KAUNAS
UNIVERSITY OF
TECHNOLOGY

MANTAS POVILAITIS

Study of the Steam and Gas Mixing Processes in the Containments of Nuclear Power Plants

Summary of doctoral dissertation
Technological sciences, Energetics and
Power Engineering (06T)

2013, Kaunas

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LIETUVOS ENERGETIKOS INSTITUTAS

Mantas Povilaitis

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INTRODUCTION

During a severe accident in the nuclear power plant large amounts of hydrogen may be generated, which could be released into the containment atmosphere. Release would lead to explosive/flammable hydrogen-air mixtures, if hydrogen volume fraction in the mixture were between 4-75%. An explosion of such mixture would endanger the containment integrity. The strength of an explosion would depend on the quantity of the explosive mixture, the hydrogen concentration in it and combustion mode. Therefore, to ensure the integrity of the containment it is necessary to be able to estimate behavior of hydrogen in the atmosphere, which would allow the development of effective risk mitigation measures.

Therefore, the nuclear power plant containment atmosphere mixing is an important nuclear safety issue associated with hydrogen explosion hazard. A large number of international experimental and numerical studies, including some international standard problems (ISPs), have been devoted to this issue.

One of the results of these studies is a conclusion that modeling of containment atmosphere mixing using lumped-parameter codes, which are extensively used in nuclear safety, is complicated due to the modeling approach used in these codes. However, it was also found that in certain cases, when suitable nodalisation schemes were used, lumped-parameter codes provided sufficiently accurate results.

Thesis presents the study of containment atmosphere mixing performed using the lumped-parameter method. In the course of the study to experiments of MISTRA test facility were modelled – M5 and ISP47. Simulations were performed using lumped-parameter code COCOSYS.

Methodology has been developed during the study for the simulation of containment atmosphere mixing processes in the case of vertical gas or vapor jet injection.

Relevance of the work.

Nuclear power plant containment is the final barrier to prevent release of radioactive substances into the environment. Therefore, it is extremely important to maintain the integrity of the containment during the accident. One of the main threats to the integrity of the containment during the severe accident is a potential hydrogen combustion/explosion. The severity of such explosion depends on the distribution of hydrogen gas and flows in the containment, since the composition of the mixture and its turbulence determine combustion mode. In particular, it is important to foresee if dangerous local concentrations will form due to gas mixing and stratification. Therefore, in order to properly assess the threat posed by hydrogen in order to determine the necessary preventive or accident management tools, gas mixing estimates shall meet the appropriate accuracy requirements. However, the ability of lumped-parameter codes, which are used in nuclear safety and validated for the simulation of design-basis accidents, to accurately (with accuracy sufficient for the assessment of hydrogen explosion hazard) simulate gas mixing is not fully established in the case of stratification and string gas flows.

Aim of this work.

Examine the containment atmosphere mixing using lumped-parameter approach.

The tasks of this work.

1. To develop the containment atmosphere mixing modeling methodology for the lumped-parameter approach.
2. To verify developed methodology by applying it to the simulation of experiments, which investigated gas mixing processes.
3. To perform numerical study of containment atmosphere mixing using lumped-parameter approach.
4. To carry out uncertainty and sensitivity analysis of performed simulations.

Defensive propsitions of the work.

1. If recommendations found in the literature for gas mixing modeling in the case of vertical gas jet injection are used, obtained steam and gas distribution and thermohydraulic parameters do not correspond to the experimental results..
2. The methodology developed by the author makes it possible to model with greater accuracy the formation of the vapor concentration and temperature stratification in the case of vertical jet injection using lumped-parameter approach compared to recommendations in the literature.
3. Injected steam jet together with the hot and cold surfaces determine the gas flow, temperature, and steam distributions in the atmosphere of the facility. The pressure value is determined by the injected and condensed steam mass flow rates.
4. The most significant sources of uncertainty in modeling the M5 and ISP no. 47 experiments are the uncertainties of these parameters:
    - initial pressure,
    - thermal isolation's heat conductivity coefficient,
    - junction resistance coefficient,
    - effective area of condensers.

The practical importance of work.

Application of lumped-parameter codes for containment atmosphere mixing simulations is complicated and not completely justified in some special cases due to the limitations associated with this method. The work develops methodology to take into account these constraints when modeling such processes, which enables application of lumped-parameter codes in the simulations of these special gas mixing cases.

The novelty of the work.

- Developed methodology of studying gas mixing in the case of vertical gas jet injection for the lumped-parameter approach.
- Study of containment atmosphere mixing performed using developed methodology, considering processes at the injection point, whole jet height and the rest of the containment volume.

1 GAS MIXING PROCESSES IN THE CONTAINMENTS OF NUCLEAR POWER PLANTS

Most nuclear power plants have a containment - sealed steel or reinforced concrete structure surrounding the reactor and its cooling circuit. If, during an accident, the reactor coolant piping were to rupture, coolant contaminated with radioactivity would flow into the containment, where the radioactive material would be contained until it could be treated or its activity would decrease due to radioactive decay [1, 2].

Containments of different nuclear power plants differ from one another in size, shape, materials and pressure-reduction measures.

Containment is the last barrier during an accident preventing release of radioactive substances into the environment. Therefore, it is extremely important to maintain the containment integrity, enabling it to perform the barrier function [3].

Each containment can withstand only a finite maximum pressure without losing integrity. Therefore, in the case of a loss of coolant accident (LOCA), the containment could retain coolant only for a limited period of time, unless pressure was decreased or heat was removed by additional systems. An example is the Three Mile Island Nuclear Power Plant accident during which part of the nuclear fuel melted, but the containment contained radioactive materials, and the maximum allowable containment pressure was not exceeded. However, after some time after the accident, part of the radioactive gases was intentionally released into the environment from the containment atmosphere, in order to prevent the pressure rising above the safe values [4].

Another phenomenon that can damage the integrity of the PC is a hydrogen combustion/explosion. During a severe accident of light water reactor (LWR) large amounts of hydrogen may be generated, which, together with the coolant would flow into containment atmosphere and mix with the air, forming flammable mixture [5–7]. The risk posed by combustible mixture would depend on hydrogen combustion mode. Combustion modes are determined by the relatively narrow hydrogen and steam concentration ranges, therefore, in order to estimate the risk and effective prevention and accident management measures, sufficiently accurate calculations of gas distribution in the containment are needed [8].

In case of accident and coolant release into the containment, gas distribution in the containment atmosphere is determined by a number of complex, interacting heat and mass transfer processes (gas mixing, changes in the composition, aerosol transport, etc.).

The containment atmosphere mixing includes processes, during which the individual gas flows with their separate characteristics form one mixture. The main characteristics of these flows can be temperature and component concentration. For example, when the hydrogen flows into the mixture of air and steam, the flow mixes with surrounding atmosphere – air and steam are entrained into the flow, while the flow itself is expanding. If such mixing process proceeds to the end, a homogenous hydrogen, steam and air mixture is formed. However, in many cases, the process of mixing does not complete, if in such case stationary state is attained, stratified conditions form [9].

In the "State-of-the-art report on containment thermalhydraulics and hydrogen distribution", published in 1999 by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development the following containment atmosphere mixing processes were identified:

- gas jet interaction/entrainment of surrounding atmosphere into the jets
- density difference/stratification,
- density difference/interaction with the walls,
- turbulent diffusion,
- water spray dynamics,
- fan dynamics.

There is a well-established international consensus that in order to estimate localized hydrogen, steam and air distributions in the containment atmosphere, detailed knowledge of containment thermal-hydraulics is necessary [10]. Considerable international efforts were dedicated to better understand related phenomena by performing experiments and analytical assessments of their results. Since it is not possible to perform containment thermal-hydraulics experiments in the existing nuclear power plants due to safety concerns, experiments are performed in special facilities, which imitate containments or their parts. However, such devices are usually smaller in size and have simpler geometry than containments they correspond to, therefore, in order to study processes on the containment scale, numerical experiments are also performed using computer codes. Codes are used for simulation of experiments, performed in the experimental facilities, too, in order to better understand experiments, and to verify code ability to simulate occurring processes.

Two main approaches are used for thermal-hydraulic process modeling – lumped-parameter and three-dimensional field (which can be simplified to two-dimensional in some cases).

Lumped-parameter approach is based on the fundamental assumption of homogeneity of selected volumes, called "control volumes" (CV). Using this approach, containment volume is described by control volumes, connected by junctions. Each control volume can have an unlimited number of connections with other control volumes. Each junction has a momentum equation, and each control volume – energy and mass conservation equations. Obtained set of conservation equations is a system of ordinary differential equations, which can be solved by using known numerical methods [9].

The characteristic feature of lumped-parameter approach is that mass and energy are transferred between control volumes by junctions, according to momentum equation solution for each junction. However, since each of the momentum equation is one-dimensional (from-to), and the control volumes doesn't have their momentum equations, multidimensional effects due to the momentum transfer can not be modeled [9].

The main field of application for lumped-parameter codes in the nuclear safety is an integral containment analysis. An integral containment analysis requires models of various interacting processes, e.g., containment thermal-hydraulics, aerosol behavior, fission product transport, hydrogen combustion, safety systems, etc. Lumped-parameter codes have a number of advantages compared tu three-dimensional field codes [9]:

- lower requirements for initial, boundary and geometrical data,
- significantly faster calculations (low computer resource requirements),
- implementation of integral models,
- advanced calculation methods with a large validation database, reflecting the accumulated long-term experience.

However, they have some disadvantages also:

- lack of models to simulate some of the local gas mixing details (e.g., entrainment of surrounding atmosphere into the jet),
- deficiencies in simulating molecular/turbulent diffusion,
- limited possibilities to assess speeds of flows.

ISPs no. 23, 29 and 37 showed that lumped-parameter codes tend to overestimate the mixing of containment atmosphere. Therefore, they can provide good results in the cases, when containment atmosphere is not stratified. In the stratified cases, lumped-parameter codes usually overestimate the gas concentrations at the lower elevations, and underestimate at the higher elevations.

However, ISP no. 47 showed that a user of lumped-parameter code can bypass this restriction of codes, by selecting appropriate nodalisation scheme, and obtain results as accurate as with a three-dimensional field code. The selection of the nodalisation scheme is mainly governed by the individual experience of the code user, since there is no general methodology for the selection of the nodalisation, appropriate for the vertical jet injection and gas entrainment simulation.

One of the recommendations how to simulate jet injection was provided in [11]. It recommends using special “injection zones”, the scheme of which is provided below :

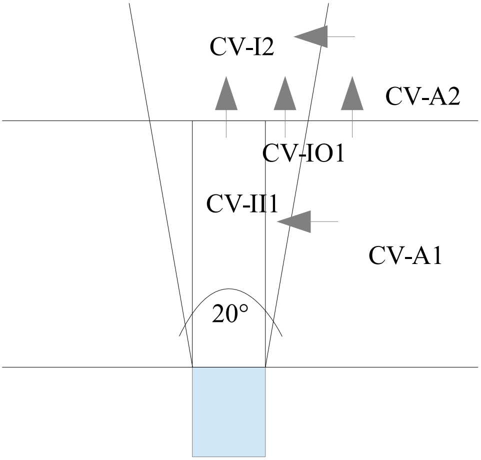

Figure 1.1. Scheme of injection zones according to [11]

Under this scheme, two injection zones (control volumes) have to be defined over the physical injection point – inner (II) and outer (IO). Their parameters (volume, areas) should correspond to geometrical values. Inner injection zone has a cylinder shape and only one junction, at the top. Outer injection zone has an inverted truncated cone shape, the central part of which is inner injection zone. Expansion cone angle is 20°, like in a physical jet. This zone has two junctions – at the top and side. The injected gas mass flow should be equally divided between these two zones. If the injected jet is simulated correctly, the code should calculate gas entrainment from the surroundings of the jet.

Summary. During the nuclear power plant accident, flows and heterogeneous conditions may form, which would be complicated to simulate using lumped-parameter codes. However, as revealed by a review of studies, in separate cases this problem has been solved by using adequate nodalisation schemes. In these cases lumped-parameter codes had an advantage over three-dimensional field codes, because lumped-parameter codes provided results of the same accuracy, but in a few times or even order of magnitude shorter time duration. However, there is no well-developed methodology, which would define how to choose appropriate nodalisation schemes for simulation of gas mixing induced by vertical jet injection. The recommendations provided in the literature are not sufficiently specific and involves only injection point description. They have been tested for only a few experiments carried out in two experimental facilities. Therefore, this work aims to review the proposed recommendations by modeling additional experiments in a different experimental facility (MISTRA), and assess their suitability for the simulation of containment atmosphere mixing. Depending on the results of the review, the literature recommendations are to be developed into the methodology of containment atmosphere mixing induced by vertical jet gas release simulation, which will be verified.

2 DESCRIPTION OF EXPERIMENTS

Simulated experiments (M5 and ISP47) were performed in the French test facility MISTRA, located in the Saclay center of Atomic Energy Commissariat (CEA). MISTRA facility is used in the nuclear power plant containment thermal-hydraulics and hydrogen safety research. Experiment M5 was a part of a containment atmosphere -- water spray interaction research program. Both experiments started with the homogeneous conditions inside the facility.

MISTRA facility is a vertical stainless steel cylinder with a rounded bottom (Fig. 2.1). The height of the facility is 7.38 m, the inner diameter is 4.25 m and the free volume is 97.4 m^3 [12]. External walls of the facility are not thermally regulated, but they are thermally isolated with a 20 cm thick rock-wool layer.

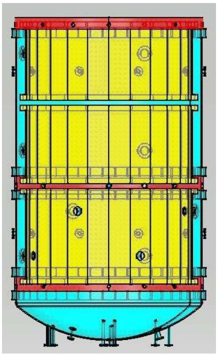

Figure 2.1. Scheme of MISTRA facility

Inside the facility there are three cylindrical structures situated one above each other, called “condensers”. The inner diameter of these cylindrical structures is 3.8 m. They are also made from stainless steel. The temperature of condensers is regulated, their surface facing walls of the facility is coated with 2 cm of synthetic foam. The volume between the condensers and the facility walls, so called “dead volume”, takes up about 13 % of the total free volume of the facility. Spurious condensation can occur on the vessel walls and bottom [12].

Facility has two steam injection lines. The main line is equipped with a diffusion cone functioning as an upwards directed nozzle. Inside the diffusion cone gas injected from different gas lines (e.g. helium and steam) mixes before being injected into the facility. In the M5 experiment only steam injection was used, in the ISP47 experiment steam and helium. Additional line, has 8 nozzles at the bottom of the facility by the facility walls. Four of them are directed upwards and four directed to the rounded bottom of the facility. This line is used to preheat the structures of facility [12].

Experiment M5 is started from the homogeneous room conditions, 24 °C temperature and 1.007 bar pressure. Initial relative humidity was not measured and is assumed to be 50 %. The purpose of the experiment is to create a stratified steam atmosphere inside the facility. For this purpose additionally to steam injection, a temperature gradient of the condensers is used. The specified temperature of the bottom condenser is 80 °C, whereas of other condensers 140 °C [12]. The temperatures of the condensers increase from the room temperature up to their specified values and stay constant during the rest of the experiment.

Experiment was performed in two phases. During the first phase, called "preheating phase", both steam injection lines were used and the facilities pressure, temperature and steam content were increasing. During the second phase only the main injection line was used and the injection mass flow rate was lower than in the first phase. In this phase equilibrium between injected and condensed steam inside the facility is reached and stable stratified atmosphere is formed. The parameters of the steam injection are presented in Table 1.

Table 1. Experiment M5 parameters

Phase	Injection pressure, bar	Injection temperature, °C	Mass flow rate, main line, kg/s	Mass flow rate, additional line, kg/s	Duration, s
I	14±0.09	235±1.5	0.0919±0.0016	0.0196±0.0003	10380
II	12.1±0.09	230±1.5	0.0798±0.0014	0	31440

Simulated ISP No. 47 experiment consisted of five phases, two of which were stationary. The injection parameters and temperature of condensers are presented in Table 2.

Table 2. ISP47 experiment parameters

Phase	Duration, s	Steam mass flow rate, kg/s		Helium mass flow rate, kg/s	Condensers' temperature, °C	
		Main line	Additional line		Initial	Final
I	11250	0.092±0.0016	0.048±0.0008	-	33±1	134±1
II	1380	-	-	-	134±1	115±1
III	16205	0.130±0.0022	-	-	115±1	115±1
IV	1740	0.130±0.0022	-	0.0106±0.0002	115±1	115±1
V	20000	0.130±0.0022	-	-	115±1	115±1

Experiment starts from homogeneous conditions of 1 bar pressure and 33 °C temperature. The first phase is a pre-heating phase. Steam is injected into the facility in order to increase its structures' temperature. The temperature of condensers is also increased during the first phase, but decreased during the second phase. No gas is injected during the second phase. Starting with the third phase the temperature of condensers and the steam injection mass flow rate are kept constant till the end of the experiment. The third phase is the first equilibrium phase. During the fourth phase helium is injected together with steam into the facility. During the fifth phase equilibrium is again established, only this time with a helium presence in the facility atmosphere.

3 METHODOLOGY OF THE STUDY

Simulations presented in this work were performed using a lumped-parameter code COCOSYS. COCOSYS is being developed for the simulation of all the relevant processes occurring in the containment during the course of design basis accidents and severe accidents [13]. COCOSYS is developed by the German organisation GRS mbH. This code is widely used internationally for the analysis of transient thermal-hydraulic processes in nuclear power plant containments by the nuclear energy research institutions and safety authorities [14–17] and by Lithuanian Energy Institute [18–20].

When choosing a code for the simulations, other applicable codes were also considered – ASTEC [21], MELCOR [22] and CONTAIN [23]. MELCOR and ASTEC are integral codes which can simulate not only containment processes, but also the cooling circuit, therefore in order to keep short computation times they tend to use simpler physical and parametric models of processes. COCOSYS is intended only for the containment process modeling, which allow it to have more detailed, mechanistic process models. CONTAIN code is also intended for the containment simulations, but its development is stopped. Most of the organisation have stopped using this code and instead are using MELCOR, COCOSYS or ASTEC. Given the topic of the dissertation, intended use, advantages and disadvantages of the codes, and LEI experience in using them in national and EU projects, COCOSYS code was selected for the containment atmosphere mixing analysis.

In the COCOSYS and other lumped-parameter codes there are two main sources of flows between control volumes – differences between their pressures and heights. When a flow reaches control volume, it changes the mass and energy inside the volume, but the flows momentum is lost. Consequentially, if a high momentum flow enters the control volume, the flow through the opposite junction will arise only due to increased pressure in the control volume, and not due to conserved momentum. If physical flows are modeled,which are physically caused by pressure differences, such modeling assumptions do not cause significant uncertainties. However, if flows with high momentum dominate, e.g., jets, uncertainties may become significant. It is possible to compensate this limitation by using appropriate nodalisation schemes.

4 RESULTS OF THE STUDY

Results of the experiment M5 simulation. A number of nodalisation schemes were tried. The basic scheme was obtained by subdividing the facility volume into 12 vertical layers and 4 radial parts (Fig. 4.1).

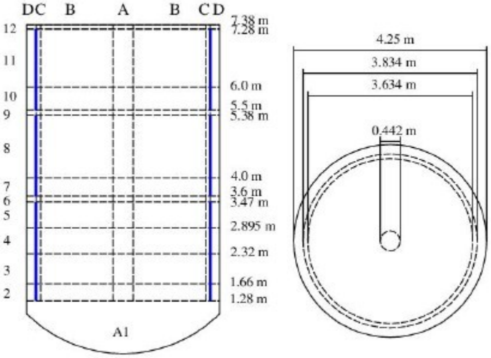

Figure 4.1. Basic nodalisation scheme of MISTRA test facility

Additional nodalisation schemes were obtained by increasing the a number of vertical layers by four or a number of radial subdivisions by one (fig. 4.2).

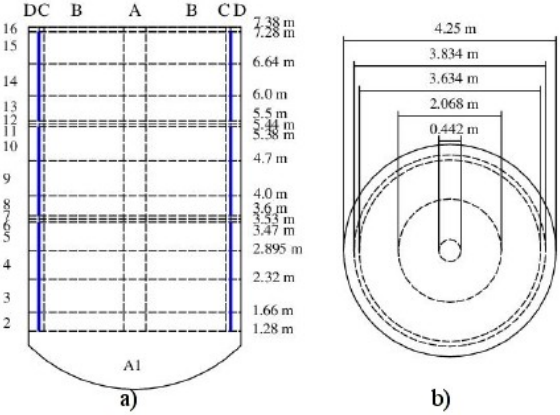

Figure 4.2. Schemes with an increased number of subdivisions, a) vertical, b) radial

These three schemes were also modified by adding injection zones (Fig. 1.1). And example of obtained scheme in the basic case is shown in Fig. 4.3.

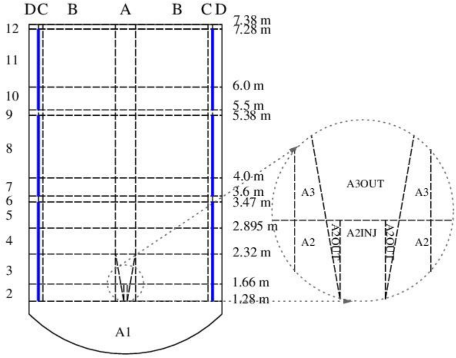

Figure 4.3. Basic scheme with injection zones

Fig. 4.4 presents comparison of pressure evolutions obtained from the calculations and measurements.

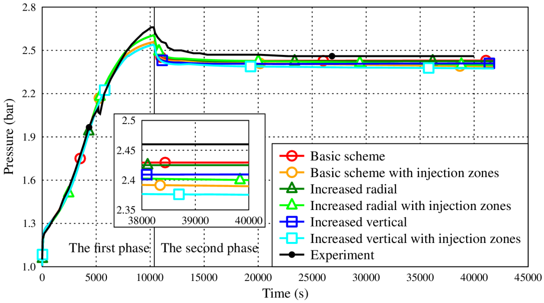

Figure 4.4. Calculated and measured pressure evolution

Differences of nodalisation schemes have no impact during the most part of the first phase. At the end of the second phase schemes with injection zones give lowest pressure values. Increasing a number of vertical layers also decreases the pressure, while increasing a number of radial parts has a very small impact.

Fig. 4.5 presents comparison of steam volume fraction distributions obtained from the calculations and measurements.

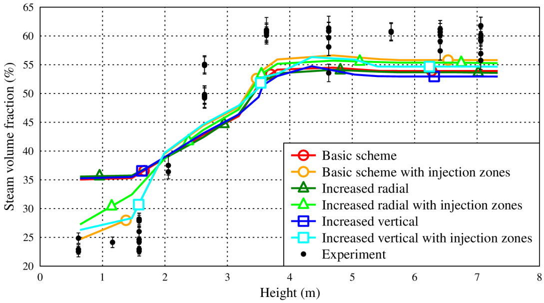

Figure 4.5. Calculated and measured steam distribution at the end of the experiment

Differences of nodalisation schemes have little influence at the upper part of the facility, however schemes with injection zones provide results closer to experimental values. At the lower part of the facility differences are much more pronounced and have the same tendency – schemes with injection zones provide results closer to the experimental values. This explains why schemes with injection zones provided worse pressure results – injection zones have influence only in the vicinity of the injection point, therefore steam concentration in the lower part of the facility decreased by 10 % almost to the experimental values, but in the upper part concentration increase was much lower, resulting in sum decrease of steam content in the facility, decreasing the pressure. The same applies to temperature too, only in this case injection zones had no impact in the upper part of the facility (Fig. 4.6).

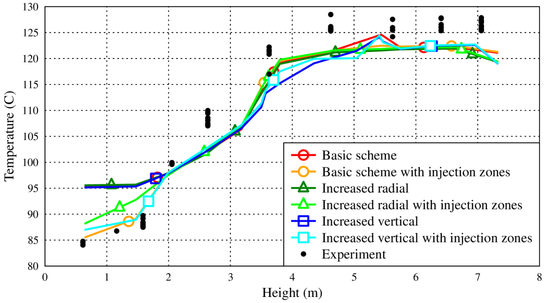

Figure 4.6. Calculated and measured temperature distribution at the end of the experiment

Fig. 4.7 shows the impact injection zones have on flow configuration in the lower part of the facility.

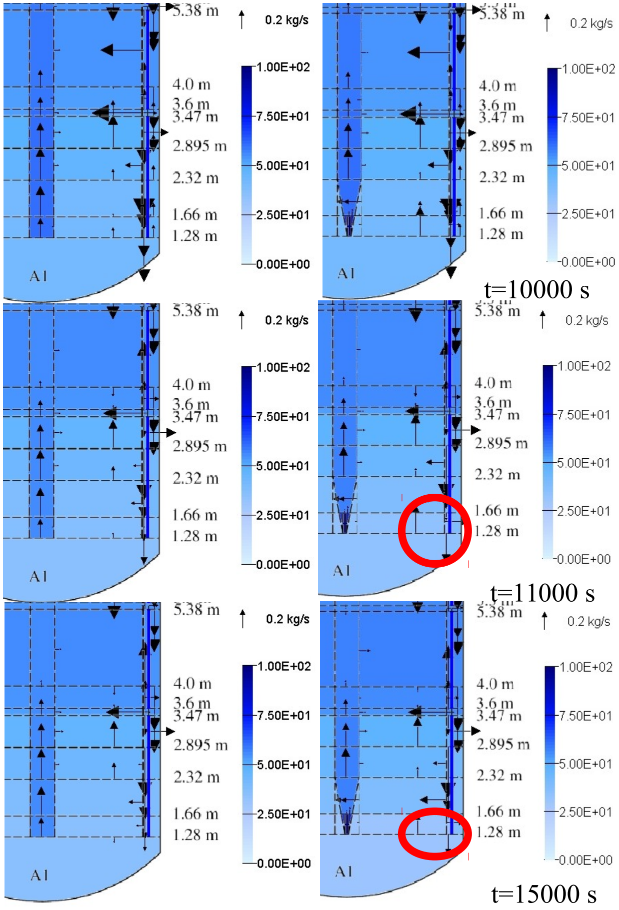

Figure 4.7. Gas flows obtained from the calculations with basic nodalisation scheme with and without injection zones

At the end of the first phase, 10000 s, flows are similar in both cases, with and without injection zones. The main difference is that with injection zones there is no flow from the bottom of the facility (zone “A1”) to the injection zones (“A2” and injection zones). Instead of that bigger flow is flowing into volume “B2”. This difference becomes very important when flows change during phase two. At 11000 s using basic scheme gas flows down along the bottom condenser to the volume “A1” and then flows up through the center of the facility. Using injection zones, very small flow reaches lower part of the bottom condenser, instead there is a closed loop formed flowing from the bottom of the bottom condenser to the volume “A1”, then “B2” and then again to the bottom condenser. So while in the basic scheme bottom volume of the facility participates in the global gas mixing, when using injection zones it becomes “cut off”, allowing for the steam concentration and temperature to fall. At 15000 s flows have the same configuration, but are smaller, showing that the isolation of the lower part of the facility is stabilizing.

As the injection zones allowed to obtain local correct results at the injection elevation, but were insufficient to obtain global correct results, dissertation author further developed recommendations found in the literature. According to developed method, the injection zones have to expand further, up to the top of the facility. The angle of the injection cone should not necessarily be equal to 20°. While modeling experiments M5 and ISP47 best results were obtained with 14° angle. The nodalisation scheme obtained using this method is shown in Fig. 4.8.

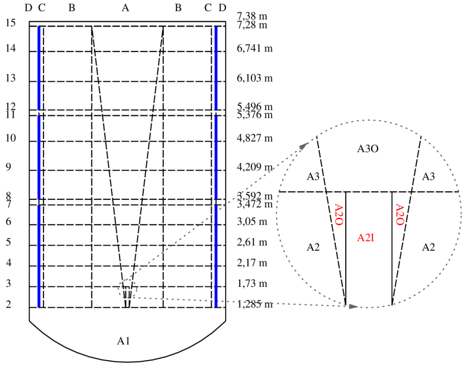

Figure 4.8. Nodalisation scheme according to developed methodology

The results presented below are compared to the results of nodalisation scheme prepared according to literature recommendations (Fig. 4.9).

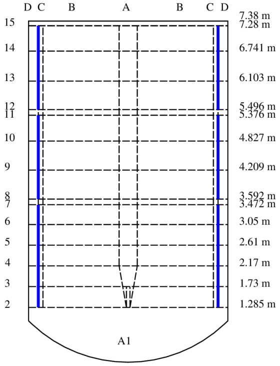

Figure 4.9. Nodalisation scheme according to literature recommendations

Fig. 4.10 presents pressure evolutions obtained from the calculations and the experiment.

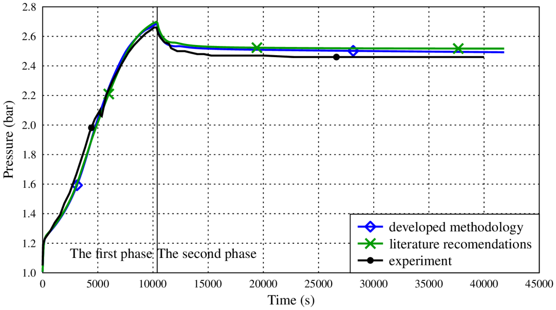

Figure 4.10. Calculated and measured pressure evolution

Qualitatively calculation results correspond to the experimental ones, quantitatively maximum first phase's pressure is over-predicted by 0.02 bar (0.75 %), final pressure is over-predicted by 0.03 bar (1.2 %). When using nodalisation prepared according to literature recommendations, simulations are less accurate – pressure differences are 0.04 bar and 0.06 bar.

Fig. 4.11 presents the comparison of steam volume distributions obtained from the calculations and measurements.

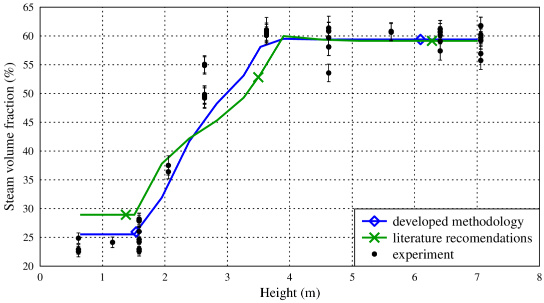

Figure 4.11. Calculated and measured steam distribution at the end of the experiment

Using methodology developed by the dissertation's author, steam volume fractions in the stratification layers obtained from the calculations fall into the intervals of measured values. Using nodalisation scheme prepared according to literature recommendations, steam concentration at the lower part of the facility is over-estimated by almost 5 %, also gradient part has a shape which does not correspond to the experiment measurements.

Fig. 4.12 presents comparison of temperature distributions obtained from the calculations and measurements.

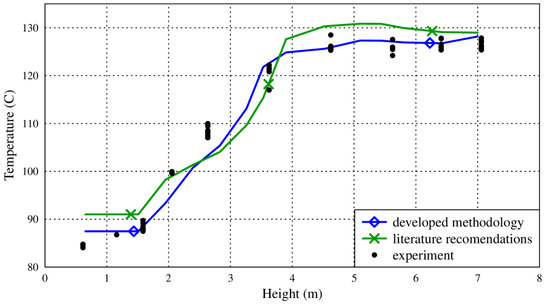

Figure 4.12. Calculated and measured temperature distribution at the end of the experiment

Temperature obtained from the calculations using developed methodology correspond to the experimental values, except at 2 – 3 m height. The results obtained using literature recommendations show temperature over-estimation for the most part of the facility.

Uncertainty and sensitivity analysis of the simulation results was performed using GRS methodology [24] and their software package SUSA [25]. 34 parameters were varied:

1. initial temperature, 23 – 25 °C, according to measurements,
2. initial pressure, 0.98 – 1.034 bar, according to measurements,

3. initial saturation, 40 – 60 %, no measurements were performed,
- I phase steam injection parameters:
    4. temperature, 199.4 – 201.4°C, according to measurements,
    5. pressure, 7 – 14 bar, 14 bar is circuit pressure, it should decrease in the injection cone by the unknown amount, no measurements were performed,
    6. mass flow rate (main), 0.0903 – 0.0935 kg/s, according to measurements,
    7. mass flow rate (additional), 0.0193 – 0.0199 kg/s, according to measurements,
- II phase steam injection parameters:
    8. temperature, 194.4 – 196.4 °C, according to measurements,
    9. pressure, 6 – 12.1 bar, 12.1 bar is circuit pressure,
    10. mass flow rate (main), 0.0784 – 0.0812 kg/s, according to measurements,

11. inner temperature of the bottom condenser, 76 – 80 °C,
12. inner temperature of the upper condensers, 139 – 141 °C,
13. heat transfer to the environment coefficient, 2 – 6, W/(m^{2}K), unknown, best estimate value of 4 W/(m^{2}K),
14. heat transfer to the condensers coefficient, 7000 – 9000, W/(m^{2}K), reference value 8000 W/(m^{2}K),
15. junction resistances, 0.25 – 1.75, modeling parameter, reference value 1,
16. heat-up time of the condensers, 6750 – 8250 s, best estimate value 7500 s,
17. opening area behind the bottom condenser, 0.652 – 1.434 m^2, values provided in the experiment specification,
18. opening area behind the upper condensers, 0.652 – 1.434 m^2, values provided in the experiment specification,
19. opening area between the condensers, 0.02 – 0.685 m^2, upper limit provided in the experiment specification,,
20. steam diffusion constant, 0.000052 – 0.000064 m^2/s, standard value ±10%,
21. air diffusion constant, 0.000018 – 0.000022 m^2/s, standard value ±10%,
22. steel specific heat, 400 – 525 J/K, standard value ±10%,
23. synthetic foam specific heat, 1200 – 1800 J/K, standard value ±10%,
24. rock wool specific heat, 640 – 960 J/K, standard value ±10%,
25. steal heat conductivity coefficient (multiplier, since a table of different coefficient values at different temperatures is used), 0.9 – 1.1, standard value ±10%,
26. synthetic foam heat conductivity coefficient, 0.02 – 0.032 W/(m K),

standard value ±10%,

27. rock wool heat conductivity coefficient, 0.15 – 0.45 W/(m K), standard value is 0.045 W/(m K), however previous experience and literature [26] shows, that due to structures which cross the isolation, effective heat conductivity coefficient is approximately 0.3 W/(m K).
28. steal density, 7000 – 8600 kg/m^3, standard value ±10%,
29. synthetic foam density, 85 – 115 kg/m^3, standard value ±10%,
30. rock wool density, 88 – 132 kg/m^3, standard value ±10%,
31. area behind the condensers, 2.302 – 2.545 m^2, values provided in the experiment specification,
32. fraction of steam injected into inner injection zone, 0.4 – 0.6, modeling parameter,
33. fraction of steam injected through additional line behind the condensers, 0.4 – 0.6,
34. effective area of condensers (fraction of geometric area), 0.8 – 1, due to irregular shape and additional elements (e.g., windows).

200 calculation runs were performed.

Fig. 4.13 shows obtained pressure tolerance limits.

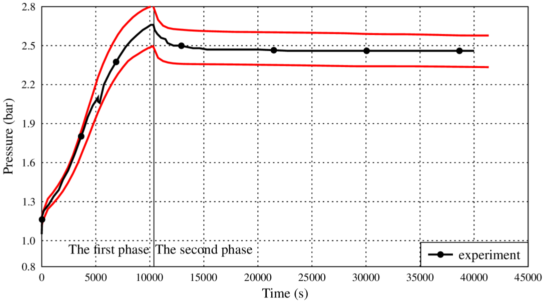

Figure 4.13. 0.95/0.95 tolerance limits of pressure

Experimental values fall into the tolerance interval during the whole experiment. Fig. 4.14 presents correlation coefficients of pressure and varied parameters (correlation coefficients which exceed 0.3 are shown).

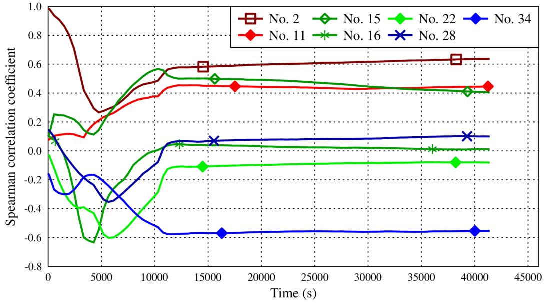

Figure 4.14. Correlation coefficients of pressure and varied parameters

The highest pressure correlation coefficient during almost all of the experiment is with an initial pressure (par. no. 2). Other parameters have higher coefficients only during the first phase – heat-up time of condensers (par. 16) and steal specific heat (par. 22). These parameters influence rate of temperature increase. Other influential parameters during the experiment are related to condensation – effective area of condensers (par. 34) and temperature of lower condenser (par. 11) and related to flow configuration – junction resistances (par. 15).

Fig. 4.15 Shows the obtained temperature and steam volume fraction distribution tolerance limits.

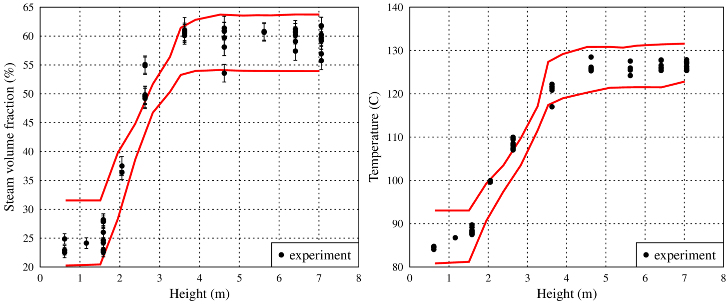

Figure 4.15. Tolerance limits of steam volume fraction (left) and temperature (right) at the end of the experiment

Both steam concentration and temperature tolerance intervals cover experimental values, except at 2.8 m height. If we looked at correlation coefficients (fig. 4.16), we would see that for the whole height of the facility, especially in steam concentration case, highest correlation coefficient is for the junction resistances (par. 15). Except at 2.8 m height, where junction resistance correlation coefficient is changing signs and other two parameters become influential – effective area of condensers and temperature of lower condenser. Since calculations provide accurate results where the dominating parameter is related to flows, and inaccurate where dominating parameters are related to condensation, we can conclude, that the developed methodology allows accurate simulation of gas mixing and observed inaccuracy of results is caused by issues in modeling of other processes, in this case – condensation.

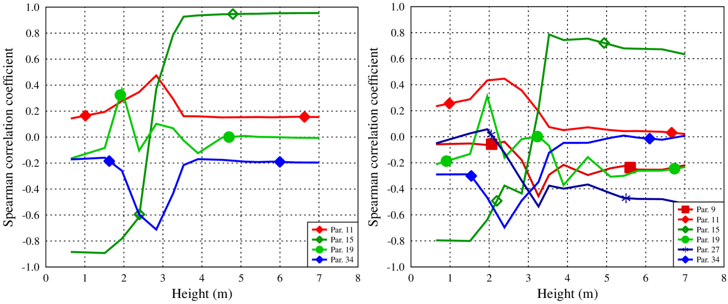

Figure 4.16. Spearman correlation coefficients of steam volume fraction (left) and temperature (right) at the end of the experiment

In order to make first step in verifying universality of developed methodology, other experiment was simulated with the same nodalisation scheme. It was selected to simulate ISP47 experiment, as it was performed in the same facility, but had different conditions – different mass flow rate of injected steam, different temperatures of condensers, no stratification and injection of helium gas. Fig. 4.17 shows calculated and measured pressure evolutions.

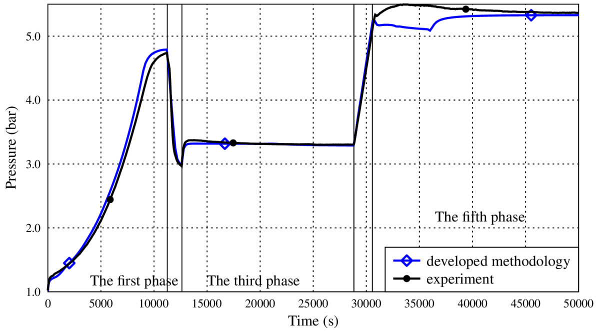

Figure 4.17. Calculated and measured pressure evolution

Numerical and experimental results have a good agreement, except at the beginning of the fifth phase, when helium injection is terminated and, initially, incorrect flow configuration is obtained, which is corrected after 36000 s. The flow configurations at 35000 s and 40000 s are presented in Fig. 4.18.

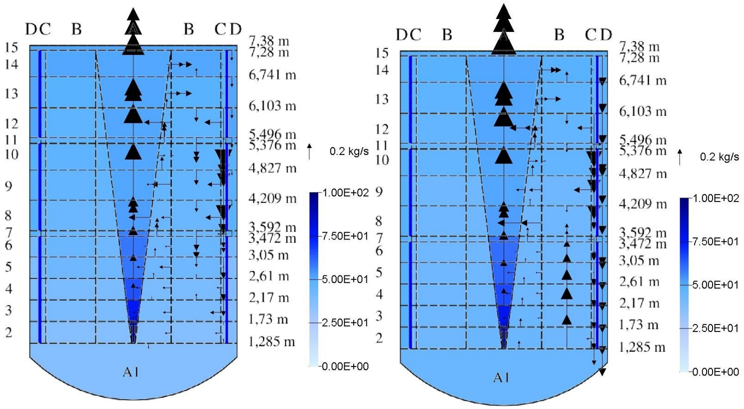

Figure 4.18. Flows in the facility at 35000 s (left) and 40000 s (right)

The main difference is the absence of flow behind the lower condenser at 35000 s. Fig. 4.19 presents temperature distribution at the end of the experiment.

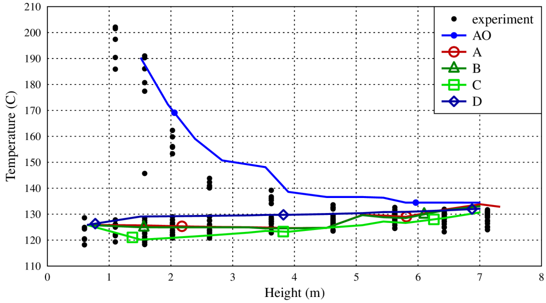

Figure 4.19. Calculated and measured temperature distribution at the end of the experiment

Correct values were obtained in the main volume of the facility, and slightly overestimated values were obtained in the jet mixing region. However, this discrepancy may be caused by a defect present in the diffusion cone during the experiment, which was later found. After defect was fixed, later experiments corresponding the simulated experiment show up to 5 °C higher temperatures in the mixing region [26].

Uncertainty and sensitivity analysis of the ISP47 experiment was also performed. The same parameters were varied as in M5 experiment case,except when conditions differed in the experiment (e.g. the initial conditions were different). Fig. 4.20 shows the obtained pressure tolerance limits.

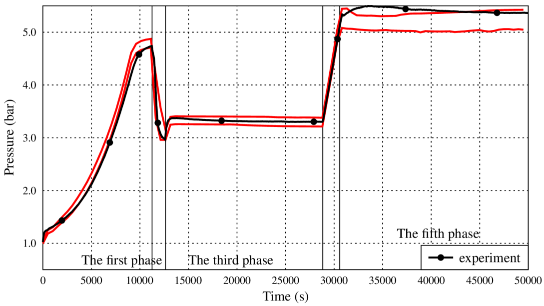

Figure 4.20. 0.95/0.95 tolerance limits of pressure

Experimental pressure values are inside the tolerance limit during the whole length of the experiment, except at the end of the first phase and beginning of the fifth phase, when incorrect flow configuration is obtained, however after flow reconfiguration tolerance interval covers the experimental results.

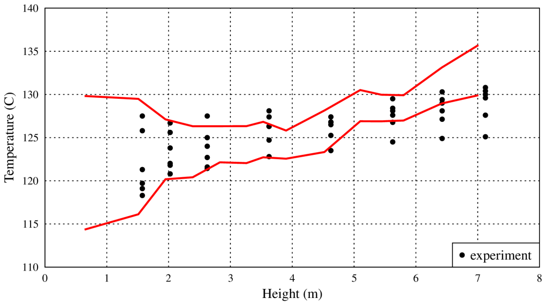

Figure 4.21. 0.95/0.95 tolerance limits of temperature distribution at the end of the experiment

Fig. 4.21 Presents the obtained tolerance limits of temperature distribution at the end of the ISP47 experiment. It can be seen that in the upper part of the facility temperature is overestimated. This may be caused by the previously described defect in the diffusion cone, because lower temperatures in the jet mixing region (rising gas region) would result in the lower temperatures of the gas reaching the top of the facility.

CONCLUSIONS

A study of gas mixing processes occurring in nuclear power plant containments was performed using lumped-parameter code COCOSYS. Methodology was developed and recommendations were provided for the lumped-parameter simulation of gas mixing initiated by the vertical gas jet injection. Experiments, conducted in the experimental facility corresponding to nuclear power plant containment, were modeled and the following conclusions were obtained:

1. Pressure obtained from the calculations performed according to the literature recommendations for the jet modeling is overpredicted by 2,4 %, steam and temperature values do not correspond to the experimental values.
2. Simulations performed using the author's developed methodology for the lumped-parameter modeling of gas mixing initiated by the jet are more accurate than the simulations performed using literature recommendations, including simulation of the entrainment of the surrounding gases and the processes occurring further away from the injection point. Using the method proposed by the author, results of the containment atmosphere mixing were:
    - 2.1. during the M5 experiment – pressure obtained from the calculations differed from the experimental by 1.2 %, steam volume fraction and temperature in the stratified zones fell into experimental intervals.
    - 2.2. TSP no. 47 experiment – pressure of stationary phases obtained from the calculations differed from the experimental results by 0.4% and 0.75%, gas and wall temperatures fell into the experimental results intervals, the concentration of helium qualitatively corresponds to the experiment.
3. The study showed that the containment atmosphere mixing in simulated cases was determined by three dominant processes - gas injection into the atmosphere, heat losses and condensation. Stationary gas and temperature distributions and pressure are the result of the interaction processes.
4. Performed uncertainty and sensitivity analysis showed that:
    - 4.1. the final pressure of M5 experiment is not sensitive to uncertainties of the processes - the range between the lower and upper limits of tolerance was 0.24 bar (~ 10% of the final pressure), and is mainly governed by the initial pressure uncertainty and effective condenser area (during the most part of the experiment Spearman ordinal correlation coefficient greater than ~ 0.6);
    - 4.2. influence of parameters on the TSP No. 47 experiment pressure during the third phase of the experiment correspond to the case of experiment M5, but the coefficient of correlation with the initial pressure increases up to 0.8. Pressure of the fifth phase was determined by the flow distribution in the facility, therefore

increases influence of junction resistances' and upper condensers' temperature's uncertainties;

4.3. in the M5 experiment, steam distribution uncertainties were most affected by the gas flow related parameter – junction resistances (during the most part of the experiment Spearman ordinal correlation coefficient greater than ~ 0.7). This parameter and a coefficient of the facility insulation thermal conductivity have a significant impact on the temperature distribution.

4.4. In the TSP no. 47 experiment junction resistances remain important in the upper part of the facility, but the whole height of the stand is dominated by the uncertainties of the effective area of the condensers, upper condensers' temperature and initial pressure.

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Publications in the journals included in the main list of Institute of Scientific Information

1. Povilaitis, M., Urbonavičius, E., Rimkevičius, S., Modeling of atmosphere stratification in containments of nuclear power plants using lumped-parameter code. Nuclear Engineering and Design. ISSN 0029-5493. 2011, 241(8), 3111–3120.
2. Povilaitis, M., Urbonavičius, E., Rimkevičius, S., Babilas, E., Sensitivity and uncertainty analysis of atmosphere stratification modelling in MISTRA using lumped-parameter code COCOSYS. Nuclear Engineering and Design. ISSN 0029-5493. 2013. 265, 108-119.

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1. Povilaitis, M., Urbonavičius, E., MISTRA stende vykdytų MASP-n eksperimentų modeliavimas COCOSYS programų paketu. Energetika. 2008, 54(1), 22–29. [INSPEC, Index Copernicus]
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1. Kaliatka, A., Povilaitis, M., Urbonavičius, E., Kaliatka, T., Analysis of the consequences of targets feeding pipe rupture in Wendelstein 7-X experimental nuclear fusion device. Proceedings of NUTHOS-8. 2010 (pp. 1–12). Shanghai, China.
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2002 graduated from the Dainava secondary school in Kaunas.

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REZIUMĖ

Sunkiosios avarijos branduolinėje jėgainėje atveju būtų sugeneruoti dideli vandenilio kiekiai, kurie nutekėtų į apsauginio kiauto atmosferą. Joje susidarytų sprogūs/degūs vandenilio ir oro mišiniai vietose, kuriose vandenilio tūrinė koncentracija patektų į 4–75 % intervalą. Tokio mišinio sprogimas keltų pavojų apsauginio kiauto vientisumui. Sprogimo stiprumas priklausytų nuo sprogaus mišinio kiekio, vandenilio koncentracijos jame ir degimo režimo. Todėl, norint užtikrinti apsauginio kiauto vientisumą, yra būtina numatyti vandenilio elgesį jo atmosferoje, o tai leistų išplėtoti efektyvias riziką mažinančias priemones.

Branduolinės jėgainės apsauginio kiauto atmosferos maišymasis yra svarbi branduolinės saugos problema susijusi su vandenilio sprogimo pavojumi. Jai yra atlikta nemažai tarptautinių eksperimentinių ir skaitinių tyrimų, tarp jų ir kelios Tarptautinės standartinės problemos.

Vienas atliktų tyrimų rezultatų yra išvada, kad apsauginio kiauto atmosferos maišymosi modeliavimas naudojant branduolinėje saugoje plačiai paplitusius suvidurkintų parametrų programinius paketus yra komplikuotas dėl šiuose paketuose taikomo modeliavimo metodo. Tačiau taip pat buvo nustatyta, kad atskirais atvejais, kai modeliavimui būdavo naudojamos tinkamos nodalizacinės schemos, šiais programiniais paketais gauti rezultatai pakankamai gerai atitikdavo eksperimentinius.

Darbe pristatomas dujų maišymosi procesų apsauginiuose branduolinių įrenginių kiautuose tyrimas, atliktas taikant suvidurkintų parametrų metodą. Tyrimo metu buvo sumodeliuoti du MISTRA eksperimentiniame stende atlikti eksperimentai – M5 ir TSP nr. 47. Modeliavimui buvo naudojamas suvidurkintų parametrų programinis paketas COCOSYS.

Tyrimo metu buvo išplėtota metodika, skirta dujų maišymosi procesams apsauginio kiauto atmosferoje modeliuoti vertikalios dujų ar vandens garų čiurkšlės įpurškimo atveju.

Darbo aktualumas. Branduolinių jėgainių apsauginis kiautas yra paskutinis barjeras neleidžiantis radioaktyvioms medžiagoms patekti į aplinką. Todėl yra ypatingai svarbu avarijos metu išlaikyti apsauginio kiauto vientisumą, leidžiantį jam atlikti barjero funkciją. Viena pagrindinių grėsmių apsauginio kiauto vientisumui sunkiosios avarijos atveju yra galimas vandenilio degimas/sprogimas. Šio degimo/sprogimo pavojingumas apsauginiam kiautui priklauso nuo vandenilio ir dujų srautų pasiskirstymo jo atmosferoje, kadangi mišinio sudėtis ir turbulentiškumas nulemia jo degimo režimą. Ypač svarbu numatyti ar dėl maišymosi ir stratifikacijos nesusidarys pavojingos lokalios koncentracijos. Todėl norint tinkamai įvertinti vandenilio keliamą grėsmę, kad būtų galima nustatyti reikalingas prevencines ar avarijų valdymo priemones, dujų maišymosi skaičiavimai turi tenkinti tam tikrus tikslumo reikalavimus. Tačiau branduolinėje saugoje plačiai naudojamų ir validuotų visų svarbių projektinių avarijų metu vykstančių procesų modeliavimui suvidurkintų parametrų programų paketų gebėjimas tiksliai (tikslumu pakankamu vandenilio sprogimo pavojingumo neprojektinės avarijos atveju įvertinimui) modeliuoti dujų maišymąsi nėra iki galo pagrįstas stratifikacijos ir stiprių srovių atveju.

Darbo tikslas. Išnagrinėti dujų maišymosi procesus apsauginiuose branduolinių įrenginių kiautuose naudojant suvidurkintų parametrų metodą.

Darbo uždaviniai:

1) Išplėtoti dujų maišymosi apsauginiuose branduolinių įrenginių kiautuose modeliavimo metodiką suvidurkintų parametrų modeliavimo metodui.
2) Patikrinti išplėtotą metodiką, atliekant eksperimentų, kuriuose tiriami dujų maišymosi procesai, modeliavimą.
3) Atlikti dujų maišymosi procesų apsauginiame branduolinės jėgainės kiaute skaitinį tyrimą suvidurkintų kintamųjų metodu.
4) Atlikti modeliavimo rezultatų neapibrėžtumų ir parametrų jautrumo analizę.

Tyrimo objektas. Dujų maišymosi procesai branduolinių jėgainių apsauginiuose kiautuose.

Darbo mokslinis naujumas.

Išplėtotu suvidurkintų parametrų metodu vertikalia čiurkšle inicijuotam dujų maišymuisi modeliuoti patikslinta šio proceso apsauginiame branduolinės jėgainės kiaute tyrimo metodologija.

Naudojant pasiūlytą metodiką atlikti dujų maišymosi tyrimai, apimantys procesus ties įpurškimo tašku, visame čiurkšlės aukštyje ir likusiame apsauginio kiauto tūryje.

Ginamieji disertacijos teiginiai:

1. Naudojant literatūroje pateikiamas rekomendacijas dujų maišymosi modeliavimui vertikalios dujų čiurkšlės atveju, apskaičiuoti dujų ir garo pasiskirstymo bei termohidrauliniai parametrai nepatenka į eksperimentinių rezultatų verčių intervalus.
2. Autoriaus išplėtota metodika leidžia tiksliau sumodeliuoti garo koncentracijos ir temperatūros stratifikacijos susidarymą vertikalios dujų čiurkšlės atveju naudojant suvidurkintų parametrų programų paketus nei iki šiol literatūroje pateiktos rekomendacijos.
3. Įpurškiama garo čiurkšlė kartu su karštais ir šaltais paviršiais nulemia dujų srautų, temperatūros ir garo pasiskirstymą stendo atmosferoje. Slėgio vertė yra nulemiama įpurškiamo ir sukondensuojamo garo masių srautų dydžių.
4. Reikšmingiausi neapibrėžtumų šaltiniai modeliuojant M5 eksperimentą yra šių parametrų neapibrėžtumai:
    1) pradinio stendo slėgio,
    2) stendo termoizoliacijos – akmens vatos – šiluminio laidumo koeficiento,
    3) pasipriešinimo atmosferinėse jungtyse koeficiento,
    4) efektyviojo kondensatorių ploto.

Praktinė svarba. Suvidurkintų parametrų skaičiavimo paketų naudojimas dujų maišymosi procesams modeliuoti yra komplikuotas ir ne iki galo pagrįstas dėl apribojimų susijusių su šiuo metodu. Darbe išplėtota metodika nurodo, kaip galima atsižvelgti į šiuos apribojimus modeliuojant tokius procesus, o tai įgalina plačiai branduolinėje saugoje naudojamų suvidurkintų parametrų paketų pritaikymą ir dujų maišymosi procesams modeliuoti.

Darbo rezultatų aprobavimas. Disertacijos tema paskelbti 2 moksliniai straipsniai leidiniuose, įrašytuose Mokslinės informacijos instituto (ISI) pagrindinių leidinių sąraše bei 3 straipsniai mokslo leidiniuose, registruotuose tarptautinėse mokslinės informacijos duomenų bazėse. Rezultatai pristatyti 9 tarptautinėse konferencijose.

IŠVADOS

Atliktas dujų maišymosi procesų branduolinių jėgainių apsauginiuose kiautuose tyrimas suvidurkintų parametrų programiniu paketu COCOSYS, išplėtota metodika ir pasiūlytos rekomendacijos dujų maišymuisi modeliuoti suvidurkintų parametrų metodu vertikalios dujų čiurkšlės atveju. Atlikus eksperimentų, vykdytų stende, atitinkančiame branduolinės jėgainės apsauginį kiautą, modeliavimą, gautos išvados:

1. Atliekant M5 eksperimento modeliavimą pagal literatūroje rastas rekomendacijas čiurkšlei modeliuoti, apskaičiuotas slėgis viršija eksperimentinį 2,4 %, garo tūrinė koncentracija ir temperatūra nepatenka į eksperimentinių rezultatų verčių intervalus.
2. Naudojant autoriaus išplėstą metodiką čiurkšlei modeliuoti, suvidurkintų kintamųjų metodu galima tiksliau nei naudojant tik literatūros rekomendacijas sumodeliuoti apsauginio kiauto atmosferos maišymąsi vertikalios dujų čiurkšlės atveju, įskaitant aplinkinių dujų įtraukimą į srautą ir toliau nuo įpurškimo taško vykstančius procesus. Naudojant autoriaus pasiūlytą metodiką sumodeliuotas apsauginio kiauto atmosferos maišymasis:
    2.1. M5 eksperimento metu – apskaičiuotas slėgis nuo eksperimentinio skiriasi 1,2 %, garo tūrinė koncentracija ir temperatūra stratifikuotose atmosferos dalyse patenka į eksperimentų rezultatų verčių intervalus,
    2.2. TSP nr. 47 eksperimento metu – apskaičiuotas slėgis nuo eksperimentinio stacionariose fazėse skiriasi 0,4 % ir 0,75 %, dujų ir sienų temperatūros patenka į eksperimento rezultatų verčių intervalus, helio koncentracija kokybiškai atitinka eksperimentų rezultatus.
3. Tyrimas parodė, kad dujų maišymąsi apsauginiame kiaute modeliuotais atvejais nulemia trys vyraujantys procesai – dujų ištekėjimas į kiauto atmosferą, šilumos mainai su aplinka ir kondensacija. Nusistovintys dujų ir temperatūrų pasiskirstymai bei slėgis yra šių procesų sąveikos rezultatas.
4. Atlikta neapibrėžtumų ir jautrumo analizė parodė, kad
    4.1. M5 eksperimento slėgis nėra jautrus vykstančių procesų neapibrėžtumams – intervalas tarp apatinės ir viršutinės tolerancijos ribų yra 0,24 bar (~10 % galutinio slėgio) ir daugiausia yra nulemiamas pradinio slėgio neapibrėžtumo ir efektinio kondensatorių ploto (didžiąją eksperimento dalį Spirmeno ranginės koreliacijos koeficientas didesnis nei ~0,6);
    4.2. parametrų įtaka TSP nr. 47 eksperimento slėgiui trečiosios fazės metu atitinka M5 eksperimento atvejį, tik iki 0,8 padidėja pradinio slėgio koreliacijos koeficientas. Penktosios fazės metu slėgį nulemia srautų pasiskirstymas stende, todėl daugiausiai įtakos įgauna pasipriešinimas jungtyse ir viršutinių kondensatorių temperatūros neapibrėžtumas;
    4.3. M5 eksperimente garo pasiskirstymo neapibrėžtumams daugiausiai įtakos turi su dujų srautu susijęs parametras – pasipriešinimas

jungtyse (didžiąją eksperimento dalį Spirmeno ranginės koreliacijos koeficientas didesnis nei ~0,7). Šis parametras turi didelės įtakos ir temperatūros pasiskirstymui, kaip ir stendo izoliacijos šiluminio laidumo koeficientas.

4.4. TSP nr. 47 eksperimente jungčių pasipriešinimai išlieka svarbūs stendo viršuje, tačiau per visą stendo aukštį vyrauja efektinio kondensatorių ploto, viršutinių kondensatorių temperatūros ir pradinio slėgio neapibrėžtumai.

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