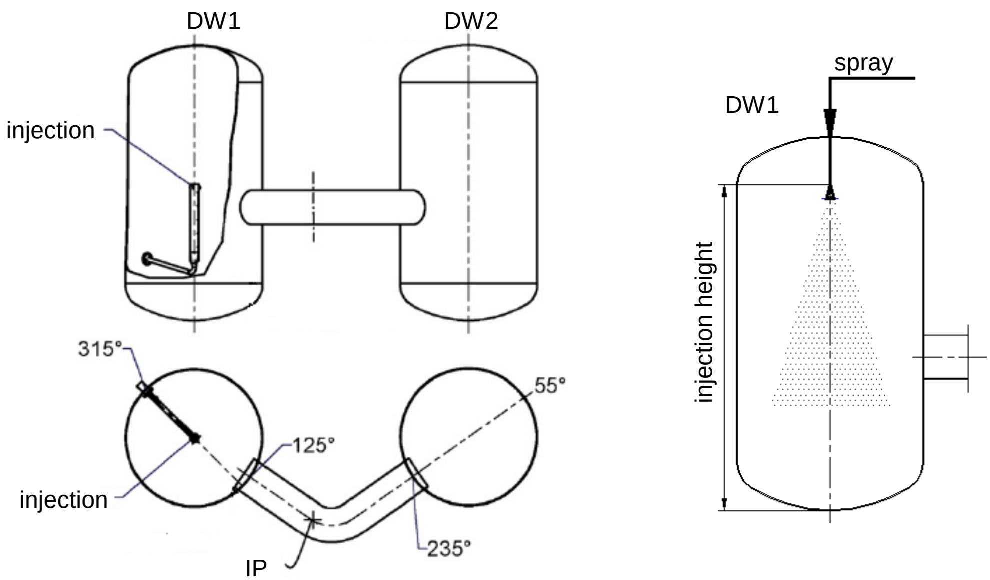


Figure 1 PANDA facility configuration for the ERCOSAM spray tests

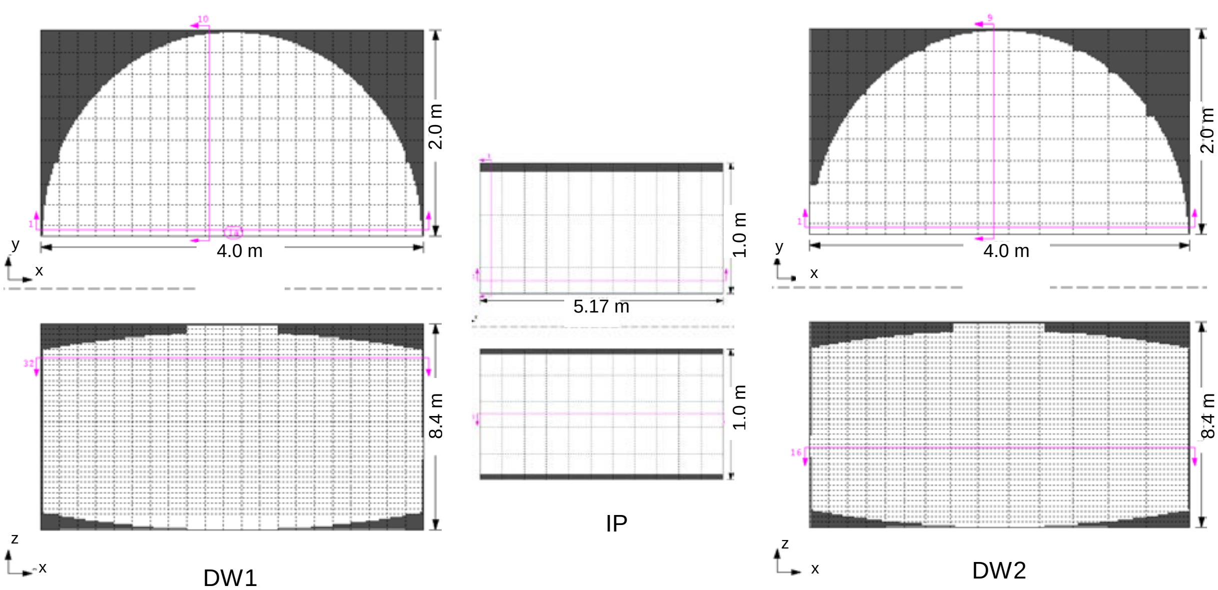


Figure 2 GOTHIC subdivided volume grids for DW1, DW2 and IP

4. Results

The initial condition for the simulations was defined as per the foreseen thermal-hydraulic conditions at the end of Phase III (vessel pressure of 250 kPa and uniform gas/wall temperatures of 140°C). The gas and wall temperatures are purposely set 20°C above the saturation temperature (120°C for 80% steam). The purpose is to eliminate wall condensation during the spray operation in order to simplify the complex process involving mass and heat transfer between the droplets and gas and wall. The vessels are filled with steam, helium and air, with a helium-rich layer in the top of the DW1. In the DW1, there is 10% He and 70% steam above the elevation of the IP (3.8 m), 50% steam and no helium below the IP (2.8 m), and 80% steam (saturated) in-between. In the DW2, there is 70% steam above 2.8 m and 50% steam below 2.8 m. In the IP, there is 70% steam.

Heat removal by spray and the associated steam condensation are governed by such factors as spray temperature, supply rate, nozzle geometry and location, initial droplet size and shape distribution, spray droplet velocities, as well as thermal-hydraulic conditions of the atmosphere. For the current study, the sensitive parameters are focused on the spray flow rate and temperature as well as height. A spray flow rate of 0.54, 0.72, or 1.0 kg/s is used, which corresponds to an initial droplet diameter of 900, 700, or 500 μm (close to the measured Sauter Mean Diameter), and initial droplet velocity of 17, 22 or 31 m/s respectively. The spray temperature is varied between 30 and 70°C. A spray injection height of 7 m is always used unless otherwise stated. These parameters, particularly the flow rates normalized by the vessels volume and the injection height normalized by the facility height, are relevant to that of a real containment. For example, the normalized spray injection rate is ~0.004 kg/s-m^3 and the injection height ratio is ~0.8 for a PWR 1300 design.

4.1 Reference Case (T_{spray}=40°C, m_{spray}=0.72 kg/s)

The time histories of pressure, condensate, hydrogen and steam volume fractions along the vertical axis of DW1 for a spray temperature of 40°C and flow rate of 0.72 kg/s are shown in Figure 3. The pressure (Figure 3a) starts to decrease immediately after the activation of the spray. The depressurization rate is the largest at the beginning of the transient and quickly decreases after the first 100 s. The condensate mass (Figure 3b) is the total liquid mass excluding the injected mass of spray. The condensation rate reaches its peak (0.077 kg/s) at ~30 s. During the early stage of the transient (10-20 s, see Figure 3c), the helium concentration slightly increases between the elevation of the IP (3.8 m) and spray (7 m). This is attributed to the steam condensation and gas entrainment from the top and side. As well, the helium concentration below 1 m increases to ~5% by 10 s. At ~220 s, the helium is well mixed below the spray. Above the spray, the thickness of the helium layer gradually decreases from 10 to 400 s. At ~1300 s, the helium concentration is uniform at 6.5% (±0.1%) along the entire height of the DW1, indicating that the helium layer has been completely eroded. At the beginning of the steam transient (Figure 3d), the steam concentration increases to ~65% below 2.8 m and decreases between 2.8 and 3.8 m (elevation of the IP) due to the mixing induced by the spray. Up to 100 s, the steam concentration is almost uniformly mixed below 6 m and it keeps decreasing with more spray injected due to steam condensation. Above the spray, only half of the height (between the spray and the ceiling) show a decrease in steam concentration, which appears to be a stable stratification with higher steam concentration. This is mainly because the temperature of the upper vessel wall remains high (pre-heated).

Figure 4 shows contour plots of helium and steam volume fractions and density at 100 and 1500 s. The general features are consistent with that observed in Figure 3. At 100 s, the helium and steam is almost uniformly mixed below the spray (7 m) and the helium layer has moved up to 7.5 m in the DW1. The steam distribution displays no significant change in the DW2. In the IP, a counter-current flow is observed. In the lower portion of the IP, the flow (~0.2 m/s) moves from the DW2 to DW1, driven by the pressure difference due to depressurisation. The return flow (~0.1 m/s) from the DW1 to DW2 through the upper portion of the IP is driven by the density difference (the density above the elevation of the IP in DW1 is slightly higher than that in DW2 due to steam condensation). The cross flow directions are reversed by 1500 s. With more spray being injected, the gas density in the lower region of the DW1 becomes larger than that of the DW2. As a result, the heavier mixture in the DW1 starts to migrate to the DW2 through the lower portion of the IP and moves (~0.3 m/s) downward in the DW2. On the other hand, the return flow (~0.3 m/s), driven by pressure difference, transports from the DW2 to DW1 though the upper portion of the IP and continues to move upward (the density of the return flow is smaller due to higher steam concentration and temperature). At 1500 s, the helium layer in the DW1 has been completely eroded.

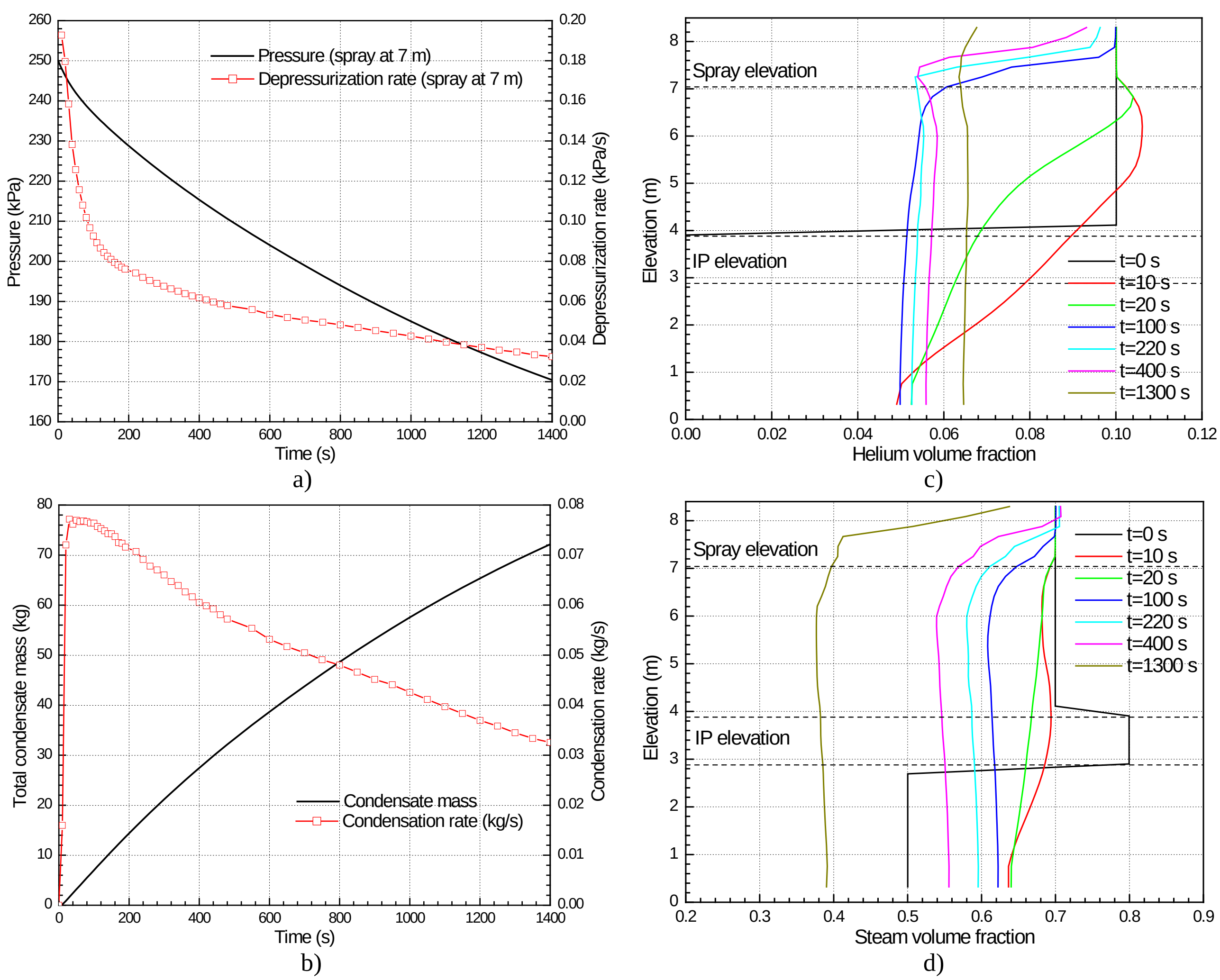


Figure 3 Time histories of pressure (a), condensate (b), hydrogen (c) and steam (d) volume fractions in DW1 (T_{spray}=40°C and m_{spray}=0.72 kg/s)

4.2 Effect of Spray Temperature and Flow Rate

Based on the reference case discussed above, several simulations were performed to examine the effect of spray water temperature and injection flow rate on depressurization and the break-up of the helium layer. Figure 5 compares the time histories of pressures and condensations rates for the spray temperature varied from 30 to 70 °C and the spray flow rates from 0.54 to 1.0 kg/s. As expected, GOTHIC predicts that the pressure decays faster and the maximum condensation rate is larger with a higher mass flow rate at a given spray temperature and for a lower spray temperature at a given spray mass flow rate. A spray temperature of 70°C with a flow rate of 1.0 kg/s results in almost the same depressurization and condensation rate as a spray temperature of 60°C with a flow rate of 0.72 kg/s, indicating that the total heat transferred between the spray and the gas mixture is similar for both cases.

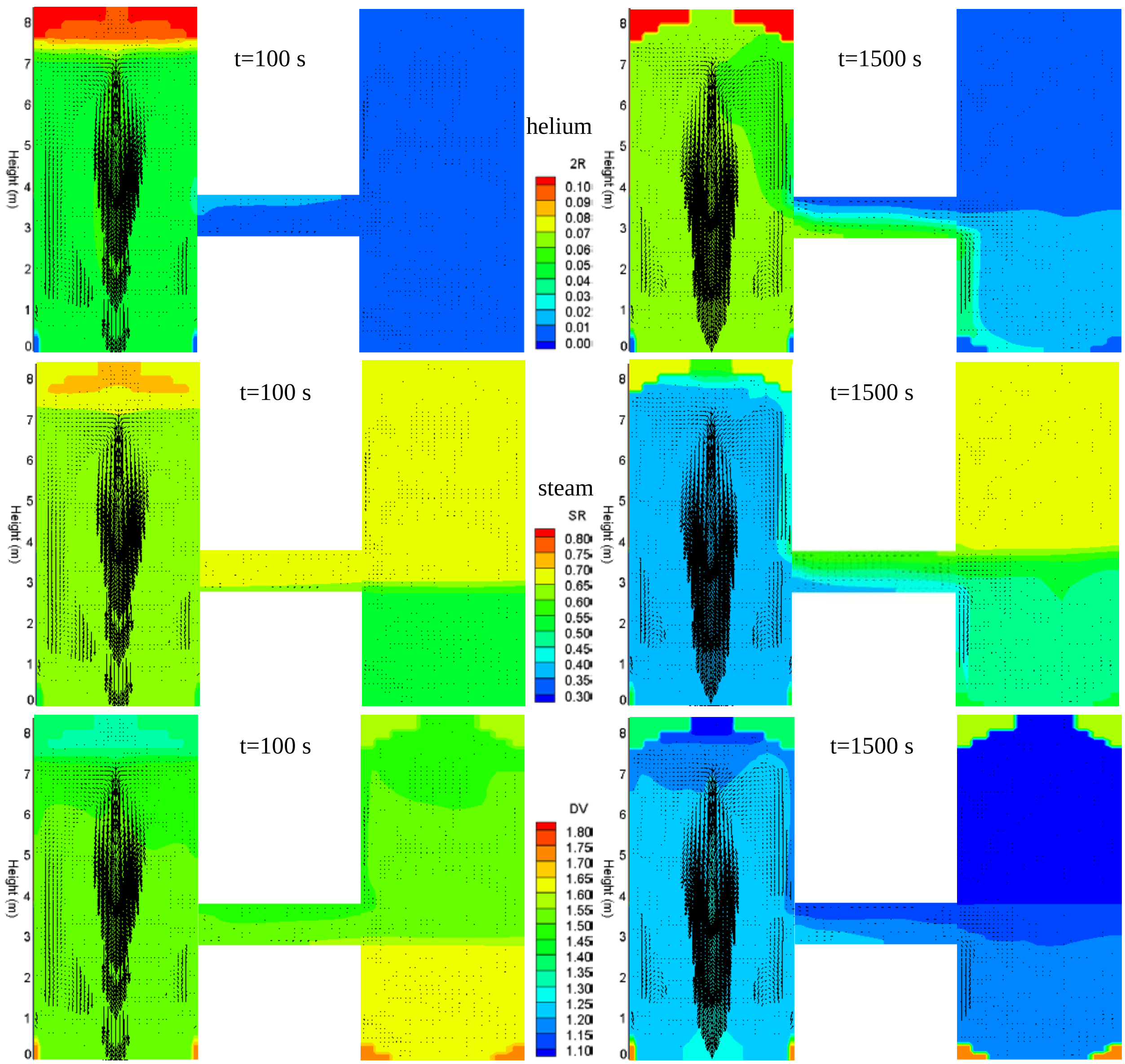


Figure 4 Contour plots of helium and steam volume fractions and gas mixture density (kg/m^3) distribution at 100 and 1500 s (Reference Case: T_{spray}=40°C and m_{spray}=0.72 kg/s); Note the corner regions are blocked cells and they remain at the initial values corresponding to their neighbor cells

The effect of spray temperature and flow rate on gas mixing is shown in Figure 6 (T_{spray}=60°C and m_{spray}=0.72 kg/s) and Figure 7 (T_{spray}=40°C and m_{spray}=0.54 kg/s). The general trends of helium and steam transients of these two cases are similar to the reference case (Figure 3c and d). With the increase in the spray temperature from 40 to 60°C for the flow rate of 0.72 kg/s (Figure 3 vs. Figure 6), the time for the helium to be well mixed in the DW1 is almost the same (~1300 s) except the final average helium concentration is slightly smaller for the spray temperature of 60°C due to higher steam

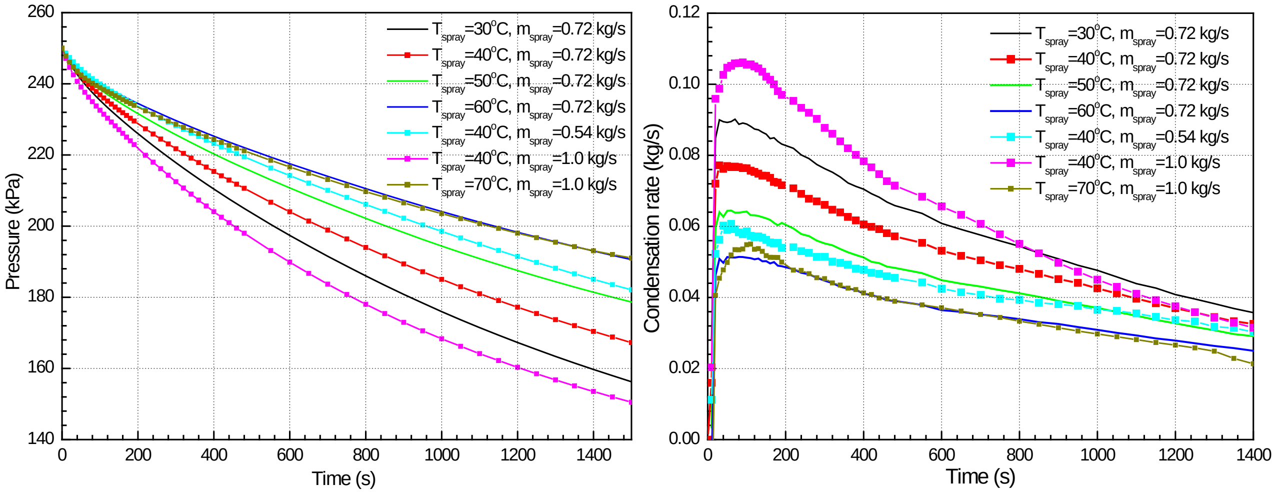


Figure 5 Effect of spray temperature and flow rate on depressurization and condensation

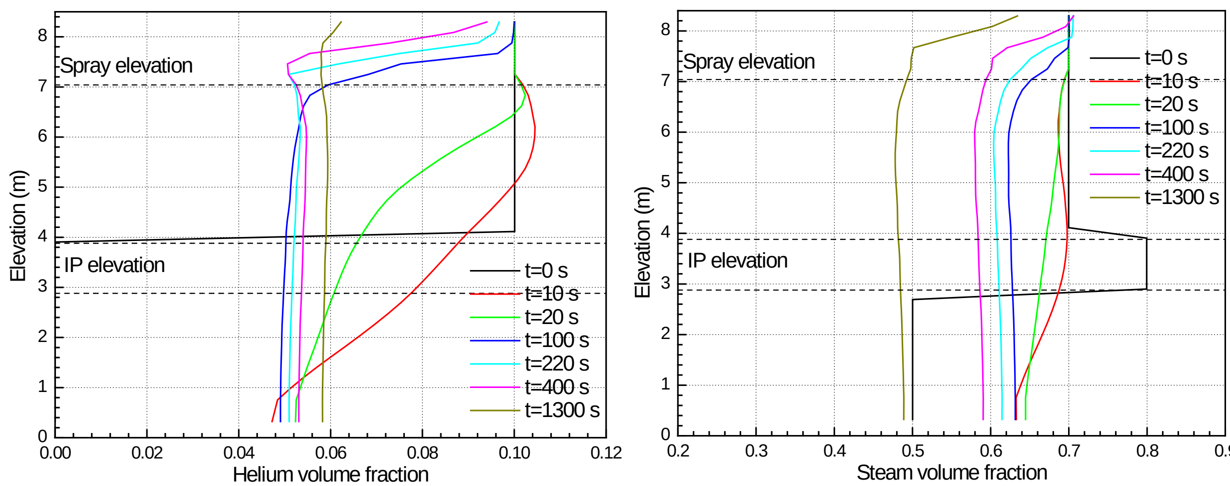


Figure 6 Time histories of hydrogen and steam volume fractions along the vertical axis of DW1 (T_{spray}=60°C and m_{spray}=0.72 kg/s)

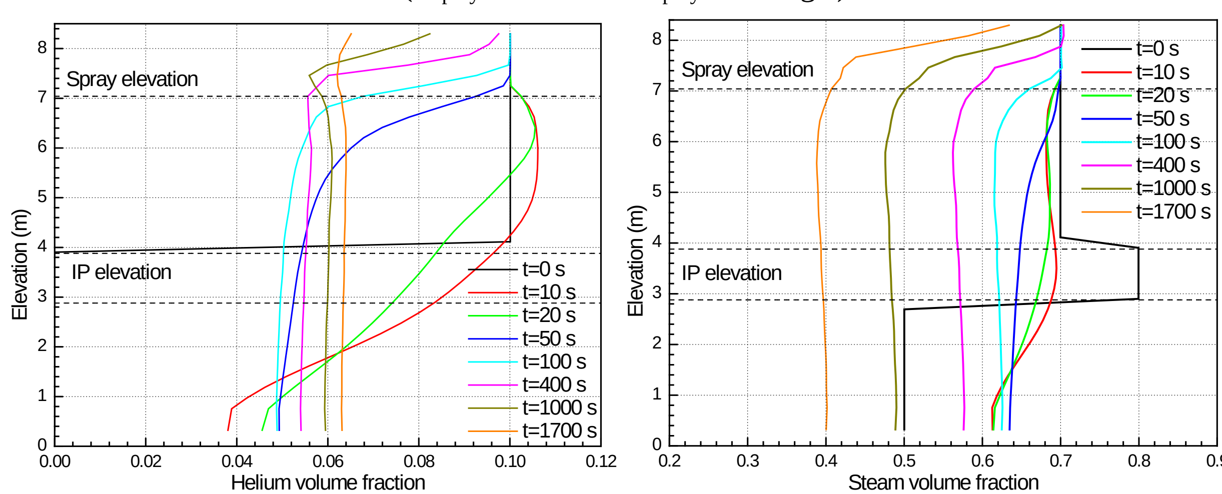


Figure 7 Time histories of hydrogen and steam volume fractions along the vertical axis of DW1 (T_{spray}=40°C and m_{spray}=0.54 kg/s)

concentration (lower condensation rate). With the decrease in the flow rate from 0.72 to 0.54 kg/s for the spray temperature of 40°C, the helium concentration near the bottom of the DW1 is much higher for the higher flow rate at 10 and 20 s, showing that the stronger downward flow is more effective in transporting helium early in the transient. For the flow rate of 0.54 kg/s, the helium is nearly well mixed till 1700 s, indicating a slower erosion process, and the average steam concentration decreases slower due to slower steam condensation.

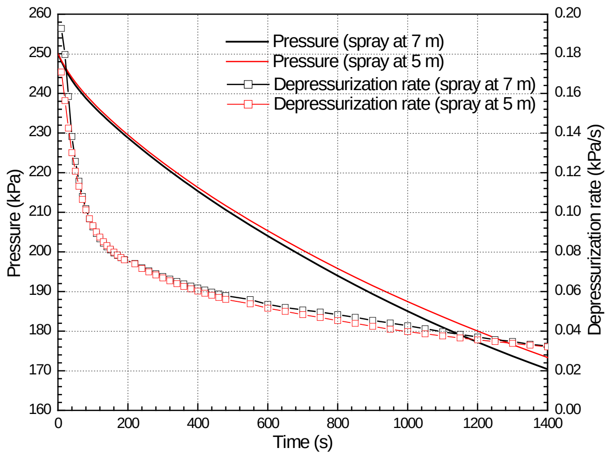
4.3 Effect of Spray Injection Height

To examine the sensitivity of spray injection height on depressurization and the break-up of the helium layer, one simulation case was performed by relocating the spray nozzle from 7 to 5 m and the other parameters remain the same as the base case. The time histories of its pressure, condensate, hydrogen and steam volume fractions along the vertical axis of the DW1 are shown in Figure 8. The pressure (Figure 8a) and condensation rate (Figure 8b) follow the same trends as the reference case, but the pressure, with the spray at 5 m, is slightly larger and the condensation rate is slightly smaller at any given time. For the helium and steam concentrations, the transients are similar below the spray injection. With the spray at 5 m, the helium is almost well mixed below the spray injection at ~400 s. However, the erosion for the helium layer above the spray injection is much slower. The steam and helium concentrations remain fairly constant above 7.5 m up till 3000 s, suggesting a much slower erosion process, as would be expected, because the helium-rich layer above the spray is much thicker than in the reference case.

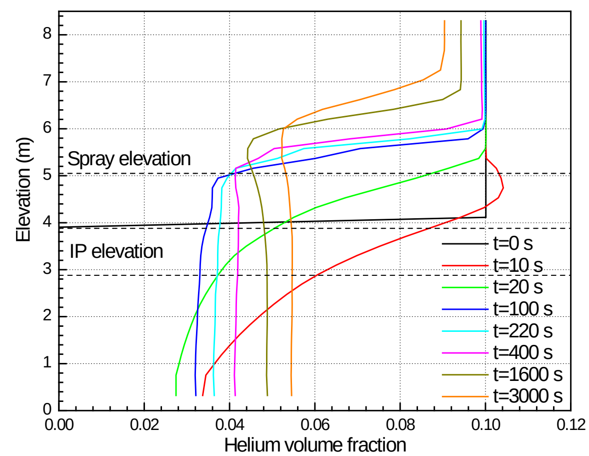
The contour plots of helium and steam volume fractions and density at 100 and 1500 s for the spray at 5 m are shown in Figure 9. At 100 s, the helium is almost well mixed below the spray (5 m) except the region near the entrance of the IP, where the helium is diluted by the steam-air mixture transported from the DW2. Above the spray in the DW1, the helium concentration remains fairly constant and the helium rich layer moves up to ~6.5 m at 1500 s. In the DW2, the mixture composition is nearly uniform above the elevation of the IP. The transport behaviour in the IP is slightly different from the reference case (spray at 7 m early in the transient. Before 100 s, the flow (~0.1 m/s), driven by the pressure difference, moves from the DW2 to DW1 through the upper portion of the DW1, and the counter current flow from the DW1 to DW2 is driven by the density difference and its velocity decreases. At 100 s, the flow from the DW1 to DW2 decreases to zero and no counter-current flow exits. A counter-current flow is re-established around 500 s and continues to the end of simulation. At 1500 s, the flow pattern is the same as before 100 s, but with a much higher flow velocity (~0.3 m/s).

5. Conclusion

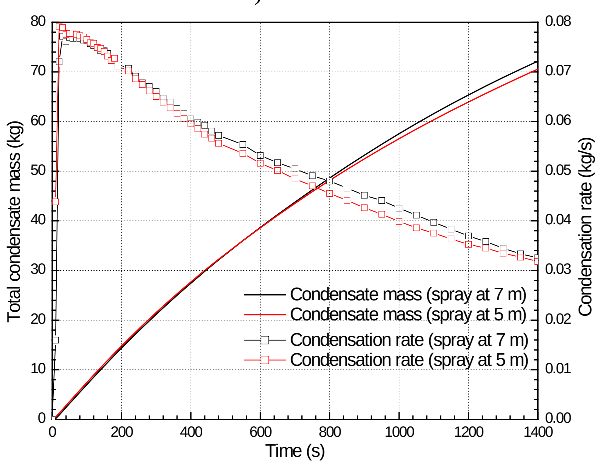
Numerical analyses were performed in the framework of the ERCOSAM-SAMARA project to determine sensitivity parameters that affect the effectiveness of spray system on depressurization and break-up/erosion of a helium layer. The results have shown that a higher spray temperature or a smaller spray injection flow rate can reduce the condensation rate, thus leading to slower depressurization. The spray temperature has negligible effect on the erosion speed of a helium layer, but a higher spray flow rate can reduce the mixing time significantly. The spray injection height has no significant effect on the depressurization and condensation rate, but it has a significant impact on the time needed to completely break up a helium layer above the spray nozzle. The effective mixing region above the spray is limited to less than ~2 m, but the mixture below the spray can always be well mixed regardless of the spray elevation. At this point, no conclusion can be made about the exact behaviour of spray system in a real containment, mainly due to relative height-scaling questions (spray height vs. containment height), which remain open. This will be addressed in the final phase of the project (synthesis of experimental and analytical work), when the experimental results from all facilities are available and the capability of the codes to reproduce the phenomena at various scales is verified.



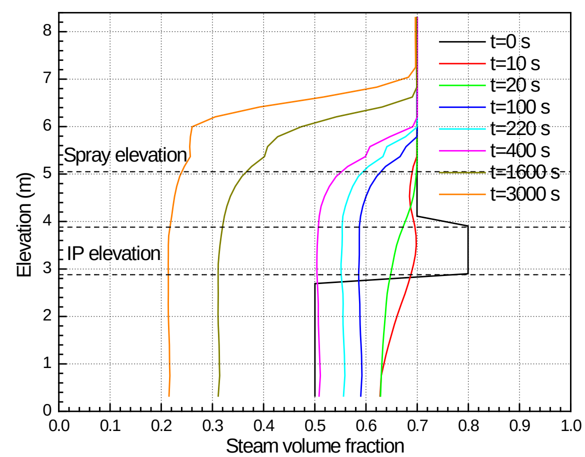
a) Pressure



c) Helium



b) Condensate



d) Steam

Figure 8 Time histories of pressure (a), condensate (b), hydrogen (c) and steam (d) volume fractions in DW1 (T_{spray}=40°C and m_{spray}=0.72 kg/s) for the spray nozzle at 5 m

Acknowledgements

The authors gratefully acknowledge the support of EUROATOM (grant # 249691) and ROSATOM as well as all the international organizations participating in ERCOSAM-SAMARA project.

6. References

[1] D. Paladino, et al., "The EURATOM-ROSATOM ERCOSAM-SAMARA Projects on Containment Thermal-hydraulics of current and future LWRs for Severe Accident Management", ICAPP 2012, Paper 12325, Chicago, USA.

[2] D. Paladino, R. Zboray, P. Benz and M. Andreani, "Three-Gas Mixture Plume Inducing Mixing and Stratification in a Multi-Compartment Containment", *Nuclear Engineering and Design*, Vol. 240, p. 210-220, 2010

[3] R. Zboray and D. Paladino, "Experiments on Basic Thermalhydraulic Phenomena Relevant for LWR Containments: Gas Mixing and Transport by Buoyant Jets in a Multi-Compartment Geometry", *Nuclear Engineering and Design*, Vol. 240, p. 3158-3169, 2010

[4] M. Andreani, D. Paladino and T. George, "Simulation of Basic Gas Mixing Tests with Condensation in the PANDA Facility Using the GOTHIC Code", *Nuclear Engineering and Design*, Vol. 240, p. 1528-1547, 2010

[5] M. Andreani and N. Erkan, "Analysis of Spray Tests in a Multi-Compartment Geometry Using GOTHIC Code", Proceedings of the 18th International Conference on Nuclear Engineering, ICONE 18, Xi'an, China, May, 2010

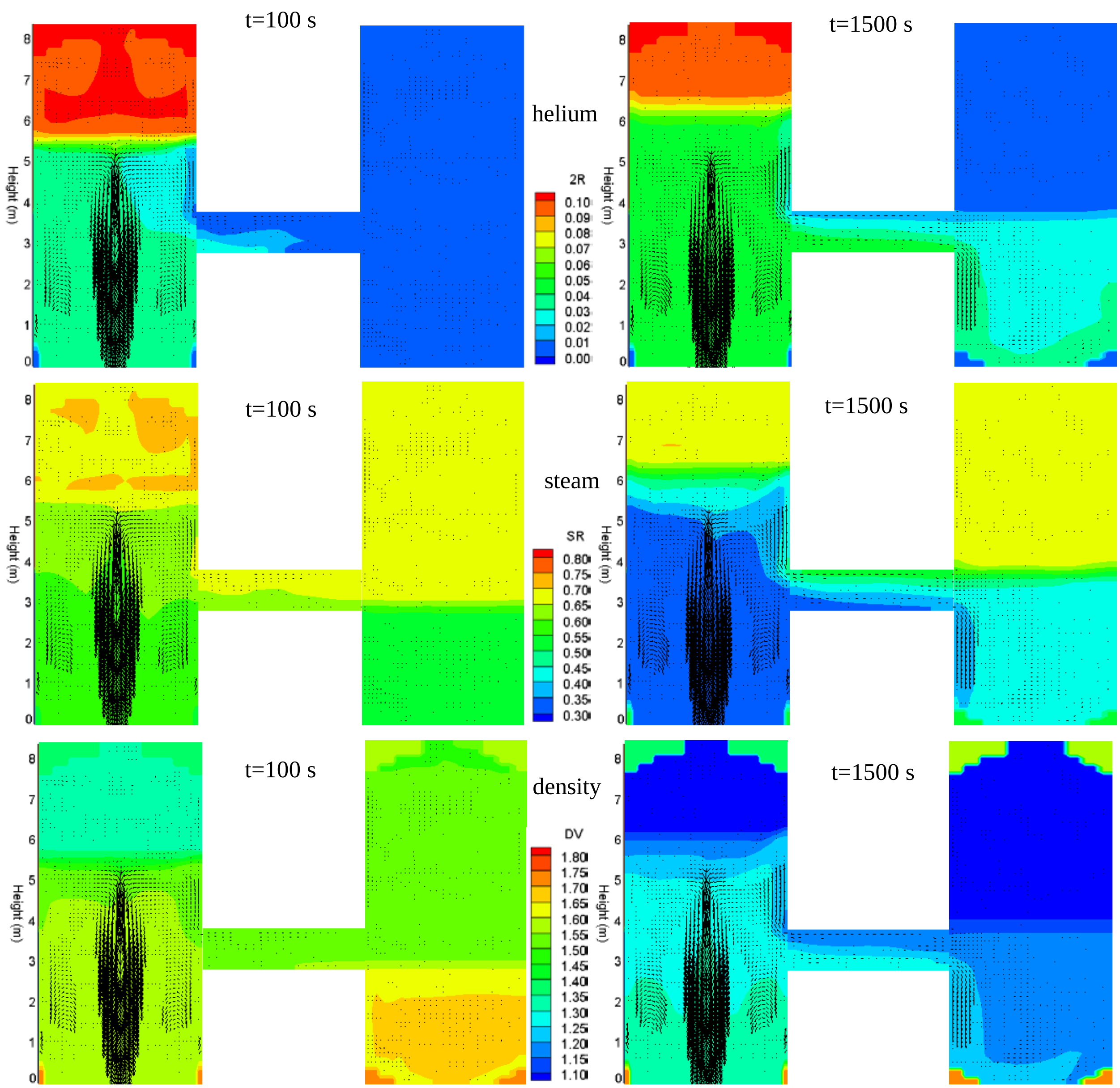


Figure 9 Contour plots of helium and steam volume fractions and gas mixture density (kg/m^3) distribution at 100 and 1500 s (T_{spray}=40°C, m_{spray}=0.72 kg/s) for the spray nozzle at 5 m elevation (Note: The corner regions are blocked cells and they remain at the initial (fictional) values corresponding to their neighbor cells.)