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Research Article

Simulation of MASPn Experiments in MISTRA Test Facility with COCOSYS Code

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An issue of the stratified atmospheres in the containments of nuclear power plants is still unresolved; different experiments are performed in the test facilities like TOSQAN and MISTRA. MASPn experiments belong to the spray benchmark, initiated in the containment atmosphere mixing work package of the SARNET network. The benchmark consisted of MASP0, MASP1 and MASP2 experiments. Only the measured depressurisation rates during MASPn were available for the comparison with calculations. When the analysis was performed, the boundary conditions were not clearly defined therefore most of the attention was concentrated on MASP0 simulation in order to develop the nodalisation scheme and define the initial and boundary conditions. After achieving acceptable agreement with measured depressurisation rate, simulations of MASP1 and MASP2 experiments were performed to check the influence of sprays. The paper presents developed nodalisation scheme of MISTRA for the COCOSYS code and the results of analyses. In the performed analyses, several parameters were considered: initial conditions, loss coefficient of the junctions, initial gradients of temperature and steam volume fraction, and characteristic length of structures. Parametric analysis shows that in the simulation the heat losses through the external walls behind the lower condenser installed in the MISTRA facility determine the long-term depressurisation rate.

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1. INTRODUCTION

Loss-of-coolant accidents from ruptures in the primary loop of light water reactors (LWRs) are generally fully controlled by the engineered safety systems. Nevertheless, there is a small probability that due to failure of designed emergency core cooling measures during accident, the reactor core could overheat and chemical reaction of steam and strongly overheated zircaloy could produce significant amounts of hydrogen. This hydrogen would then be released into the containment. Without counter measures, the flammable mixtures could then form and cause combustion loads that could threaten the integrity of the containment. The hydrogen combustion had occurred in the containment of Three Mile Island NPP and caused pressure spike of ~2 bar [1].

Detailed experimental and analytical hydrogen mixing research has been performed at several laboratories and experiment facilities TOSQAN, MISTRA, and THAI in the frame of international standard problem (ISP-47) [2]. Performed analyses identified the phenomena, which should be further addressed in the code development and what further experiments could be performed to enhance knowledge about hydrogen mixing in the containments.

The installed water sprays could enhance gas mixing in the containments and prevent local accumulation of hydrogen. In order to evaluate the ability of containment modelling codes to simulate the spray behaviour and the interaction with gas atmosphere, severe accident research network (SARNET) initiated the spray benchmark in two test facilities: TOSQAN and MISTRA [1]. Lithuanian Energy Institute participated in the benchmark by simulating MASPn tests performed in the MISTRA facility. The MISTRA spray tests MASP1 and MASP2 concern the depressurisation of the containment atmosphere by spray, while MASP0 is the reference case without spray.

The simulation of MASPn experiments was performed with the lumped-parameter code COCOSYS. Only the measured depressurisation rates during MASPn were available for the comparison with calculations at this stage of benchmark. In this work, most of the attention was concentrated on MASP0 experiment simulation, since MASP0 is the less complex experiment than MASP1 and MASP2 (sprays are not used during MASP0). Therefore, it was decided to test developed nodalisation, defined initial and boundary conditions and selected modelling parameters by simulating this experiment. When the MASP0 test simulation was performed and acceptable agreement with measured depressurisation rate was achieved then the analyses of MASP1 and MASP2 experiments were performed to check the influence of sprays on the depressurisation rate.

This paper presents a short description of MISTRA facility, specification of MASPn tests performed in this facility, developed nodalisation for COCOSYS code and the obtained results. The performed analysis showed that a clear and detailed specification of initial and boundary conditions of the tests is essential in order to perform the correct simulation of the experiments. The performed parametric analysis revealed the importance of the conditions in the so-called "dead-end" volume behind the condensers, installed in MISTRA test facility.

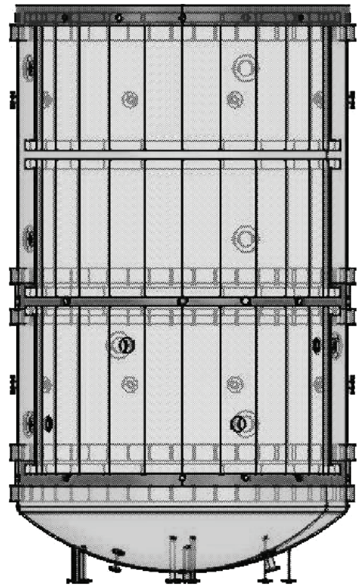

Figure 1: Schematics of MISTRA test facility [1].

2. EXPERIMENTS

There were three experiments—MASP0, MASP1, and MASP2—performed in MISTRA test facility. Each MASP experiment followed after an M5 experiment, during which the stratified atmosphere of the containment was created by a centred steam release into the facility and a high-thermal gradient of the temperatures of the condensers. Therefore, initial conditions of the MASP tests were the conditions of the M5 tests steady-states. Temperatures of the condensers during the MASP tests were the same as during the M5 tests.

MASP1 and MASP2 experiments can be divided into two phases—phase of the depressurisation due to the thermal losses (0 second–2100 seconds) and spray phase (2100 seconds–3900 seconds). During the first phase, the pressure of the containment is decreasing only due to thermal loses through the external walls of the facility and steam condensation on the lower condenser. During the second phase, water sprays are activated and the dominant processes affecting depressurisation is steam condensation on the water droplets and atmosphere mixing. MASP0 experiment is a reference case and only has one phase—depressurisation due to the thermal losses (0 second–3900 seconds). Detailed description of experiments can be found in [3].

2.1. MISTRA test facility

MISTRA facility is a vertical stainless steel cylindrical vessel with curved bottom (Figure 1). The free volume of the cylinder is $\sim$99.5 m^3, internal diameter $-$4.25 m, maximal internal height $-$7.38 m. Vessel is thermally insulated with 20 cm of rock wool. Three cylinders with controlled surface temperature, called condensers, are inserted inside the vessel. Inner diameter of every condenser is equal to 3.8 m. The condensate is collected by gutters. Condensers are situated between 1.285 m and 7.28 m of cylinder height. Condensation occurs only on surfaces of condensers facing the inside of MISTRA facility. Total condensing surface is about 69 m^2. Outside surfaces of the condensers are insulated with 2 cm synthetic foam layer. There is some space, the so-called "dead volume," between condensers and facility walls. Vertical spaces between condensers ($\sim$0.12 m) are partially hidden by gutters. Further description of MISTRA facility can be found in [3, 4].

2.2. Experimental results

During the MASP tests phase of the depressurisation due to thermal losses containment pressure dropped from the initial value of 2.4 bar to $\sim$2.2 bar in the first $\sim$500 seconds and then was slowly decreasing (Figure 2) [3]. At the end of MASP0 experiment ($\sim$4000 seconds) the pressure had decreased down to $\sim$2.03 bar. During MASP1 and MASP2 tests the sprays were activated after 2100 seconds. Until this time, the pressure behaviour in all three cases was very similar and small differences were caused by the different conditions that had appeared after each M5 test. After spray activation, a rapid depressurisation was observed. In the MASP1 experiment, the pressure after 4000 seconds was $\sim$1.6 bar and in the MASP2 experiment it was $\sim$1.45 bar. The different final pressures of the MASP1 and MASP2 experiments spray phase were due to the different temperatures of injected water (Table 1). Lower spray water temperature induced a larger containment pressure decrease.

3. NODALISATION SCHEME, INITIAL AND BOUNDARY CONDITIONS

Experiments were simulated with lumped-parameter code COCOSYS version V2.3v11 [5]. Developed nodalisation scheme of the MISTRA test facility (Figure 3) consisted of 31 nodes, which were connected by 50 atmospheric junctions. Water film flow along condensers was modelled with 4 junctions. Condensers were simulated by 14 structures, walls of

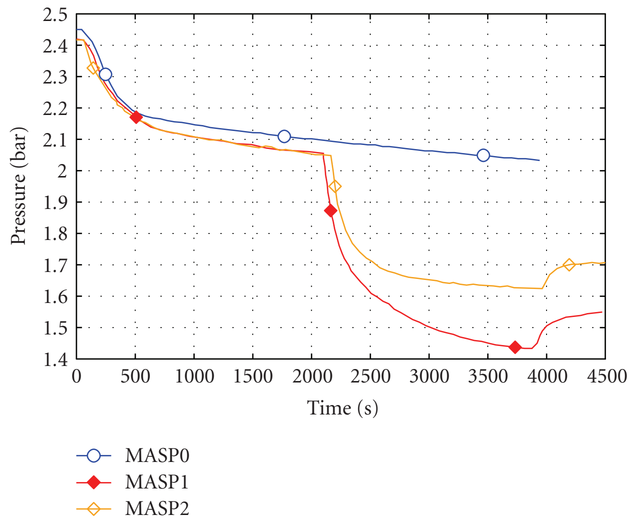

Figure 2: Experimental results [3].

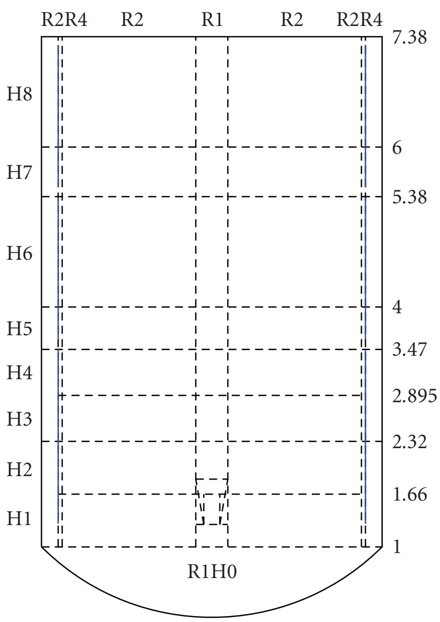

Figure 3: Nodalisation scheme for COCOSYS code.

containment—11 structures. This nodalisation scheme was developed on the basis of the MISTRA facility nodalisation, which was used in the frame of ISP-47 [2]. In order to simulate the temperature and steam fraction gradients in more detail the previous nodalisation was refined. In the current nodalisation, there are four vertical subdivisions at the level of lower condenser instead of two in the previous ISP-47 nodalisation because the level of lower condenser corresponds to a region between 1 m and 4 m of the facility height and the gradients of both temperature and steam volume fraction are created in this region. Regions of middle and upper condensers were left subdivided into two vertical parts.

Table 1: Benchmark specifications—Part A [1].

Parameter	MASP0	MASP1	MASP2
Pressure	2.4 bar	2.4 bar	2.4 bar
Mean gas temperature	124°C	124°C	124°C
Steam volume fraction	0.45	0.45	0.45
Air mass	~115 kg	~115 kg	~115 kg
Water temperature in the nozzle	—	40°C	60°C
Droplets mass flow-rate	—	0.87 kg/s	0.87 kg/s
Temperature of lower condenser	80°C	80°C	80°C
Temperature of medium and upper condensers	140°C	140°C	140°C

Nodalisation scheme includes 3 radial nodes in the central part of the containment and one in the "dead volume" behind the condensers. There are 8 vertical levels with detailed radial subdivision. A single node defined below the lower condenser simulates the sump. The heat transfer through convection, radiation, and condensation is considered. Outer sides of the facility walls in the model were kept at room temperature during whole simulations. COCOSYS code is capable of calculating gradients of temperature inside the wall from this external condition and conditions in the control node the wall is facing.

For the simulation of MASP1 and MASP2 experiments, several paths of the falling spray droplets were identified according to nodalisation. Fraction of the total water inlet mass flow of the spray system related to each spray path was calculated according to the part of the base area of the cone, which corresponds to a given path. The spray droplet size distribution was not given in the specification; a value of around 1 mm was specified [3]. The spray model, which is implemented in COCOSYS code, simulates only monodisperse droplets, that is, does not allow defining a droplet size distribution.

4. CALCULATIONS

Simulations of the experiments in the MASPn benchmark were performed in two parts: (1) part A, where only mean values of gas temperature and steam volume fraction were specified (Table 1), and (2) part B, where the steam content and temperature stratification conditions were specified.

At first, the initial and boundary conditions for the base case calculations were set according to the part A specification [1], where the gas stratification was not identified. Temperature of the external sides of the facility walls was set equal to 20°C. When using mean gas temperature and mean steam volume fraction as homogenous initial conditions for vessel volume, the calculated pressure drop in MASP0 case was too high compared to the experimental results (Figure 4). Calculations showed that after 4000 seconds the pressure would drop to almost 1.8 bar, but in experiment it was still higher than 2 bar. This result shows that it is not possible to model MASP tests using homogenous initial

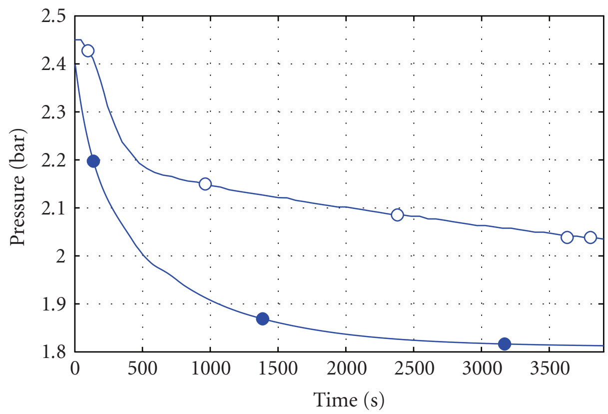

Figure 4: Pressure evolution using homogenous initial conditions.

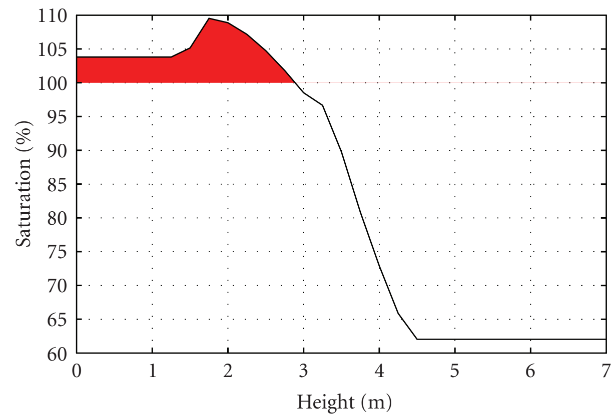

Figure 6: Relative humidity obtained with conditions from part B specification.

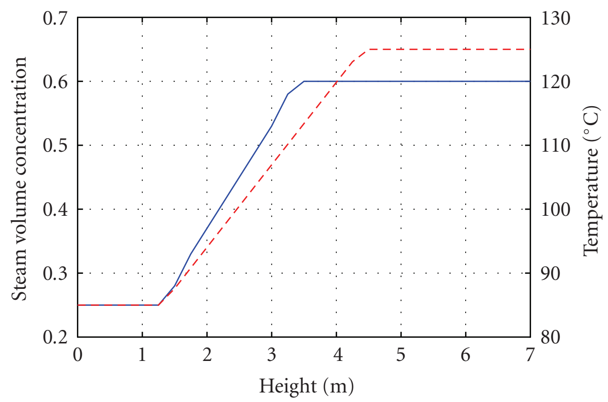

Figure 5: Additional experimental data in part B specification [6].

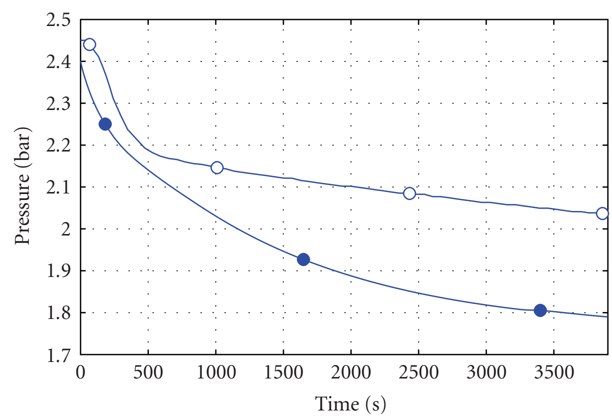

Figure 7: Pressure evolution with decreased steam volume fraction at low elevation.

conditions and experiments have to be simulated using gas temperature and steam fraction gradients for initial data.

Stratifications of steam content and gas temperature specified in part B are presented in Figure 5 [6]. One can see that after M5 test the temperature gradient is created between elevations of 1.25 m and 4.5 m. Temperature difference in this region is 40°C. The stratification of steam volume fraction changes from 0.25 at elevation of 1.25 m to 0.6 at elevation of 3.5 m.

Therefore, MISTRA nodalisation was modified to include gradients from the part B specification (Figure 5) [6]. But it was not possible to perform calculations using these conditions because they correspond to the relative humidity greater than 100% at low elevations of the facility (Figure 6). Nevertheless, it should be noted that with such temperature and steam volume fraction distribution, the calculated mass of air in the facility was 115.7 kg and corresponded to the test specification (see Table 1).

Considering that better definition of experimental boundary conditions was not available at the moment, when analysis was performed it was decided to perform parametric analyses with slightly modified conditions in order to start calculations and study the effect of these conditions on the results. As well there were performed several analyses to study the effect of modelling assumptions.

At first, it was chosen to reduce the steam volume fraction at lowest elevations of the facility from 25% to 20%. This reduced saturation in the lower part of the facility below 100% and allowed to start calculations but the obtained depressurisation rate (Figure 7) was not much different from the one received assuming homogeneous mixture in the facility (Figure 4), that is, they are significantly different from the experimental values.

The next step was to investigate the influence of modelling parameter—loss coefficient in junctions—on the depressurisation rate. In COCOSYS code, the atmospheric junctions are described by junction area, hydraulic length, and loss coefficient. Area of the junction is unambiguously defined by dividing volume of the facility into the calculation nodes. Hydraulic length is selected as distance between the

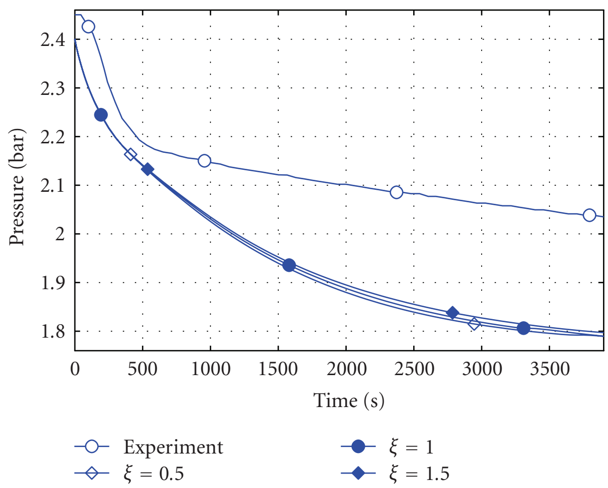

FIGURE 8: Pressure evolutions with different loss coefficients.

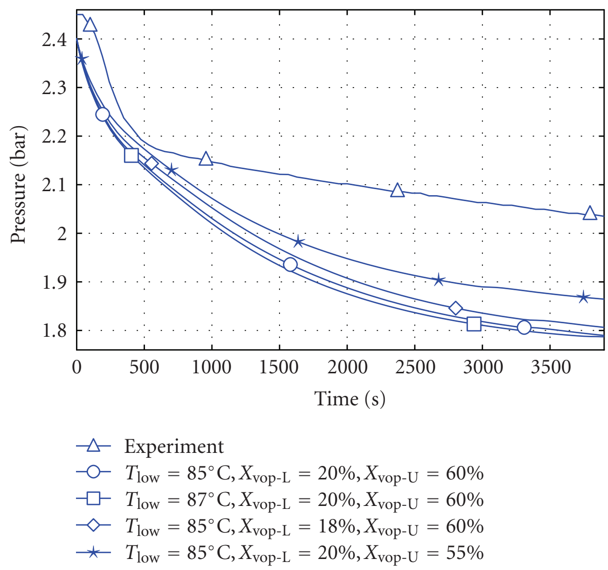

FIGURE 9: Pressure evolutions with different initial parameters.

centres of the nodes connected by the junction. The loss coefficient was selected equal to the value of 1.0 in the base case for all junctions. The loss coefficient is not very well defined in this model because there are no obstacles for gas flow and mass transfer takes place between virtually divided volumes. With the purpose of evaluating the influence of this parameter additional calculations were made, where the value of the loss coefficient was changed to 0.5 and 1.5 as different variants. The results showed that variation of the loss coefficient in junctions does not influence the results significantly (Figure 8) and could not be the reason for large differences between calculations and experiments.

Later it was decided to perform variation of initial temperature and steam volume fraction at lower and upper elevations since these measurements of these parameters include some uncertainty. At first the temperature in the lower part of the containment was defined to be 85°C instead of 87°C, then the steam fraction at low elevations was defined to be 18% instead of 20% and then the steam fraction at high elevations was defined to be 55% instead of 60%. These values were taken considering the measurement errors. Only results of the variant with 55% of steam volume fraction at high elevations showed more different pressure evolution (Figure 9). But the containment pressure was still too low compared with experiment and, furthermore, such change of the gas content changed the air mass of the facility and it became noncompliant with the test specification.

Structures of the facility in the developed model are described by the area of the structure, applicable models of the heat transfer (convection, condensation, and radiation), composition of the structure, and the characteristic height and length. The characteristic length of the structure is not well defined in the modelling methodology. According to COCOSYS user's manual [5], it is defined as $1 = A/U$, where A is an area of the structure, and U is its perimeter, but for the vertical walls the characteristic length should be equal to the height of the wall. Also, according to this user's manual, for the simulation of real power plants the value of 0.01 can be used for all vertical walls. During simulations

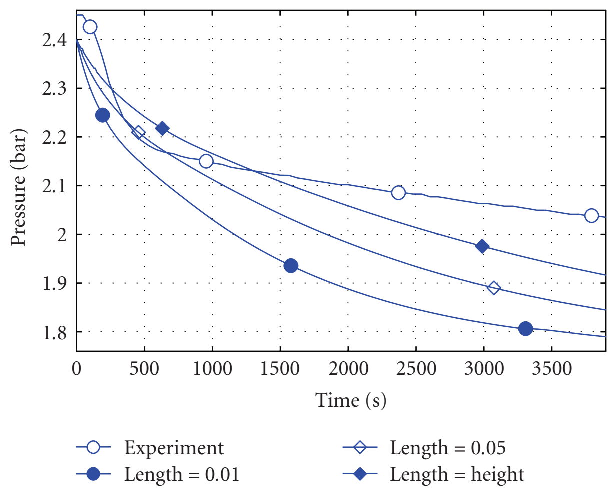

FIGURE 10: Pressure evolutions with different characteristic length values.

of aerosol deposition in the KAEVER experimental facility, the value of 0.05 for all vertical walls was determined as best for simulation of aerosol deposition [7]. Since the value of the characteristic length is not very clear, it was varied to investigate its influence on the calculation results. The performed analysis showed that this parameter had significant influence on results, but the calculated pressure was still too low compared to experiment (Figure 10). The variation of this parameter led to 0.1 bar pressure difference at the end of calculations. As well it should be noted that changing this parameter does not give initial faster pressure drop and slower decrease after 500 seconds.

The last tested assumption was simulation of the external walls of the test facility. The calculations were performed assuming that there are no external walls, that is, the depressurisation in the MASP0 case is determined only by

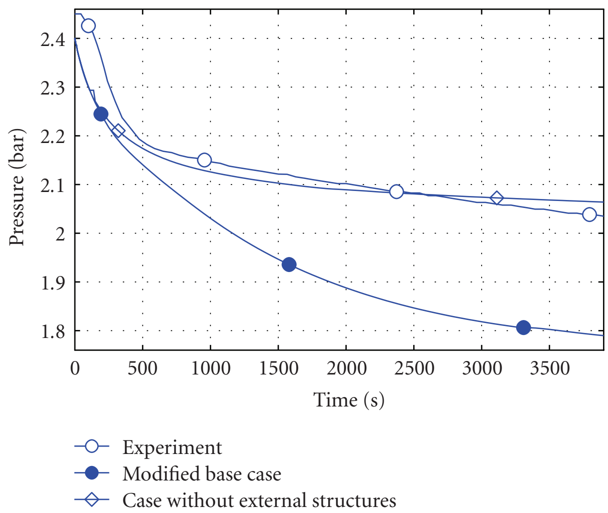

Figure 11: Comparison of pressure evolutions calculated from base case and calculated without external structures, MASP0.

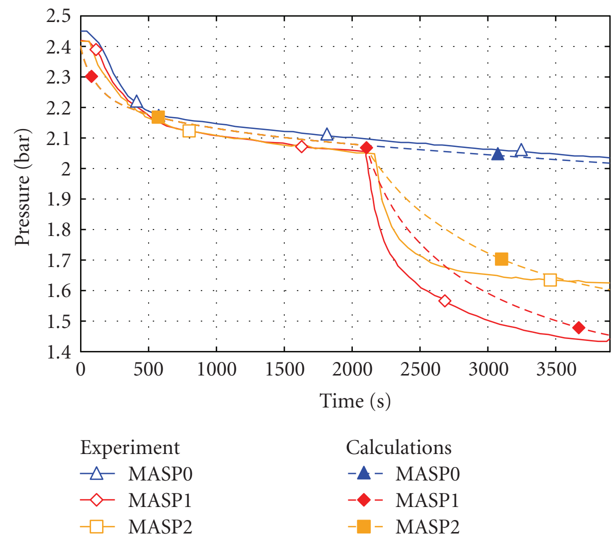

Figure 12: Pressure evolutions calculated with decreased junction area behind lower condenser.

the heat transfer to the lower condenser. The obtained results showed that the calculated depressurisation rate is similar to the measured (Figure 11). After further examinations, it was determined that only structures behind the lower condenser, which is colder than the other condensers, determined the heat loss through external structures and the depressurisation rate in the long-term.

For the final analysis of all MASPn experiments, it was decided to simulate all structures, but to decrease the area ofthe junction behind the lower condenser. This leads to a decrease of gas flow and, consequently, the heat transfer at this part of the facility. The area of the junction was selected in such a way that the calculated depressurisation rate due to heat loses, that is, MASP0 test, comply with the measured results best. The characteristic length of all structures was assumed 0.01 m. In the case of the MASP0 experiment, pressure reaches ~2.2 bar at ~500 seconds and stays a bit over 2 bar at ~4000 seconds (Figure 12), that is, results are similar to the experimental. When this MASP0 test simulation was performed and acceptable agreement with measured depressurisation rate was achieved (Figure 12), simulation of MASP1 and MASP2 experiments was performed to check the influence of the sprays. The same modelling assumptions and conditions as in MASP0 test simulation were used. Sprays were modelled with previously described assumptions. Mass flow rate of the droplets and water temperature in the nozzle were set according to specification (Table 1). Results of the calculations showed that at the end of the spray phases obtained pressure values are similar to the experimental ones in both tests, but in the beginning of the spray phase the pressure decreases too slow compared to the experiment and, accordingly, too fast in the second part of the phase. The performed analyses show that more modelling efforts and clear definition of initial and boundary conditions of experiments are required even for lumped parameter codes in order to perform a detailed and reliable modelling of the experiments. In the future, the calculations of tests will be performed by modelling M5 experiment, which preceded MASPn tests. When the M5 experiment is simulated and calculated stratification conditions fit the measured values then the detailed analysis of sprays on the destruction of atmosphere stratification could be estimated.

5. CONCLUSIONS

The analysis of MASPn experiments was performed using the lumped-parameter code COCOSYS. The influence of different experimental parameters and modelling assumptions was investigated in order to determine the most important parameters that influence the depressurisation rate during the MASP0 experiment performed in the frames of spray benchmark in MISTRA test facility.

The performed analysis showed that a clear definition of the initial and boundary conditions, including developed gas stratification, of the experiment is required in order to develop a nodalisation, which could be used for simulation of experiments.

None of the considered modelling parameters (loss coefficient in the junctions, characteristic length of structure) had major influence on the calculated results.

Variation of the atmosphere stratification conditions could not reproduce the measured depressurisation rate.

The performed simulations of MASPn experiments and obtained results show that the calculated heat losses through the external walls behind the lower condenser installed in the MISTRA facility determines the long-term depressurisation rate.

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