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APPLICATION OF COCOSYS CODE FOR INVESTIGATION OF GAS MIXING IN MISTRA TEST FACILITY

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ABSTRACT

In the case of a severe accident in a water-cooled nuclear power plant large amounts of hydrogen could be generated due to fuel claddings oxidation and released to the containment. At certain concentrations of steam air and hydrogen the hydrogen combustion could occur and challenge the structural integrity of the containment, which is a last barrier preventing from radioactive material release to the environment. Therefore, a detailed knowledge of containment thermal-hydraulics is necessary to predict the local distribution of hydrogen, steam and air inside the containment. This paper presents the experience of Lithuanian Energy Institute in simulation of the experiments performed in MISTRA test facility for the case of the International Standard Problem ISP47. The MISTRA facility is located in the Saclay center of France Atomic Energy Commissariat (CEA) and is related to the research of containment thermal-hydraulics and hydrogen safety. The MISTRA facility and its operating conditions are designed with reference to the containment conditions of a pressurized water reactor (PWR) in accident situation. The facility comprises containment inside which three condensers are set up and external circuits. Containment volume is ~100 m3, with an internal diameter of 4.25 m and a height of 7.3 m. Containment is not temperature regulated, but preheated by steam condensation and thermally insulated. The relevant physical phenomena for simulation are the following: 1)centered steam and helium (instead of hydrogen) injection in the containment; 2) pressure and temperature increase in the containment; 3) wall condensation at regulated wall temperature; and 4) flow pattern in the containment and resulting gas temperature and concentration distribution. Test sequence consisted of several transient and steady state stages, when the measurements of the gas temperature and gas concentration profiles where performed. The presented analyses were performed employing the code COCOSYS versions V2.0v2 and V2.3 developed at GRS mbH (Germany). COCOSYS is a lumped-parameter code for the comprehensive simulation of all relevant phenomena, processes and plant states during severe accidents in the containment of light water reactors. The free convection, forced convection, radiation heat transfer and condensation may be considered in the analysis. The condensation model is based on the heat and mass transfer analogy (Stefan’s law). The water and gas flows are calculated separately, i.e. different junctions have to be specified for these flows. Several zone models could be selected by the user. The EQUIL._MOD zone model assumes the perfect steam, gas and water mixture inside a zone. Each component of the mixture is in thermal equilibrium. NONEQUILIB model considers the water and gas mixture, which is not necessarily in thermal equilibrium, i.e. water and gas may have different temperatures and calculated separately in the energy balance. The experimental and analytical analyses showed that gas stratification was not observed and well-mixed atmosphere conditions were reached for the investigated case.

INTRODUCTION

The MISTRA test for ISP 47 [1] proposes experimental values for the modeling of an accidental sequence in a nuclear plant, focused on the hydrogen risk (simulated with helium). In the event of a break in the reactor coolant system, a large release of steam into the containment leads to a containment pressure increase and to simultaneous steam condensation on the concrete walls. It can be followed by a release of hydrogen resulting from the fuel cladding oxidation. Hydrogen concentration may locally reach values, beyond which deflagration or detonation may occur, thus threatening the containment integrity.

The test proposed for the ISP 47 is a coupled effect test that aims at reproducing the main phenomena occurring in an accidental situation relevant for hydrogen risk and in appropriate operating conditions. The simplified sequence is decomposed into four successive phases:

1. Preheating phase: steam injection in the containment initially full of air at normal temperature and pressure conditions in order to heat up the steel structures.
2. Air/Steam steady state: defined from the equilibrium between the injected and the condensed steam mass flow rate on temperature controlled walls.
3. Air/Steam/Helium transient: transient injection of Steam and Helium.
4. Air/Steam/Helium steady state: defined from the equilibrium between the injected and the condensed steam mass flow rate on temperature controlled walls

The objective of this test is to assess the modeling of MISTRA containment atmosphere mixing. Relevant phenomena for the modeling are the following:

- Centered steam and helium injection in the containment,
- Pressure and temperature increase in the containment,
- Wall condensation at regulated wall temperature for turbulent flow,
- Flow pattern in the containment and resulting gas temperature and concentration distribution.

MISTRA TEST FACILITY AND THE EXPERIMENT

The facility comprises containment inside which three condensers are set up and external circuits (Figure 1).

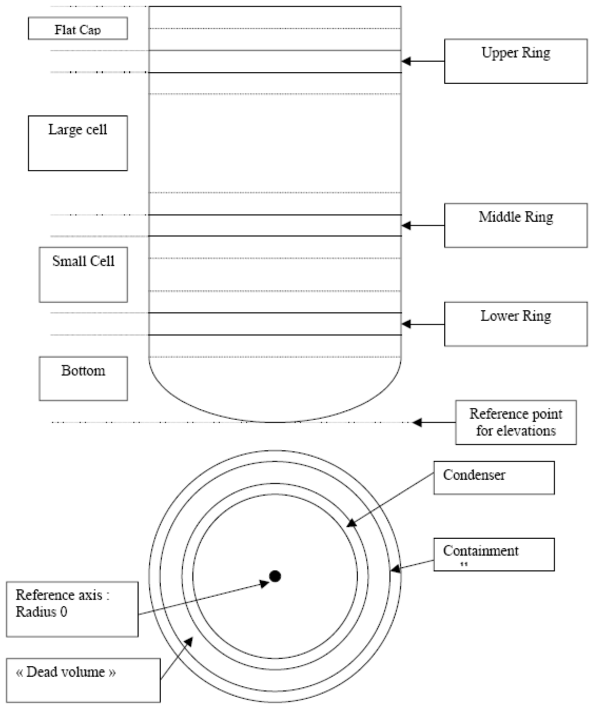

Figure 1 Schematic view of MISTRA facility

The containment

The main characteristics of the containment are the following:

- a volume of about 99.5 m^3, with an internal diameter 4.25 m and a height of 7.38 m;
- stainless steel surfaces : about 118 m² distributed as follow – 14 m² for the ceiling, 75 m² for the side walls (without flanges), 13 m² for the flanges and 16 m² for the bottom;
- stainless steel wall thickness: 0.015 m for the side walls, 0.025 m for the bottom, 0.110 m for the flanges and 0.119 m for the ceiling. This last value is an equivalent thickness due to the presence of many stiffeners.
- total mass of stainless steel: about 40 tons;
- external thermal insulation: 0.2 m of rock wool.

Built in stainless steel, the containment comprises 2 cells, a flat cap and a bottom, that are fixed together with twin flanges. The containment is not temperature regulated, but preheated by steam condensation. First experimental results have proved the insulation to be fairly good, since after the preheating phase, the wall temperatures are similar to gas temperature. Nonetheless, spurious steam condensation occurs during the test due to heat losses.

The condensers

Three condensers are inserted inside the containment and placed along the walls. Each condenser, consisting of vertical pipes, is fitted together into 24 elementary cells and has its own regulation circuit. The inlet cooling water is provided through an external and then an internal collector, and feeds each elementary cell. Inversely, the outlet water is collected from the elementary cells to an internal and then an external collector. This is specially designed to ensure the most stable and uniform condenser wall temperature: the maximum outside / inside temperature deviation is lower than 2 °C. The external part of the condensers is insulated with 2 cm of synthetic foam to prevent any condensation. The three condensers are drilled with 4 viewing windows for laser diagnostic, and separated by gutters which collect the condensate. Each gutter is made from stainless steel and divided into 4 elementary parts, with a slope of 2 %. Gutters partially mask the free space between the condensers. The total condensing area is about 69 m^2 divided into 1) lower condenser: 26.2 m^2; 2) medium condenser: 21.4 m^2; 3) upper condenser: 21.4 m^2. The non-condensing area composed of gutters and the 12 viewing windows is about 5% of the total condensing area. The outer thermal insulation of condensers is 0.02 m of synthetic foam.

There is a so-called “dead volume” situated between the condensers and facility wall. It represents about 13 % of the total free volume of the containment.

The injection nozzle

A diffusion cone fitted with a removable cap is designed for gas injection and steam/helium mixing with the injection diameter D_{inj} = 200 mm. It also ensures a flat velocity profile at the injection nozzle. It is set up in the bottom of the containment, along the central axis (the diffusion cone may be set-up at an off-centered location for tests other than ISP47). An additional steam line is also present in the bottom of the containment, but is only used for the containment wall heating: a ring with four nozzles directed towards the “dead volume”, and four nozzles directed towards the containment bottom.

The external circuits

Steam and gas (helium or other gases) are injected through two different circuits, and then mixed through the main injection nozzle inside the containment. The two lines are fitted with their own heaters. In all cases, the flow rates are controlled and measured with sonic nozzles that ensure a constant flow rate independently of the downward operating conditions. Three different circuits are built for the condensers thermal regulation. The condensed steam is collected in six circuits: 1) three circuits for the condensers, in order to set up the local mass balance, and 2) three circuits to control the occurrence of condensation on the containment walls, on the containment bottom and on the condenser's insulated external part. It should be noticed that for this test, all the condensed water is continuously evacuated, and no sump is simulated.

MISTRA Instrumentation

The measurements performed in MISTRA are related to pressure, temperature, steam and gas composition, velocity and condensed mass flow rate. They are all simultaneously and continuously recorded, all over the tests, excepted for gas concentration that proceeds with successive samplings.

Table 1 Summary of MISTRA instrumentation

Measurement type	Experimental technology	Location	Number of sensors
Pressure	Absolute Differential	Gas Gas (dead volume)	2
Velocity	Vane wheel LDV	Gas Gas	1 or 2 operating 12 viewing windows
Temperature	Thermocouple (cromel alumel)	Gas volume Sump Condensing wall Containment wall	57 5 108 102
Gas composition	Simultaneous sampling then analysis by mass spectrometry	Gas	53
Condensed steam flow rate	Continuous mass flow rate measurement Differential pressure measurement	Condensers + sump Wall containment	4 2

In the MISTRA facility, the instrumentation is located on 3 vertical half-planes (105°, 225° and 345°C). Measurements are also located in the so-called "dead volume" behind the 3 condensers and on the outer faces of the condensers (insulated face).

As the tests are dealing with axially centered flows, most of the sensors are set up in the reference plane (345°) in order to locate each physical phenomenon. The reference plane is a vertical grid with 10 heights: the condensing zone lies in the range 1285 mm < z < 7280 mm, with three gutters at z = 5495 mm; z = 3592 mm; z = 1285 mm, and injection diameter at z = 1285 mm. It is radially cut with 5 radii corresponding to different fractions of the containment internal radius: R0 = 0; R1 (=R/4) = 475 mm; R2 (=R/2) = 950 mm; R3 (=3R/4) = 1425 mm; and at 8 cm from the wall for R4 = 1815 mm.

A special attention has been paid for setting up instrumentation radially near the walls (one radius at 8 cm from the condensing wall) and axially near the injection device. Away from these areas, the sensors are uniformly distributed. Therefore the maximal distance between two sensors is less than 1 meter axially and 0.5 m radially.

Pressure is measured with membrane sensor with a precision of 0.1 % full scale. The sonic nozzle is designed according to the norm ISO 9300, and the upward pressure and temperature are regulated, so that the measurement uncertainty is estimated at 2%. Temperatures are measured with thermocouples (type K) with a calibration procedure for 4 points between 20 °C and 200 °C so that the uncertainty is improved to 0.2 °C. Condensates are quantified with continuous measurement using PROMASS mass flow meter, with an uncertainty of 0.5% full scale.

The experiment

The test is a simplified accidental sequence simulating steam and hydrogen release in the containment. It proceeds into successive phases, the two first ones being relevant for the experimental process such as the containment heating then the condensers cooling, the last ones being relevant for the physical phenomena simulation.

After the two first phases, a constant steam mass flow rate is injected all over the test, and the three condensers are wall temperature regulated at the same average temperature. A first steady state is reached, and then helium is injected for a limited time, superposed to the steam injection. In the final step, a second steady state is studied for steam injection in air/helium/steam flow.

Test facility initially is filled with air at pressure of 1 bar and temperature of 20 °C. The initial mass of air in the facility is 118 kg.

1st phase: 0 s < t < 11300 s

Heating of the containment and the condensers. This phase is dedicated to the containment wall heating, since their temperature is not directly regulated. Containment walls are heated by steam injection and condensation. Two steam injection lines are used: the central one with diameter D = 0.2 m and the second one directed to the "dead volume" and the containment bottom. To limit the condensation on the condensers, they are heated too, using water that is progressively heated with the heaters of the three external circuits.

Operating conditions of the phase: steam injection trough central line 0.092 kg/s, through the "dead volume" line 0.048 kg/s.

Condensers rate of heating is about 0.7 °C/min, initial temperature T_0 = 24°C, final temperature T = 134°C.

2nd phase: 11250 s < t < 12630 s

Cooling of the condensers. After the preheating, condensers are cooled from T = 134 °C to their nominal temperature: 115 °C. This process insures the breaking of thermal and mass stratification at the end of the heating phase, thanks to the fast pressure decrease in the containment. During this phase there is no steam injection.

Final average temperature for the three condensers:

Lower condenser – T = 115°C +/- 0.9°C
Medium condenser – T = 115°C +/- 0.7°C
Upper condenser – T = 115°C +/- 1°C

3rd phase: 12630 s < t < 28835 s

Steam injection and condensation. This phase is dedicated to the physical study of air/steam flow with condensation on the regulated wall temperature in steady state.

After the containment heating and the condensers cooling phase, steam is injected again, but only using the main line (centered injection). The steady state is defined by the equilibrium between the injected mass flow rate and the condensed mass flow rate on the structures, likewise the stability of all the parameters: pressure, temperature and air/steam concentration.

The so called parasite condensed flow rate fraction is about 12 % of the total condensed flow rate.

4th phase: 28835 s < t < 30575 s

Steam and helium injection with condensation. This phase follows the 3rd phase without stopping the steam injection, and in the same operating conditions. Helium injection is therefore superposed to steam injection, so that a helium/steam mixture is injected in the containment, through the injection nozzle. The main objective of this phase lies in the transient regime study, especially for the three components concentration distributions, till reaching a molar helium concentration of about 30% meaning to a total helium mass of 18.5 kg. The condensers are still thermally regulated at their nominal temperature.

5th phase: 30575 s < t

Steam injection with condensation in a steam/air/helium mixture. Steam injection is still on, with the same operating conditions, but helium injection is stopped. This phase is dedicated to the mixing of helium in the containment, after helium injection, and for a steam injected flow and condensation on the condensers at regulated wall temperature. A steady state is obtained for pressure, and temperature stability as well as for the mass balance.

MISTRA NODALISATION FOR COCOSYS CODE

COCOSYS code

The analysis was performed employing the code COCOSYS code versions V2.0v2 and V2.3 developed at GRS mbH (Germany). This code was transferred to Lithuanian Energy Institute in the frame of bilateral contracts sponsored by German government. COCOSYS (Containment Code System) is a lumped-parameter code for the comprehensive simulation of all relevant phenomena, processes and plant states during severe accidents in the containment of light water reactors, also covering the design basis accidents (DBAs) [2]. The free convection, forced convection, radiation heat transfer and condensation may be considered in the analysis with COCOSYS. The condensation model is based on the heat and mass transfer analogy (Stefan's law). The water and gas flows are calculated separately, i.e. different junctions have to be specified for these flows. COCOSYS code includes models of several engineering systems, e.g. spray, heat exchanger, pump, etc. Special condensing pool model (DRASYS) is available, which allows considering the vent-clearing, pool swell and condensation oscillations phases of the accident. The EQUIL._MOD zone model assumes the perfect steam, gas and water mixture inside a zone. Each component of the mixture is in thermal equilibrium. NONEQUILIB model considers the water and gas mixture, which is not necessarily in thermal equilibrium, i.e. water and gas may have different temperatures and calculated separately in the energy balance. The thermodynamic property tables for water, steam, air and several other gaseous components are included in the code by the code developers.

The computer code COCOSYS is able to evaluate the following phenomena related to ISP 47 tasks:

- pressure and temperature build-up and history,
- local temperature and pressure distributions,
- energy distribution and local heat transfer to and heat conduction in structures,
- local gas distributions (steam and different non-condensable gases),
- water distribution,
- mass and volume flow for the release of fluids via openings and leakage.

Calculations can be performed for simple and multi-compartmented containments and closed buildings of NPPs, as well as for compartmentalized systems (buildings, tunnels, pit system), with more or less large openings to the environment. Mainly, the consequences of DBAs and severe accidents were analyzed with the code in containments of LWRs i.e., for PWRs and BWRs but also in containments of VVER power plants.

For the description of the physical processes during an accident, arbitrary compartment systems and geometries can be simulated by specified volumes (the lumped-parameter concept). The conditional changes related to location and time are reduced to a purely time-dependent behavior within the control volumes (nodes). These volumes are connected by junctions. For the simulation of heat transfer and heat conduction via walls and internal components, specified structures can be coupled to the nodes. The heat conduction is described in one dimension for the simulation of heat transfer processes (heat and mass transfer); different models and correlations are available.

For the determination of the conditions in the nodes the following assumptions have been made:

- water is considered as a vapor or liquid (water) or both according to the conditions in the node. Superheated as well as saturated conditions are possible. Superheated atmospheres cannot contain water. In these cases, the water is drained immediately into the sump or distributed to other nodes;

- the gaseous components are assumed to be homogeneously mixed. Having the same temperature, they are in thermal equilibrium;
- for the drainage of water to other nodes, the water is assumed to be deposited on the floor;
- in the non-equilibrium model, the deposited and airborne water is separately balanced. The temperature of the deposited water is calculated by an additional energy balance. In this zone model, the deposited water can be drained only. Airborne water is transported by the water carryover effect;
- the number of non-condensable gases is principally arbitrary. Seven different gases (air, O2, N2, H2, CO, CO2, He) are defined, including their material properties. These gases and steam are treated as real gases with a set of correlations for their properties, valid up to temperatures of 3000 K. Additional gases can be specified by the code user.

The mass transfer between nodes is described separately for gas and liquid flow by different momentum equations (unsteady, incompressible) taking into account geodetic height differences of the node centers. The mass flow rates of the different components are calculated without slip, according to the composition of the source node. Moreover, mass transfer by diffusion is considered.

The diffusion flow rate is calculated separately in a quasi-steady way for all gas components. For the simulation of heat and mass transfer between the zone atmosphere and the structures heat transfer is described by the different physical phenomena of free and forced convection, radiation (wall to gas, gas to wall, wall-gas-wall, wall to wall) and condensation depending on the thermal status of the zone and structures.

Heat conduction is described one dimensionally by a Fourier heat equation. Walls and other internals consisting of different materials can be represented in cylinder-type geometries. Such a wall, being denoted as a structure, can consist of several materials, arranged one after another. The different materials can be separated by air-filled gaps. Each material can be subdivided into an arbitrary number of layers of a different thickness for the calculation of the heat conduction. The arbitrary materials are defined by the values for heat conductivity, specific heat, and density.

For a realistic description of accident sequences, the simulation of engineered systems, such as pumps, heat exchangers, ventilation systems, weir, doors and flaps of different kinds with inertia effect, spray systems, catalytic and thermal recombiners and pressure suppression systems, which contain 1D hydrodynamic pool models, is possible.

MISTRA nodalisation

Results of calculations using two different nodalisation schemes are presented in the paper – original nodalisation (Figure 2), in which internal volume of the facility was split into 24 zones, and new, more detailed and improved nodalisation (Figure 3).

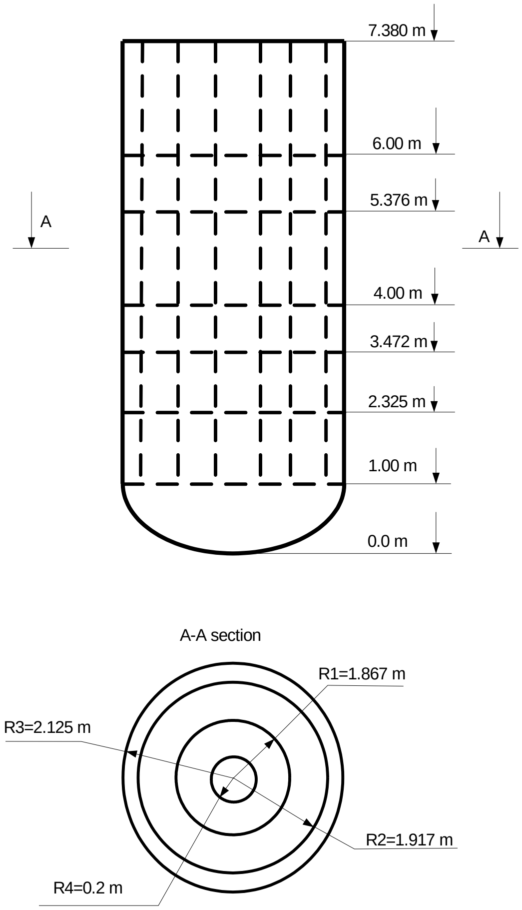

Figure 2 Scheme of an original MISTRA nodalisation scheme

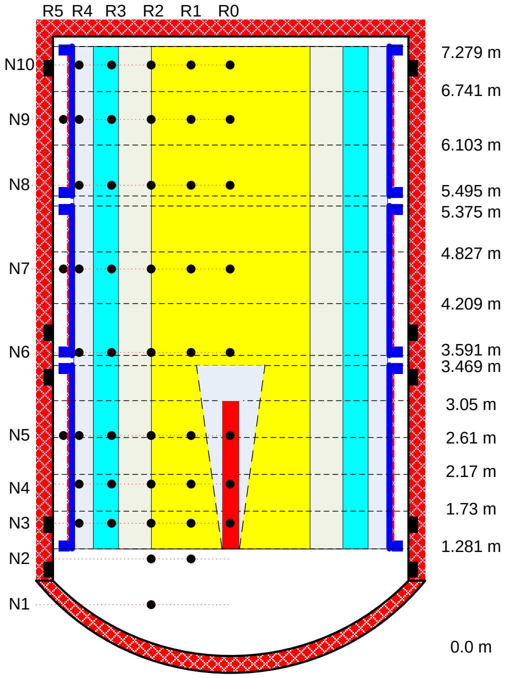

Figure 3 Scheme of an improved MISTRA nodalisation scheme (dots mark measurement points of the facility for reference)

In both schemes all zones are simulated using NONEQUILIB model. The sump is drained at the lowest point of the facility. Steam and helium injections were taken from the boundary conditions provided by ISP 47 team. The facility initially is assumed to be filled with air of 20 °C. As there was no specification on the initial humidity – 60 % saturation was assumed. Initial pressure in the facility – 1 bar.

The main differences between nodalisation schemes are:

- The number of zones (and, consequently, junctions). Original nodalisation scheme had 7 vertical levels and 4 radial subdivisions, resulting in 24 zones. Updated scheme has 15 vertical levels and 6 radial subdivisions, resulting in 89 zones. More detailed nodalisation is obtained by having additional vertical layers between and above condensers, also by subdividing height of condensers. One additional radial subdivision is added in the “dead-volume” and in the main volume. Radial subdivisions in the main volume are selected such, that cross-section areas of zones in the main volume are equal (for the improved nodalisation).
- In the original nodalisation the containment walls and the condenser surface covered with foam were not simulated. In the improved nodalisation all surfaces are modeled.
- Additional special zones for the jet injection are inserted in the updated nodalisation [3]. These zones form a truncated cone with 20° angle with the jet direction. Above the geometrical gas injection point the INJ zone is described. It has only one junction, at the top. Geometrical shape of this zone is cylinder. Additional INJ zones are added one on the top of another, all having junctions only at the bottom and top. INJ zones are surrounded by OUT zones. They have the form of upside down truncated cone, from which central cylinder (INJ zone) is cut out. The first OUT zone has two junctions – at the top and side. Higher OUT zones also have junctions at their bottoms, to a lower OUT zone. Injected gas is divided equally to lowest INJ and OUT zones. This division should correspond to radial distribution of steam mass in a real jet.
- The rate of temperature increase of condensers during the first phase was modified in the updated nodalisation to follow experimental values more closely (Figure 4).
- Since original nodalisation had no external walls and outer surface of condensers simulated, it could not predict spurious condensation on these surfaces. To account for it, injection mass flow used with this nodalisation was lowered according to mass flow rate of spurious condensation, given by ISP47 team. In the updated nodalisation scheme full injection mass flow rate is used (Figure 5).
- In the improved nodalisation some new, previously unavailable COCOSYS capabilities are used:
    - water flow along the walls (previously a chain of water junctions connecting walls and their coupled zones was used)
    - condensed water drops falling from the ceiling (previously unmodeled)

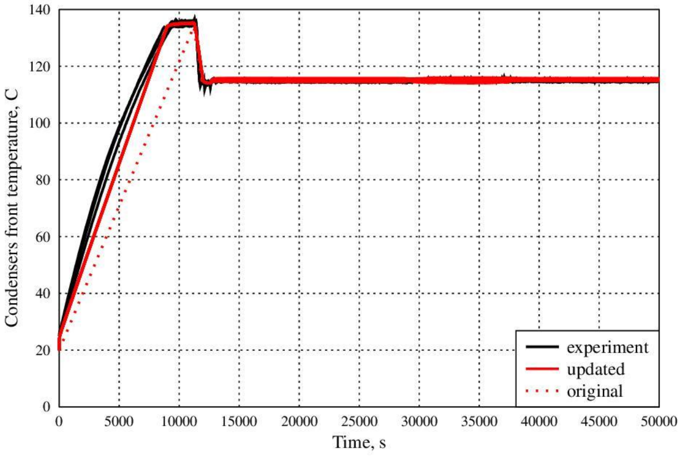

Figure 4 Evolutions of condensers temperature

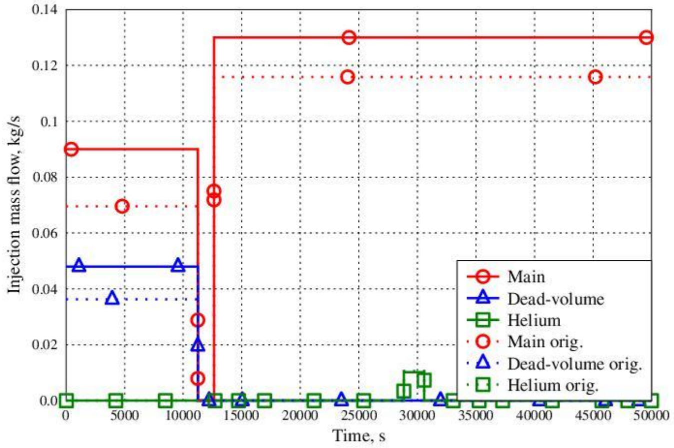

Figure 5 Steam and helium injection mass flow rates

RESULTS

Calculation results of MISTRA ISP47 experiment are presented in Figure 6 - Figure 15. Presented results are obtained using modified nodalisation, except where specifically noted otherwise. Figure 6 presents pressure evolutions during the test sequence. At the start of the experiment pressure increases due to steam injection and heating of condensers. At the end of the first phase pressure reaches almost 4.8 bar. Then steam injection is terminated and the temperature of condensers is decreased, leading to the decrease of pressure to about 3 bar. Then steam injection is restored and the first steady state is obtained with pressure of about 3.4 bar. During the helium injection it rises from this value to about 5.4 bar and stays at this value during second steady state after helium injection termination. Calculation results match experimental ones with two exceptions:

1. During the preheating phase results obtained using original nodalisation show slower pressure increase. This may be attributed to the used rate of condensers temperature increase, which was specified for the experiment, but has differences compared to the measured rate (Figure 4).
2. Pressure of second steady state is not reproduced (difference of 0.3 – 0.4 bar). This may be attributed to incorrect steam distribution in the atmosphere obtained from calculations; also total amount of injected helium should be checked.

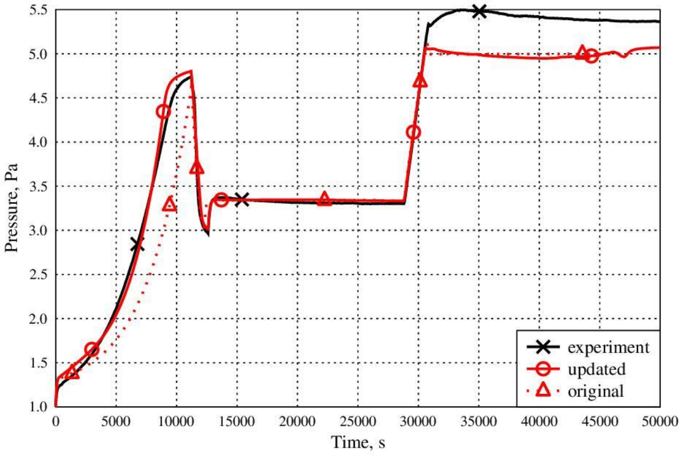

Figure 6 Pressure evolutions (both nodalisations)

Figure 7 presents condensation mass flow rates during the test sequence. Initially condensation starts with steam injection on cold condensers and decreases when they heat up. During two steady states also a steady condensation rates can be observed. Results obtained from the calculations do not reproduce experimental ones. This can be attributed to unsatisfactory modeled steam distribution in the facility atmosphere. Updated model overestimates condensation rate on the condensers, especially the middle one.

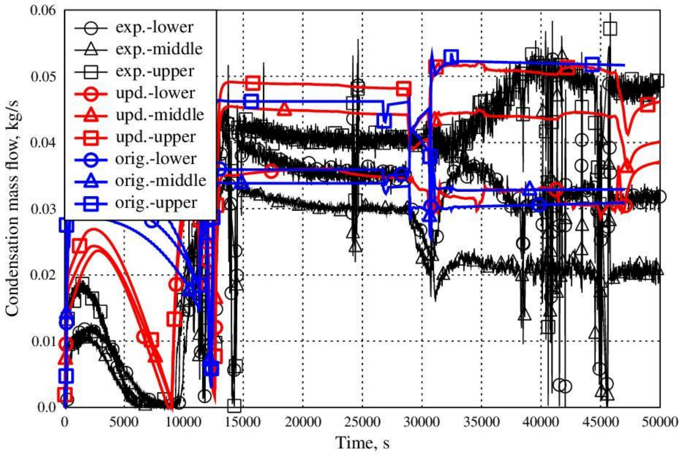

Figure 7 Condensation mass flow rates on three condensers (both nodalisations)

It can be noted, that surfaces added in the updated nodalisation (walls, condensers outer surfaces) did not account in the calculations for the spurious condensation observed in the experiment (Figure 8).

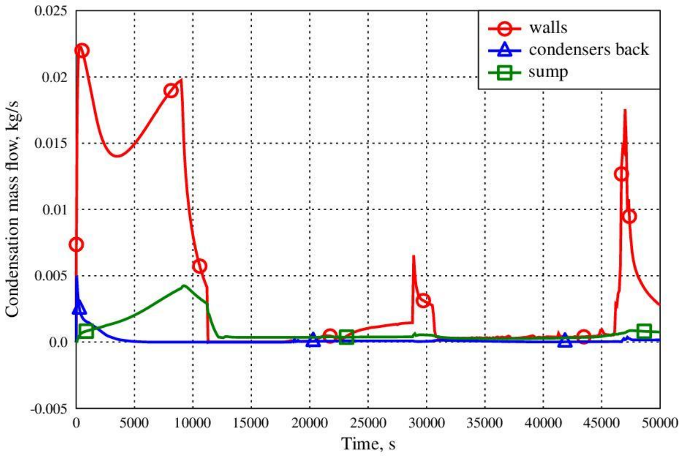

Figure 8 Condensation mass flow rates on additional surfaces and sump (updated nodalisation)

According to [4], measured spurious condensation mass flow rate during steady states was 15 - 17 g/s distributed as follow: 6 – 7 g/s on containment walls, 6 – 7 g/s on sump and 3 – 3.5 g/s on external side of the condensers. There was obtained practically no condensation on back sides of condensers and very small condensation flows on the walls and the sump from the calculations (Figure 8). Since the containment walls' temperatures were simulated with good accuracy (except facility ceiling, Figure 9), it is reasonable to assume that the main reason for failure to simulate spurious condensation is incorrect steam distribution obtained in the calculations.

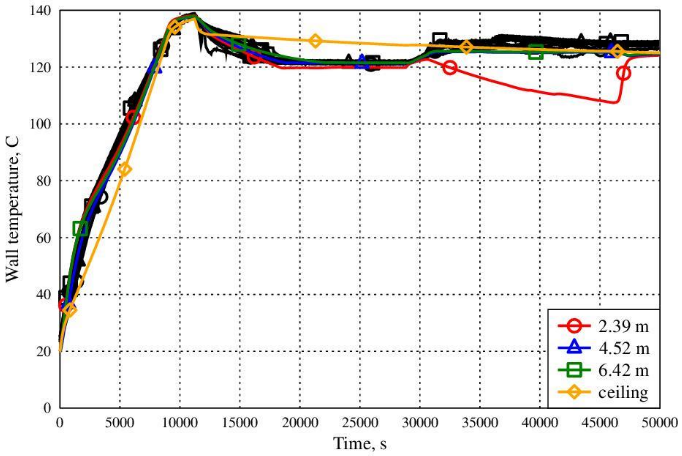

Figure 9 Facility walls' temperature (updated nodalisation) (black lines – experimental values)

MISTRA test facility walls are covered with 20 cm rock wool thermal insulation. The nominal value of heat conductivity of rock wool is 0.045 W/m/K. However using this value gave unsatisfactory results. It is noted in [4], that heat losses in the experiment correspond to the 0.3 W/m/K heat conductivity of insulation material. Results presented in this paper were obtained using this value for rock wool conductivity.

In the Figure 9 a noticeable decrease of temperature of wall behind the lower condenser can be observed. It is caused by “shutting-off” of a “dead-volume” behind the lower condenser. Dead volume behind the lower condenser has only two openings – upper, at the top of the condenser, and lower, at the bottom. In the Figure 10 mass flow rate through these openings is presented.

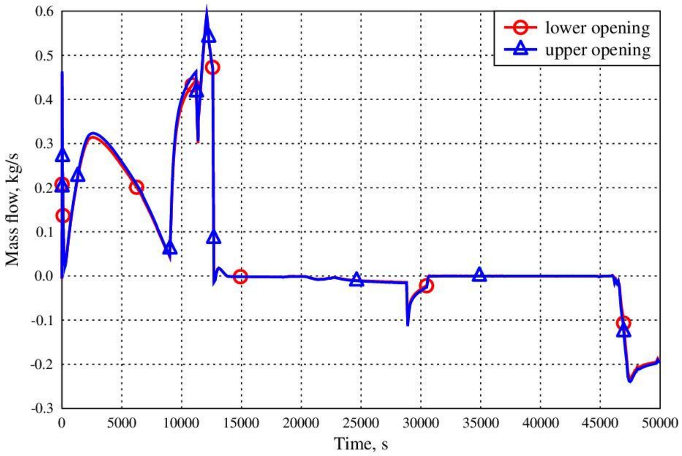

Figure 10 Mass flow rates to and from “dead-volume” behind the lower condenser (positive values are upward direction).

During most of the second steady phase there is no mass transfer through “dead-volume” behind the lower condenser, this leads to the cooling of the volume and walls, due to heat losses. The flow appears at about 46000 s, this leads to spurious condensation spike (Figure 8) and wall temperature increase (Figure 9). The changes affect the whole facility volume – condensation mass flow rates on the condensers also changes (Figure 7).

Figure 11 present some selected gas temperature evolutions. They are representative for all facility – in the first steady phase obtained temperature is equal to experimental, while during the second steady state numerical temperature is underestimated by a few degrees. Overall agreement is satisfactory.

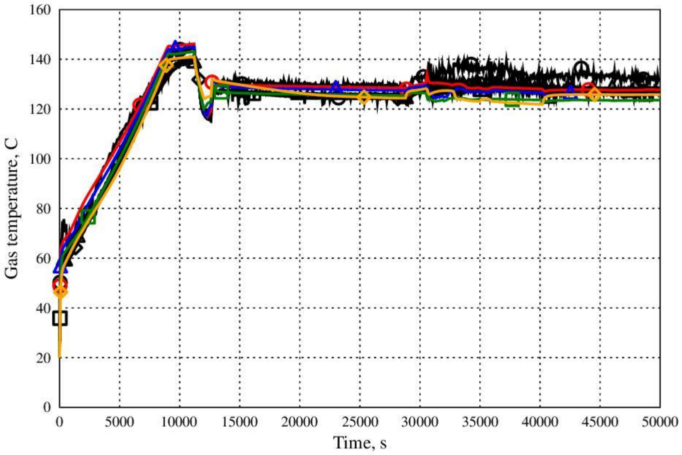

Figure 11 Gas temperature evolutions (black lines – experimental values)

Figure 12 presents some more gas temperature evolutions at some important points. Injection temperature is obtained higher than in the experiment, but this temperature is from the INJ zone, which does not mix with the entrained gas. The temperature bellow the injection point follows the same principle as the most of the facility – accurate prediction during the first steady phase and underestimation during the second. OUT zone one level above the injection point also shows accurate prediction during the first steady phase, and overestimation during the second.

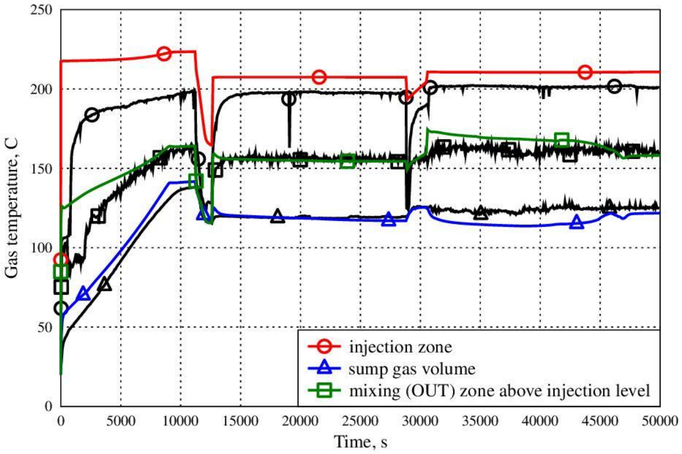

Figure 12 Gas temperature evolutions (black lines – experimental values)

Figure 13 presents vertical temperature profiles in the facility at the end of the test sequence. As it was mentioned, temperature is underestimated.

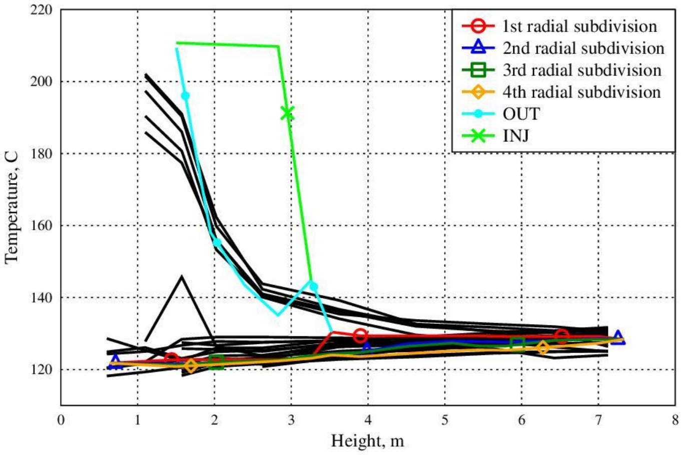

Figure 13 Gas temperature profile at the end of the test sequence (black lines – experimental values)

Figure 14 presents vertical steam volume concentration profiles in the facility at the end of the first steady state. Steam concentration is underestimated by up to 10 %. This is in accordance with the overestimated condensation on the condensers and may be caused by incorrect numerical gas flow patterns resulting from the gas injection.

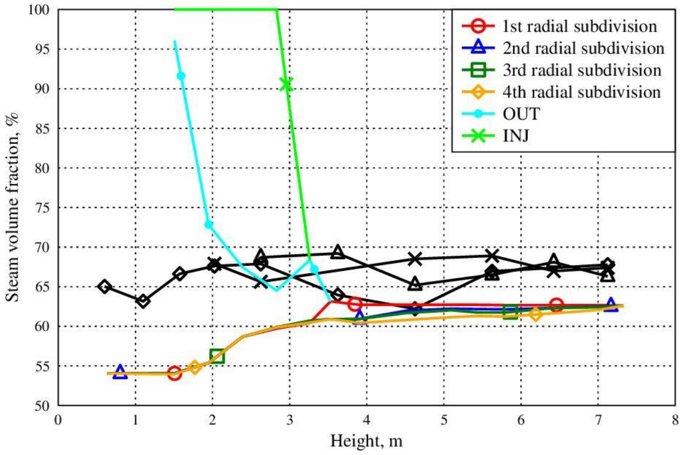

Figure 14 Steam volume concentration profile at the end of the first steady state (black lines – experimental values)

Lumped-parameter approach is not well suited for the gas jet injection modeling. However, it may be possible to simulate such processes using lumped-parameters, if corresponding measures are used. In the updated nodalisation special injection zones were used to correctly simulate injection jet. From the steam distribution at the end of the steady state (Figure 14) conclusion could be drawn, that this special nodalisation was used incorrectly or insufficiently. This topic needs further investigation, especially regarding the extent of special nodalisation to be used. When jet is correctly simulated using this nodalisation, gas should be entrained into the jet from its surroundings. Figure 15 presents flows from and into the jet (sides of OUT zones). Gas entrainment is correctly simulated for the most part of the test sequence, except at the end of the second steady state.

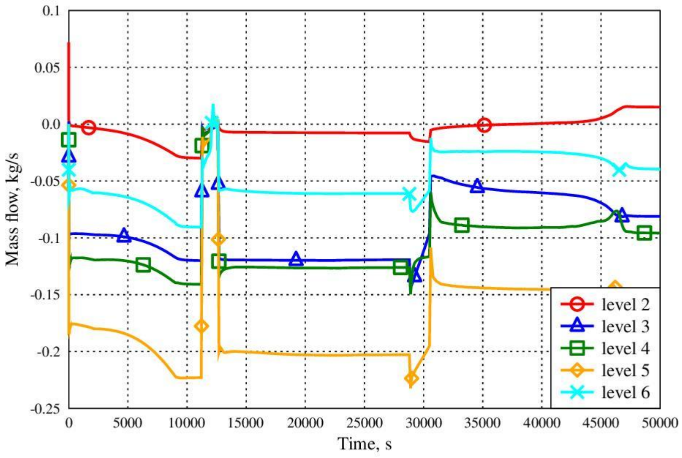

Figure 15 Gas flows to and from jet (OUT zones) (negative values – gas entrainment)

CONCLUSIONS

MISTRA test facility ISP47 experiment test sequence was modeled using lumped parameter code COCOSYS. Nodalisation updated with external walls allowed for experiment simulation using full steam injection rate. When using original nodalisation, injection flow had to be artificially reduced to obtain correct pressure behavior. Special jet zone nodalisation allowed correct simulation of injection flow, however, obtained steam distribution in the facility was incorrect. It may be related to the impact of the lumped parameter approach. The application of injection zones needs further investigations to allow for correct steam distribution calculations. One of the specific issues may be the height required for these zones. As a result of incorrect steam distribution, condensation on the condensers was overestimated and almost no spurious condensation was simulated. Using 0.3 W/m/K as heat conductivity of insulation material allowed to correctly predict containment walls temperature.

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