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Modeliranje razslojene atmosfere v eksperimentalni napravi jedrske elektrarne s popisom z zgoščenimi parametri

Modelling of the Stratified Atmosphere in a Nuclear Power Plant Experimental Facility with a Lumped-Parameter Description

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Opisano je modeliranje nehomogene večkomponentne atmosfere v večprostorskem zadrževalnem hramu jedrske elektrarne z uporabo popisa z zgoščenimi parametri. Modeliranje je uporabljeno pri obravnavanju obnašanja vodika v hramu v nezgodnih razmerah. Glavna prednost predlaganega postopka je možnost modeliranja pojavov v zapletenih večprostorskih zadrževalnih hramih. Kot ponazoritev je bil simuliran poskus E11.2 "Porazdelitev vodika v tokovni zanki", ki je bil izveden na integralni eksperimentalni napravi "Heissdampf Reaktor" (Nemčija). Vhodni model za metodo zgoščenih parametrov je bil razvit za računalniški program CONTAIN. Izračunani tlak, temperature in koncentracije vodika so primerjani z eksperimentalnimi vrednostmi. Dobljena je bila dobra kakovostna napoved razslojevanja atmosfere, kar podpira ustreznost postopka z zgoščenimi parametri.

(Ključne besede: modeli zgoščenih parametrov, mešanje, razslojevanje, CONTAIN)

In this paper we describe the modelling of a non-homogeneous multi-component atmosphere in a multi-compartment nuclear power plant containment using a lumped-parameter approach. The modelling is applied to the topic of hydrogen behaviour in the containment at accident conditions. The main benefit of the proposed approach is the possibility of modelling the phenomena in complex, multi-compartment containments. As an illustration, the experiment E11.2 "Hydrogen distribution in loop flow geometry", which was performed in the integral experimental facility "Heissdampf Reaktor" (HDR) in Germany, was simulated. A lumped-parameter input model of the HDR facility was developed for the computer code CONTAIN. The calculated pressure, temperature and hydrogen concentrations are compared to experimental values. A good qualitative prediction of the atmosphere stratification was achieved, which supports the adequacy of the lumped-parameter approach.

(Keywords: lumped-parameter models, mixing, stratified atmosphere, CONTAIN)

0 UVOD

Pomemben predmet raziskav na področju jedrske varnosti je mešanje in razslojevanje nehomogene večkomponentne atmosfere v velikih eno- ali večprostorskih zadrževalnih hramih. Čeprav povečanje računalniške moči zadnjih nekaj let omogoča modeliranje teh pojavov s trenutnim lokalnim popisom (npr. z uporabo t.i. programov za računalniško dinamiko tekočin), ti izračuni še vedno terjajo razmeroma veliko računskega časa. Poleg tega, ker se razvoj numerične mreže za večprostorski hram lahko izkaže za zapleteno nalogo, prednosti uporabe trenutnega lokalnega postopka ne bodo

0 INTRODUCTION

An important research topic in the field of nuclear safety is the mixing and stratification of a non-homogeneous multi-component atmosphere in large single or multi-compartment containments. Although the increase in computer power in the past few years allows the modelling of these phenomena with local instantaneous description (for instance, using so-called Computational Fluid Dynamics codes), these calculations still require relatively long computation times. Besides, as the development of a numerical grid for a multi-compartment containment can prove to be a complicated task, the benefits of using a local instantaneous descripvedno upravičile potrebni napor. Zato bodo postopki, ki temeljijo na "brez-razsežnem" popisu z zgoščenimi parametri, do nadaljnjega verjetno še naprej prevladovali, vsaj za močno razdeljene zadrževalne hrame. Pri tem postopku je hram modeliran kot mreža nadzornih prostornin, ki so povezani s tokovnimi potmi. Pogoji v vsaki prostornini so modelirani kot homogeni, medtem ko je tok tekočine v tokovnih poteh modeliran kot enorazsežen. Učinki fizikalnih pojavov, ki so primarni vzrok za mešanje in razslojevanje atmosfere (vzgon, turbulenca, konvektivni tok, prenos toplote), so torej modelirani na krajevnih skalah reda velikosti razsežnosti predelkov v zadrževalnem hramu. Postopek z zoščenimi parametri so za modeliranje nehomogene atmosfere uporabili že številni avtorji ([1] do [5]), čeprav so nekateri izmed njih izrazili dvome o ustreznosti postopka [2]. Glavni namen tega dela je prispevati k reševanju tega vprašanja.

Vprašanje mešanja in razslojevanja atmosfere je predvsem bistveno za raziskovanje obnašanja vodika v zadrževalnih hramih jedrskih elektrarn. Med resno nezgodo v vodno hlajenih jedrskih reaktorjih bi namreč domnevno prišlo do sprostitve in izpusta velike količine vodika v zadrževalni hram elektrarne. Vodik lahko nastane pri reakciji med hladilom in gorivnimi palicami pri povišani temperaturi, pri interakciji med betonom in staljeno reaktorsko sredico ter pri radiolizi[1] vode. Atmosfera v zadrževalnem hramu bi se razslojila, ker bi se vodik zaradi manjše gostote zbiral v višjih legah hrama. Zato bi lokalna koncentracija vodika v zadrževalnem hramu lahko presegla mejno vrednost, nad katero se vodik vname in zgoreva. Zaradi toplotnih in mehanskih obremenitev bi zgorevanje vodika ogrozilo celovitost hrama, kar bi lahko privedlo do uhajanja radioaktivnih snovi v okolico. Pravilno napovedovanje obnašanja vodika pri scenarijih resnih nezgod je zato pomembno za oceno verjetnosti, da bo prišlo do zgorevanja.

Da bi razumeli obnašanje vodika v zadrževalnem hramu v primeru resne nezgode ter razvili primerne strategije ukrepanja, so bili prav tako opravljeni številni poskusi porazdeljevanja in zgorevanja vodika ([5] do [8]). Rezultati poskusov dajejo informacije o pojavih v zadrževalnem hramu med resno nezgodo ter so hkrati lahko namenjeni kot testni primeri za preizkušanje teoretičnih modelov. Eden izmed najbolj znanih poskusov o razslojevanju atmosfere je test E11.2 "Porazdelitev vodika v tokovni zanki" ([6] in [7]), ki je bil opravljen na integralni testni

tion may not always justify the necessary effort. Thus, approaches based on "zero-dimensional" lumped-parameter descriptions are likely to prevail for the time being, at least for strongly compartmentalised containments. In this approach, a containment is modelled as a network of control volumes that are connected by flow paths. The conditions in each control volume are modelled as homogeneous, whereas the fluid flow in flow paths is modelled as one-dimensional. Thus, the effects of the physical phenomena that are primarily responsible for atmosphere mixing and stratification (buoyancy, turbulence, convective flow, heat transfer) are modelled on length scales of the order of magnitude of the compartment dimensions in the containment. The lumped-parameter approach has already been used for modelling a non-homogeneous atmosphere by many authors ([1] to [5]), although some of them have questioned the adequacy of the approach [2]. The main purpose of the present work is to contribute to the resolution of this issue.

The topic of atmosphere mixing and stratification is mostly relevant to an investigation of hydrogen behaviour in the containments of nuclear power plants. This because during a severe accident in a water-cooled nuclear reactor, large quantities of hydrogen would presumably be generated and released into the containment of the plant. Hydrogen could be generated as a result of a reaction between the coolant and the fuel rods at high temperatures, as a result of an interaction between the containment concrete and the molten reactor core and as a result of water radiolysis[1] . The containment atmosphere would stratify, as hydrogen would accumulate in the higher containment regions due to its lower density. Local hydrogen concentrations could thus exceed flammability limits. Hydrogen burning would threaten the containment integrity due to thermal and mechanical loads, which could result in the release of radioactive material to the environment. An accurate prediction of the non-homogeneous hydrogen distribution is thus necessary to estimate the likelihood of combustion.

To understand hydrogen behaviour in a containment during a severe accident and to develop adequate mitigating procedures, experiments on hydrogen distribution and combustion have been carried out ([5] to [8]). Experimental results provide information about containment phenomena during severe accidents and can also be used as benchmarks for testing theoretical models. One of the most well-known experiments on atmosphere stratification is the test E11.2 "Hydrogen distribution in loop flow geometry" ([6] and [7]), which was performed on the integral experimental facility napravi “Heissdampf Reaktor” (HDR - reaktor s pregreto paro RPP) v Nemčiji leta 1989 ter bil kasneje uporabljen za OECD Mednarodni standardni problem ISP-29 ([9] in [10]). Test E11.2 je simuliral pojave v zadrževalnem hramu zaradi hipotetične male izlivne nezgode in izpusta vodika. Namen poskusa je bila analiza prostorske porazdelitve vodne pare, zraka in vodika v večprostorskem zadrževalnem hramu jedrske elektrarne v razmerah resne nezgode. V tem delu so eksperimentalni rezultati uporabljeni za oceno primernosti postopka z zgoščenimi parametri za modeliranje nehomogene prostorske porazdelitve plinastih komponent.

1 VHODNI MODEL Z ZGOŠČENIMI PARAMETRI TESTA E11.2

1.1 Popis z zgoščenimi parametri

Pri popisu z zgoščenimi parametri je zadrževalni hram jedrske elektrarne, modeliran kot mreža medsebojno povezanih nadzornih prostornin ali “celic”[2]. V vsaki celici so razmere (tlak, temperatura, sestava atmosfere) modelirane kot homogene ter ustrezajo prostorninskim povprečjem. Celice lahko ustrezajo dejanskim predelkom ali delom predelkov[3] (če naj bi modelirali nehomogeno atmosfero v predelku). Pri nekaterih popisih lahko celice vsebujejo bazen kapljevine na dnu. Celice so povezane s t.i. tokovnimi potmi, ki omogočajo pretok plina in kapljevine. Tok v tokovnih poteh je modeliran z enorazsežnim popisom, kar vključuje predpisovanje koeficientov tokovnih izgub in t.i. “vztrajnostnih dolžin” poti. Tok plina in kapljevine znotraj celic ni modeliran. Domnevne vrednosti hitrosti plina znotraj celic, ki so lahko potrebne v korelacijah za prenos toplote in snovi, so določene iz hitrosti plinov v tokovnih poteh, ki so povezane z obravnavano celico. Celice lahko tudi vsebujejo “toplotne strukture”, ki delujejo kot sprejemniki toplote in ponujajo kondenzacijske površine. Vmesne toplotne strukture, npr. stene, ki so skupne več celicam, prav tako omogočajo prenos toplote med celicami.

1.2 Termo-hidravlični računalniški program CONTAIN

V tem delu je bil postopek z zgoščenimi parametri dopolnjen z uporabo programa CONTAIN [11]. Program je bil razvit v Sandia National Laboratories (ZDA) s sofinanciranjem Zvezne

“Heissdampf Reaktor” (HDR) in Germany in 1989 and was later used for the OECD International Standard Problem ISP-29 ([9] and [10]). The test E11.2 simulated containment phenomena due to a hypothetical small-break loss-of-coolant accident and hydrogen release. The purpose of the experiment was to analyse the spatial distribution of steam, air and hydrogen in the multi-compartment containment of a nuclear power plant under severe accident conditions. In the present work, the experimental results were used to assess the adequacy of the lumped-parameter approach for modelling the non-homogeneous spatial distribution of gaseous components.

1 LUMPED-PARAMETER MODEL OF TEST E11.2

1.1 Lumped-parameter description

In the lumped-parameter description, the containment of a nuclear power plant is modelled as a network of interconnected control volumes or “cells”[2] . In each cell the conditions (pressure, temperature, atmosphere composition) are modelled as homogeneous and correspond to volume-averaged values. The cells can correspond to actual compartments or parts of a compartment[3] (if the non-homogeneous atmosphere in a compartment is to be modelled). In some descriptions, cells can contain a liquid pool on the floor. The cells are connected by so-called flow paths, which allow the flow of gas and liquid. The flow in flow paths is modelled using one-dimensional descriptions, which includes the prescription of flow-loss coefficients and so-called flow-path “inertial lengths”. The flow of gas and liquid within cells is not modelled. The values of gas velocities within cells, which may be needed in correlations for heat and mass transfer, are determined from the gas velocities in flow paths connected to the considered cell. Cells may also contain “heat structures”, which act as repositories of thermal energy and provide condensation surfaces. Intermediate heat structures, such as walls, which are common to more than one cell, also enable heat transfer between cells.

1.2 The CONTAIN thermal-hydraulic computer code

In the present work, the lumped-parameter approach was implemented using the CONTAIN code [11]. The code was developed at Sandia National Laboratories (USA) under the sponsorship of the US Nuclear upravne jedrske komisije ZDA (US NRC) za analizo pojavov v zadrževalnem hramu v razmerah projektnih in resnih nezgod. CONTAIN omogoča napoved fizikalnih, kemičnih in radioloških razmer znotraj hrama po izpustu razcepkov iz reaktorskega hladilnega sistema. Program ne obravnava pojavov v hladilnem sistemu. Na Institutu “Jožef Stefan” so bile s programom CONTAIN že izvedene različne simulacije ([12] do [17]).

1.3 Opis eksperimentalne naprave HDR

Zadrževalni hram integralne eksperimentalne naprave HDR ima krožni prerez s polkrogelno kupolo (sl. 1). Višina zadrževalnega hrama je 60 m, prosta prostornina pa približno 11300 m^3. Spodnji del hrama je razdeljen na 70 predelkov, medtem ko je prostorna kupola (približno 4800 m^3) nerazdeljena. Dve diametralno nasprotni stopnišči (vijačno in navadno) sta glavni navpični tokovni poti v hramu.

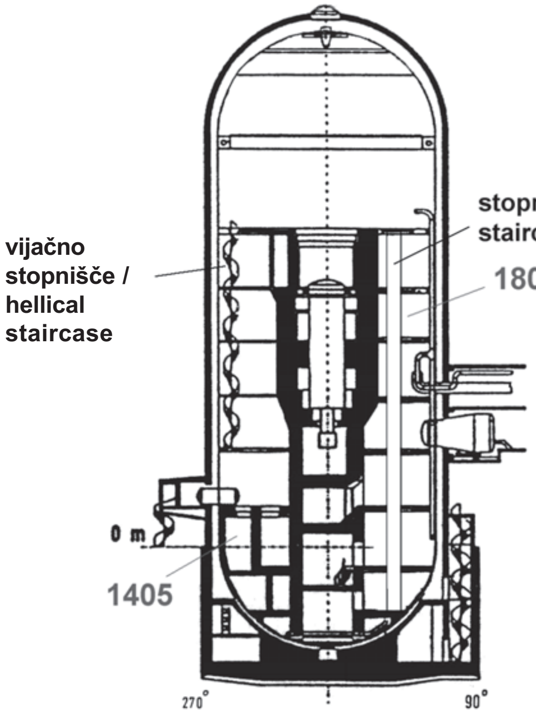
Zunanje prhe so nameščene na zgornjem delu kupole med zunanjo betonsko steno in notranjo jekleno lupino hrama. Prhe so zasnovane tako, da omočijo zunanjo stran polkrogelnega dela jeklene lupine.

Regulatory Commission for analysing containment phenomena under design-basis and severe accident conditions. CONTAIN allows the prediction of physical, chemical and radiological conditions inside the containment following the release of fission products from the reactor coolant system. The code does not model phenomena in the coolant system. At the “Jožef Stefan” Institute, the CONTAIN code has already been used to carry out various simulations ([12] to [17]).

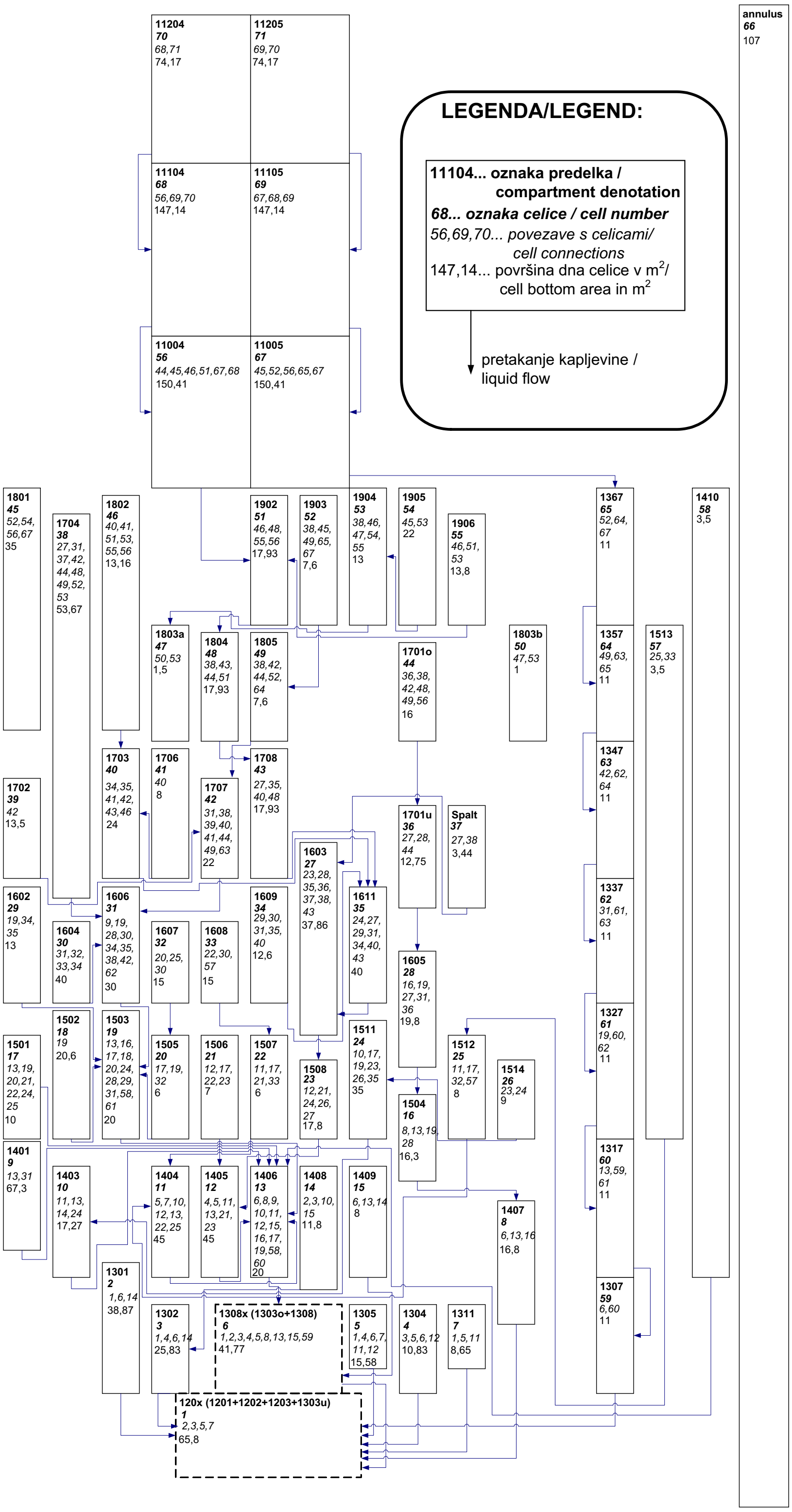
1.3 Description of the HDR experimental facility

The containment of the HDR integral experimental facility has a circular cross-section with a hemispherical dome (fig. 1). The containment is 60-m high with an approximate free volume of 11300 m^3. The containment lower part is divided into 70 compartments, whereas the large dome (approximately 4800 m^3) is not subdivided. Two diametrically opposite staircases (hellical and normal) represent the main vertical flow paths in the containment.

External sprays are located in the dome’s upper part, between the outer concrete wall and the inner containment steel shell. The sprays are designed to wet the external surface of the hemispherical part of the steel shell.



Sl. 1. *Shematični prikaz zadrževalnega hrama HDR in izvirov [9]*
Fig. 1. *Schematic of HDR containment and sources [9]*



Sl. 2. *Shematični prikaz razporeditve in povezav celic v vhodnem modelu*

Fig. 2. *Schematic of cell disposition and connections in the input model*

1.4 Celice zadrževalnega hrama

Za program CONTAIN je bil razvit vhodni model HDR, ki temelji na podatkih o napravi in opisu testa E11.2 [9]. Prostorski vhodni model sestoji iz 71 celic (sl. 2). Dodatna celica (št. 72) predstavlja okolico, ki je v toplotnem stiku z zunanjo steno zadrževalnega hrama. Vsaka celica v modelu predstavlja po en predelek v hramu, razen kupole, dna hrama in predelka št. 1803 (zaprta pot). Kupola zadrževalnega hrama je zaradi modeliranja konvektivnih tokov po vklopu zunanjih prh razdeljena na 6 celic. Višine celic v kupoli so bile predpisane z upoštevanjem položaja merilnih instrumentov. Spodnji predelki hrama so bili zaradi zmanjšanja računskega časa združeni v eno celico (št. 1). Predelek št. 1803 je razdeljen na dve celici, tako da je omogočeno kroženje plina znotraj predelka. Vmesni prostor med jekleno lupino hrama in betonsko steno je modeliran z eno celico (št. 66). Vhodni model je podrobno opisan v viru [18].

1.4 Containment cells

An input model of the HDR facility for the CONTAIN code was developed, based on data about the facility and the description of the test E11.2 [9]. The spatial input model consists of 71 cells (fig. 2). An additional cell (no. 72) represents the environment, which is in thermal contact with the containment's outside wall. Each cell in the model represents a containment compartment, except for the dome, the containment's lower part and compartment no. 1803 (dead end). The containment dome is divided into 6 cells to model convective flows after the actuation of the external sprays. The respective heights of the dome cells were prescribed by taking into account the position of the measuring instruments. The containment's lower compartments were merged into a single cell (no. 1) to reduce the computing time. The compartment no. 1803 is subdivided into two cells to allow the circulation of gas inside the compartment. The intermediate space between the containment's steel shell and the concrete wall is modelled as a single cell (no. 66). A detailed description of the input model is provided in ref. [18].

1.5 Povezave med celicami zadrževalnega hrama

Celice so med seboj povezane s tokovnimi potmi, ki določajo pretok snovi in energije. Masni tok skozi tokovno pot je določen iz naslednje gibalne enačbe [11]:

1.5 The flow paths between containment cells

The cells are interconnected with flow paths, which determine the flow of mass and energy. The mass flow through a flow path is calculated from the following momentum equation [11]:

$$\frac{dW}{dt}=\left(\Delta P-C_{FC}\frac{|W|W}{\rho\left(A\right)^{2}}\right)\frac{A}{L} \qquad (1),$$

kjer so: W masni tok, ΔP tlačna razlika med koncem in začetkom povezave, C_{FC} koeficient tokovnih izgub, ρ gostota tekočine, A prerez tokovne poti in L vztrajnostna dolžina poti. Vrednost razmerja A/L ima močan vpliv na modeliranje razslojevanja atmosfere in se predpiše v vhodnem modelu.

Zaradi zmanjšanja računskega časa so bile tokovne poti v vhodnem modelu uporabljene le za modeliranje pretoka plinaste faze. Modeliranih je 263 tokovnih poti, ki so shematično prikazane na sliki 2. Ker lastnosti posameznih povezav med predelki niso podane [9], so bile pri vseh tokovnih poteh predpisane enake vrednosti koeficienta tokovnih izgub C_{FC} in razmerja A/L. Vrednost C_{FC} je 1,0 (enako kakor v viru [5], kjer je opisano modeliranje poskusa v eksperimentalni napravi NUPEC s programom CONTAIN), medtem ko je vrednost A/L 0,15. Predpis enakih vrednosti za vse tokovne poti pomeni, da je simulacija določena s

where W is the mass flow rate, ΔP is the pressure difference over the flow path, C_{FC} is the flow-loss coefficient, ρ is the fluid density, A is the flow-path cross-section, and L is the flow-path inertial length. The value of the ratio A/L has a significant influence on the modelling of atmosphere stratification and is prescribed in the input model.

To reduce the computing time the flow paths in the input model were only used to model the flow of the gas phase. Two hundred and sixty three flow paths are modelled, which are shown schematically in Fig. 2. As the individual characteristics of the connections between the compartments are not provided [9], the same values of the flow-loss coefficient C_{FC} and of the ratio A/L were prescribed for all the flow paths. The value of C_{FC} was set to 1.0 (as in ref. [5], where the modeling of an experiment in the NUPEC experimental facility with the CONTAIN code is described), whereas the value of A/L was set to 0.15. The prescription of identical values for all the flow paths means that the fizikalnimi in numeričnimi modeli programa ter ni umetno popačena z "nastavljanjem" vrednosti koeficientov. Pretok kapljevine je modeliran tako, da se kapljevina nad predpisano največjo višino bazena kapljevine na dnu celice (0,01 m) prenese v naslednjo predpisano celico (sl. 2). Podoben postopek je bil uporabljen v viru [5].

Ker je kupola zadrževalnega hrama razdeljena na šest celic, nekatere od njih (celice št. 68 do 71) nimajo določenega bazena kapljevine v spodnjem delu. Kapljevina, ki nastane zaradi kondenzacije v teh celicah, se prenese v spodnji celici kupole (celici št. 56 in 67).

Poleg v že omenjenem viru [5], je bil postopek modeliranja nehomogene atmosfere z razdelitvijo večjega prostora na nadzorne prostornine in uporabo programa CONTAIN uporabljen tudi pri drugih analizah. Simulacija razslojevanja atmosfere v zadrževalnem hramu dvozančne tlačnovodne jedrske elektrarne tipa Westinghouse je opisana v viru [4], pri čemer so bili dobljeni rezultati, ki so kakovostno podobni rezultatom poskusa v napravi NUPEC [5]. V viru [17] je avtor obravnaval preprost sistem, sestavljen iz 4 enakih celic (sl. 3). V začetnem stanju je bil vodik (prisoten) samo v celici 1. Avtor je z določeno izbiro razmerja *A/L* (enakega za vse tokovne poti) dobil na koncu simulacije s programom CONTAIN višjo koncentracijo vodika v celicah 2 in 3 kakor v celicah 1 in 4 ter tako pokazal, da je v načelu simulacija razslojevanja atmosfere izvedljiva s postopkom, ki je uporabljen v tem delu.

1.6 Toplotne strukture

Toplotne strukture so vsi elementi, ki zbirajo toplotno energijo, dovedeno v zadrževalni hram med

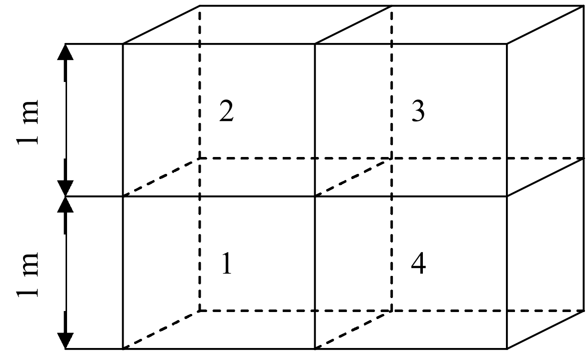
simulation is still determined by the code's physical and numerical models, and is not artificially distorted by "tuning" the values of the coefficients. The flow of liquid was simulated by transferring to the next prescribed cell (see Fig. 2) all the liquid exceeding the maximum prescribed pool height at the bottom of the cell (0.01 m). A similar approach was used in Ref. [5].

As the containment dome is divided into 6 cells, some of them (cells nos. 68 to 71) do not have a defined liquid pool on the floor. The liquid obtained from the steam condensation in these cells is transferred to the floor of the dome's bottom cells (nos. 56 and 67).

Apart from Ref. [5], the approach of modeling the non-homogeneous atmosphere by dividing a larger volume into control volumes and using the CONTAIN code has also been used in other analyses. A simulation of atmosphere stratification in the containment of a two-loop Westinghouse-type Pressurized Water Reactor nuclear power plant is described in Ref. [4], where the calculated results were qualitatively similar to the experimental results from the NUPEC facility [5]. In Ref. [17], the author considered a simple system, built from 4 identical cells (Fig. 3). Hydrogen was initially present only in cell 1. With a certain choice of the ratio *A/L* (identical for all flowpaths), the author obtained at the end of the simulation with the CONTAIN code a higher hydrogen concentration in cells 2 and 3 than in cells 1 and 4, and thus showed that atmosphere stratification can, in principle, be simulated with the approach used in this investigation.

1.6 Heat structures

The heat structures are all elements that accumulate thermal energy introduced into the con-



Sl. 3. *Shema preprostega sistema za preizkušanje simulacije razslojevanja*
Fig. 3. *Schematic of simple system for testing the simulation of stratification*

nezgodo, in tako zmanjšujejo mehanske in toplotne obremenitve hrama zaradi tlaka in temperature atmosfere. V programu CONTAIN lahko prenos toplote na strukture in s tem povezan prenos snovi potekata z naravno in prisilno konvekcijo, kondenzacijo, uparjanjem, prevodom ter sevanjem. V simulaciji so uporabljene naslednje standardne korelacije za naravno in prisilno konvekcijo med atmosfero in toplotnimi strukturami:

- za naravno konvekcijo med atmosfero in vodoravnimi površinami, če je gradient gostote plina stabilizirajoč:

tainment in the course of the accident and thus reduce the mechanical and thermal loads due to pressure and atmosphere temperature. In the CONTAIN code, heat transfer to heat structures and related mass transfer occur through natural and forced convection, condensation, boiling, heat conduction and radiation. In the simulation, the following standard correlations for natural and forced convection between the atmosphere and the heat structures are used:

- for natural convection between the atmosphere and horizontal surfaces, with a stabilizing gas density gradient:

$$Nu = 0{,}27\left(\Pr Gr\right)^{0{,}25} \qquad (2),$$

- za naravno konvekcijo med atmosfero in navpičnimi površinami ter med atmosfero in vodoravnimi površinami, če je gradient gostote plina destabilizirajoč:

- for natural convection between the atmosphere and vertical surfaces and between the atmosphere and horizontal surfaces with a destabilizing gas density gradient:

$$Nu = 0{,}14\left(\Pr Gr\right)^{0{,}33} \qquad (3),$$

- za prisilno konvekcijo:

- for forced convection:

$$Nu = 0{,}037\,\mathrm{Re}^{0{,}8}\,\Pr^{0{,}33} \qquad (4).$$

V enačbah (2) do (4) pomenijo *Nu* Nusseltovo število, *Pr* Prandtlovo število, *Gr* Grashoffovo število in *Re* Reynoldsovo število. Vrsto konvekcije določa največje izračunano Nusseltovo število. V programu CONTAIN je Reynoldsovo število določeno iz povprečij hitrosti tokov v tokovnih poteh, priključenih na obravnavano celico. Vrednost te hipotetične konvektivne hitrosti znotraj posamezne celice ni odvisna od lege strukture znotraj celice. Izračun kondenzacije vodne pare na toplotnih strukturah temelji na izračunu snovske prestopnosti iz analogije med prenosom toplote in prenosom snovi. Izračun prenosa toplote med bazeni kapljevine in atmosfero ter med bazeni in toplotnimi strukturami je podrobno opisan v navodilih CONTAIN [11].

V vhodnem modelu so upoštevane vse toplotne strukture, podane v specifikaciji ISP-29 [9]. Jeklene toplotne strukture v posamezni celici so bile združene v eno samo toplotno strukturo z namenom zmanjšanja računskega časa. Vse toplotne strukture, razen kupole, so modelirane kot ravne plošče, medtem ko je kupola modelirana z dvema deloma polkrogle. Medprostor med betonsko steno in jekleno lupino (celica št. 66) je prek toplotnih struktur povezan z nekaterimi celicami v zadrževalnem hramu in z okolico.

In Eqs. (2) to (4), *Nu* is the Nusselt number, *Pr* is the Prandtl number, *Gr* is the Grashoff number and *Re* is the Reynolds number. The type of convection is determined by the largest calculated Nusselt number. The Reynolds number is determined from averages of the velocities in flow paths that are connected to the considered cell. The value of this hypothetical convective flow velocity in each cell does not depend on the structure location within the cell. The calculation of vapour condensation on the heat structures is based on the calculation of mass transfer coefficients, using the analogy between heat and mass transfer. The calculation of heat transfer between the liquid pools and the atmosphere as well as between the liquid pools and the heat structures is described in detail in the CONTAIN manual [11].

In the input model, all the heat structures described in the ISP-29 specification [9] were taken into account. The steel heat structures in each cell were merged into a single structure to reduce the computing time. All the heat structures except the dome are modelled as slabs, whereas the dome's steel shell is modelled as two hemispherical parts. The space between the concrete wall and the steel shell (cell no. 66) is connected through the heat structures to some containment cells and to the environment.

1.7 Začetni in robni pogoji

V vseh celicah je bila predpisana začetna vrednost tlaka 101300 Pa. Začetne temperature (od 291 K do 339 K) in relativne vlažnosti (od 5,6 % do 100 %) so bile predpisane na podlagi podatkov iz vira [9].

Faze preizkusa so shematično prikazane na sliki 4. Test E11.2 predstavlja malo izlivno nezgodo (zlom hladne veje v predelku 1805), ki privede do poškodbe sredice reaktorja. Zaradi tega vodik uhaja skozi zlom v zadrževalni hram. V vhodnem modelu so vključeni viri vodne pare, vodika in helija, navedeni v [9]. Da bi namreč med preizkusom preprečili zgorevanje vodika, je bila namesto čistega vodika v hram vbrizgana mešanica t. i. "lahkih plinov" (15 vol. % vodika in 85 vol. % helija). Spodnji izvir hladiva pri preizkusu (iz predelka št. 1405) je izparevanje vode iz odcejalnika. Mesti obeh izvirov sta prikazani na sliki 1.

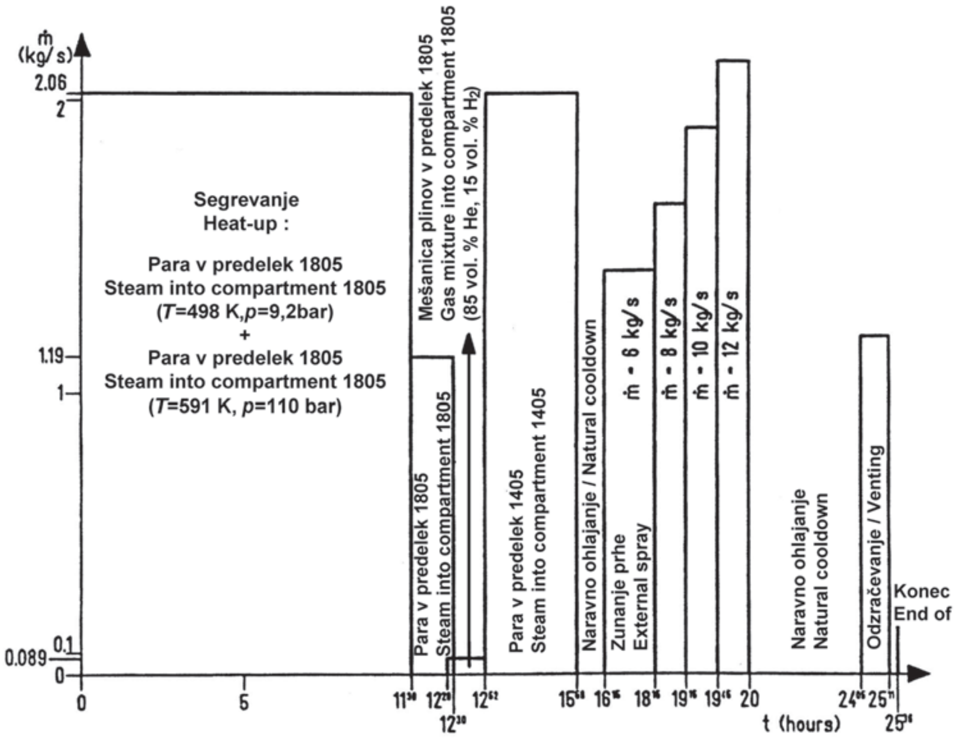
V vhodnem modelu sta upoštevana še dva dodatna ponora toplote: zunanje prhe in instrumentacijski odvod toplote iz hrama, do katerega je prihajalo zaradi meritev koncentracije vodika v

1.7 Initial and boundary conditions

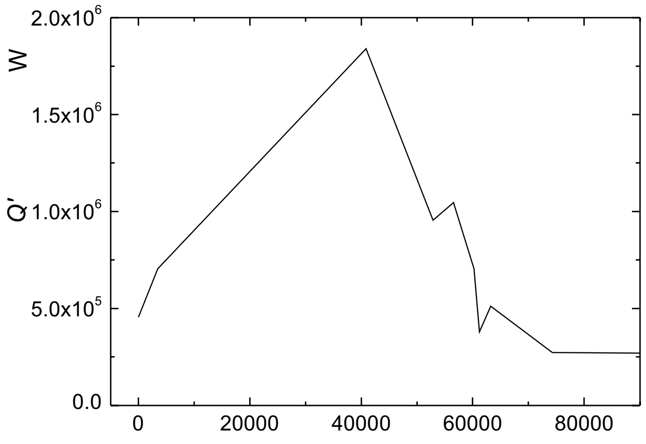
The initial pressure in all the cells was set to 101300 Pa. The initial temperatures (from 291 K to 339 K) and relative humidities (from 5.6 % to 100 %) were prescribed based on data from Ref. [9].

The phases of the experiment are schematically shown in fig. 4. The test E11.2 represents a small-break loss-of-coolant accident (cold-leg break in compartment no. 1805), which leads to reactor-core degradation. As a consequence, hydrogen is released through the break into the containment. The sources of the vapour coolant, the hydrogen and the helium specified in Ref. [9] were included in the input model. In order to prevent hydrogen combustion during the experiment, a mixture of so-called "light gases" (15% vol. % of hydrogen and 85 vol. % of helium) was injected into the containment instead of pure hydrogen. The lower coolant source in the experiment (from compartment no. 1405) represents water evaporation from the sump. The locations of both sources are shown in Fig. 1.

Two additional heat sinks were included in the input model: external sprays and instrumentation heat removal from the containment, which occurred due to measurement of the hydrogen con-



Sl. 4. *Potek poskusa E11.2*
Fig. 4. *Scenario of experiment E11.2*



Sl. 5. *Modelirani odvod toplote iz zadrževalnega hrama zaradi meritev (t: čas, Q': toplotni tok)*
Fig. 5. *Modeled heat removal from containment due to measurements (t: time, Q': heat flow)*

posameznih predelkih. Zunanje prhe so bile sprožene 58500 s po začetku testa (sl. 4). Ker je bila pri meritvah vzorcem zraka odstranjevana vodna para, je treba instrumentacijski odvod toplote porazdeliti znotraj hrama glede na trenutno koncentracijo vodne pare v atmosferi in število merilnih mest v posamezni celici. Ker je v podatkih [9] podan le skupni odvod toplote iz zadrževalnega hrama (sl. 5), je bil odvod iz posamezne celice *n* določen z utežjo f_n [19]:

centration in individual compartments. The external sprays were actuated 58500 s after the test start-up (Fig. 4). As steam was removed from gas samples during measurements, the instrumentation heat removal should be distributed within the containment according to instantaneous steam concentration and the number of gas samplers in each cell. As only the total heat-removal rate from the containment (Fig. 5) is provided in Ref. [9], the heat removal from each cell *n* was determined from the weighting factor f_n [19]:

$$f_n = \frac{p_{v,n} w_n}{\sum_i p_{v,i} w_i} \quad (5),$$

kjer $p_{v,n}$ pomeni delni tlak vodne pare v celici *n* in w_n relativni delež števila tipal v celici glede na vsa tipala v hramu. Ker v programu CONTAIN tovrstne funkcije ni mogoče definirati brez spreminjanja izvirne kode, so bili delni tlaki vodne pare najprej določeni na podlagi prvotne simulacije z identičnim vhodnim modelom, vendar brez odvoda toplote. Izračunani delni tlaki so bili nato vneseni v vhodni model v skladu z en.(5), nakar je bila izvedena druga (končna) simulacija.

where $p_{v,n}$ denotes the steam's partial pressure in cell *n* and w_n denotes the ratio of the number of gas samplers in the cell to the total number of gas samplers in the containment. As such a function cannot be defined in CONTAIN without modifying the source code, steam partial pressures were first obtained from an initial simulation with an identical input model but without heat removal. The calculated partial pressures were then included in the input model according to Eq. (5) and a second (final) simulation was carried out.

1.8 Predhodni rezultati drugih avtorjev

Test E11.2 so simulirali tudi drugi avtorji ([1] do [3]), ki so razvili drugačne vhodne modele. Pri simulaciji testa s programom CONTAIN 1.2 [1] je bil zadrževalni hram modeliran zgolj s 14 celicami. Zaradi majhnega števila celic so bile nekatere tokovne poti spremenjene tako, da so bili dobljeni primerni rezultati. Čeprav je bil napovedani tlak približno za 0,5 bar previsok, je simulacija v splošnem dala zadovoljive rezultate. Simulacija testa s programom GOTHIC [2]

1.8 Previous results from other authors

The test E11.2 has also been simulated by other authors ([1] to [3]) who developed different input models. In the simulation of the test with the code CONTAIN 1.2 [1], the containment was modelled with only 14 cells. Due to the small number of cells, some flow paths had to be modified to obtain adequate results. Although the predicted pressure was about 0.5 bar too high, the simulation produced satisfactory results, in general. The simulation of the test with the code je dobro napovedala potek tlaka, medtem ko je bilo ujemanje med izmerjenimi in izračunanimi temperaturami in koncentracijami vodika slabše. Model je bil sestavljen iz 64 celic in 107 tokovnih poti. Po mnenju avtorjev ničrazsežni programi niso primerni za napoved porazdelitve vodika v razslojeni atmosferi zadrževalnega hrama. Trdijo namreč, da se lahko razslojevanje atmosfere včasih ustrezno simulira samo z nastavitvijo koeficientov tokovnih izgub ali vztrajnostnih dolžin poti na ustrezne »umetne« vrednosti, ki so odvisne od posameznih primerov. Simulacija testa s programom MAAP4 [3] je napovedala za 25 kPa previsok tlak v hramu, medtem ko so se izračunane temperature atmosfere in koncentracije vodika zelo dobro ujemale z meritvami. Vhodni model je bil sestavljen iz 29 celic in 44 tokovnih poti. Model v tem delu je tako bolj podroben in pomeni izboljšanje glede na dosedanja dela drugih avtorjev.

2 REZULTATI IN RAZPRAVA

2.1 Pojavi v zadrževalnem hramu med testom E11.2

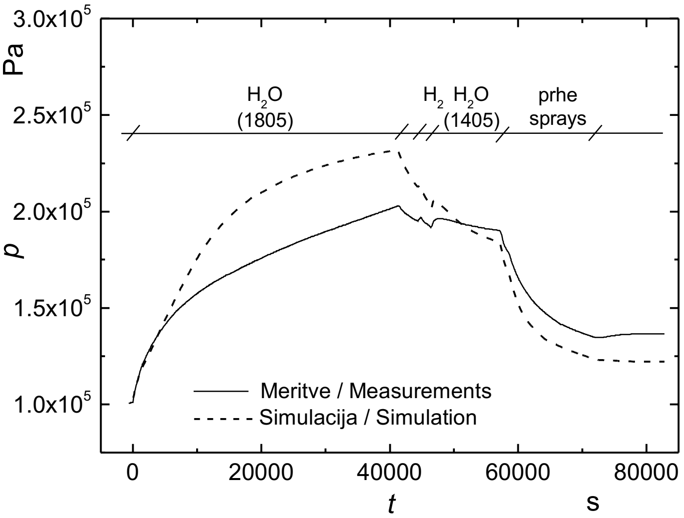
Začetno vbrizgavanje vodne pare, ki je simuliralo posledico hipotetične male izlivne nezgode, je povzročilo povečanje tlaka (sl. 6.). Tlačna konica je bila dosežena po koncu faze segrevanja. Potem ko je bilo vbrizgavanje vodne pare zmanjšano, se je tlak znižal, z eno nizko vmesno konico zaradi vbrizgavanja

GOTHIC [2] predicted the pressure history well, whereas the agreement between the measured and calculated temperatures and the hydrogen concentrations was not satisfactory. The model consisted of 64 cells and 107 flow paths. In the authors' opinion, lumped-parameter codes are not adequate for predicting the hydrogen distribution in a stratified containment atmosphere. They argue that atmosphere stratification can sometimes be well simulated only by adjusting flow-loss coefficients or flow-path inertial lengths to adequate "artificial" values that are case-dependent. The simulation of the test with the code MAAP4 [3] predicted a containment pressure that was about 25 kPa too high, whereas the calculated atmosphere temperatures and hydrogen concentrations agreed very well with the measurements. The input model consisted of 29 cells and 44 flow paths. Thus, the model in the present work is more detailed and represents an improvement over previous works from other authors.

2 RESULTS AND DISCUSSION

2.1 Containment phenomena during test E11.2

The initial injection of steam that simulated a consequence of a hypothetical small-break loss-of-coolant accident, caused a pressure increase (Fig. 6). The pressure peak was reached after the completion of the heatup phase. After the steam injection was reduced, the pressure decreased, with a low



Sl. 6. *Izmerjeni in izračunani tlak v zadrževalnem hramu (t: čas, p: tlak)*
Fig. 6. *Measured and calculated pressure in containment (t: time, p: pressure)*

mešanice lahkih plinov. Po začetku drugega vbrizgavanja vodne pare se je tlak nekoliko zvišal pred ponovnim počasnim zniževanjem. Ko so zunanje prhe pričele delovati, se je tlak sunkovito znižal. Po prenehanju delovanja prh se je tlak nekoliko zvišal ter ostal na stalni vrednosti, ker so notranje strukture in odcejalnik oddajali nakopičeno notranjo energijo.

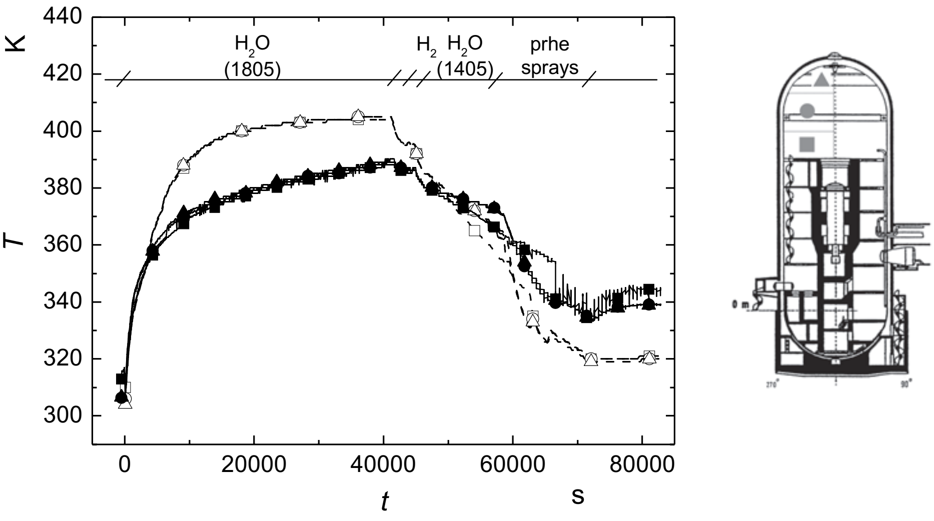
Začetno vbrizgavanje pare je povzročilo temperaturno razslojenost atmosfere (sl. 7 do 10) zaradi dvigovanja vroče pare. Vbrizgavanje lahkih plinov v temperaturno razslojeno atmosfero je povzročilo koncentracijsko razslojenost (sl. 11 do 14): vroče področje nad "zlomom" je bilo bogato z lahkimi plini (sl. 12), medtem ko je bila koncentracija plinov v spodnjem področju hrama precej nižja (sl. 14). Drugo vbrizgavanje vodne pare (po vbrizgavanju lahkih plinov) je povzročilo povišanje temperature v spodnjem delu hrama in porušilo stabilno toplotno razslojitev v obeh stopniščih. Vbrizgavanje pare je tudi potisnilo mešanico lahkih plinov v višje lege. Atmosfera v kupoli je prav tako postala razslojena, z večjimi koncentracijami lahkih plinov v zgornjem delu kupole (sl. 11).

Atmosfera v višjih delih hrama je ponovno postala homogena šele po daljšem delovanju zunanjih prh. Intenzivna kondenzacija vodne pare na notranji steni zgornjega dela kupole zadrževalnega hrama je najprej povzročila povečanje koncentracije vodika (sl. 11). Ker se je v zgornjem delu kupole tudi znižala temperatura atmosfere, je

intermediate peak due to the injection of the light-gas mixture. After the second steam injection started, the pressure increased somewhat before slowly decreasing again. Following the actuation of the external sprays, the pressure dropped sharply. After the sprays stopped, the pressure increased somewhat and remained at a constant level as internal structures and sumps released their accumulated internal energies.

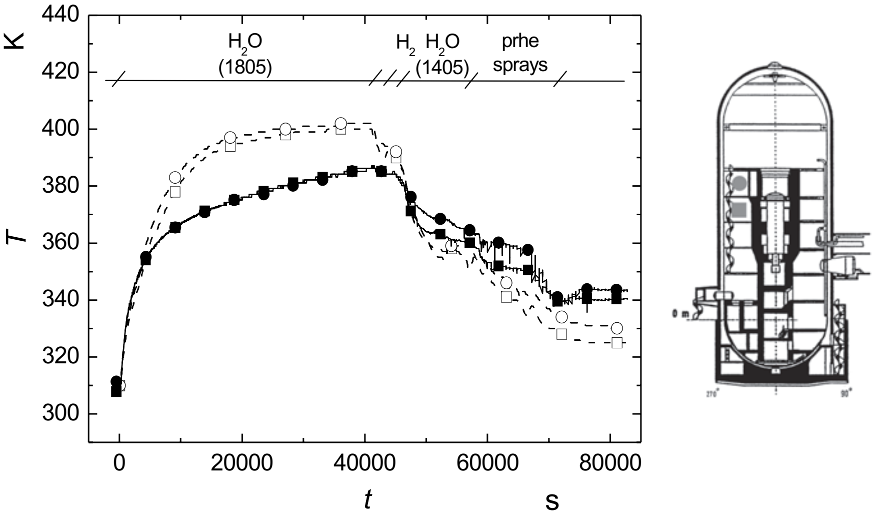
The initial steam injection caused a thermal stratification of the atmosphere (Figs. 7 to 10) due to upward convection of the hot steam. The injection of light gases into the thermally stratified atmosphere caused a concentration stratification (Figs. 11 to 14): the hot region above the "break" was rich in light gases (Fig. 12), whereas the gas concentration in the containment lower part was much lower (Fig. 14). The second steam injection (after the injection of the light gases) caused a temperature increase in the containment lower regions and broke up the stable thermal stratification in both staircases. The steam injection also swept the light-gas mixture to higher elevations. The atmosphere in the dome also became stratified, with higher light-gas concentrations in the dome's upper part (Fig. 11).

The atmosphere in the containment upper regions became homogeneous again only after a prolonged action of the external sprays. The intense condensation of the steam on the inside wall of the upper part of the containment dome first caused an increase in the hydrogen concentration (Fig. 11). As the atmosphere temperature in the dome's upper part also decreased, the stratifi-



Sl. 7. *Temperatura plinov v kupoli zadrževalnega hrama (polne črte: meritve, črtkane črte: simulacija, t: čas, T: temperatura)*

Fig. 7. *Gas temperature in containment dome (solid lines: measurements, dashed lines: simulation, t: time, T: temperature)*



Sl. 8. *Temperatura plinov v zgornjem delu vijačnega stopnišča (polne črte: meritve, črtkane črte: simulacija, t: čas, T: temperatura)*

Fig. 8. *Gas temperature in upper part of hellical staircase (solid lines: measurements, dashed lines: simulation, t: time, T: temperature)*

postala razslojenost nestabilna. Konvektivni tokovi, ki so sledili, so povzročili homogenizacijo atmosfere v kupoli. Postopek homogenizacije se je nadaljeval v spodnjem delu hrama tudi po prenehanju delovanja prh (sl. 14).

2.2 Tlak v zadrževalnem hramu

Izračunani tlak se razmeroma dobro ujema z izmerjeno vrednostjo (sl. 6). Tlačna konica je približno za 29 kPa višja od preizkusne vrednosti. Simulacija napove prevelik padec tlaka od konca prvega vbrizgavanja pare do vklopa zunanjih prh. Padec tlaka zaradi delovanja zunanjih prh je dobro napovedan. Končni izračunani tlak je nižji od izmerjenega za približno 14 kPa.

2.3 Temperatura atmosfere

V prvi fazi testa (segrevanje zadrževalnega hrama) se izračunane temperature plinov zelo dobro ujemajo z izmerjenimi vrednostmi v spodnjem delu zadrževalnega hrama (sl. 10). Temperature v zgornjem delu hrama (sl. 7, 8) so nekoliko precenjene (približno za 20 K). Večja odstopanja se pojavijo le v sredini hrama, predvsem v predelkih 1707 in 1708 (sl. 9), ki sta tik pod izvirom pare v predelku 1805.

V drugi fazi testa (vbrizgavanje vodika, helija in vodne pare do vklopa zunanjih prh) so temperature plinov v hramu dobro napovedane.

cation became unstable. The convective flows that followed caused the atmosphere in the containment dome to become homogeneous. The process of homogenisation proceeded in the containment lower part also after the sprays ceased to function (Fig. 14).

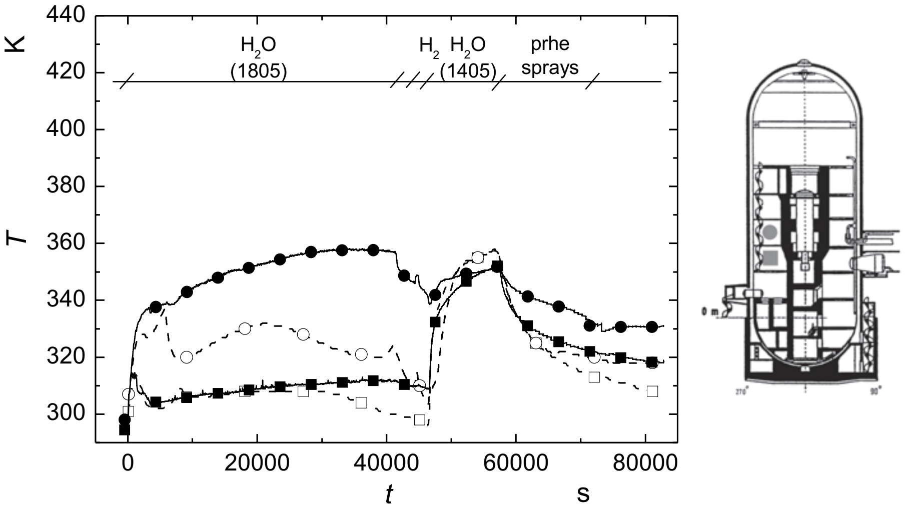
2.2 Pressure in the containment

The calculated pressure agrees relatively well with the measured value (Fig. 6). The pressure peak is about 29 kPa higher than the experimental value. The simulation predicts a too high pressure drop from the end of the first steam injection to the actuation of the external sprays. The pressure drop caused by the spray action is well predicted. The final calculated pressure is about 14 kPa lower than the measured value.

2.3 Atmosphere temperature

In the first phase of the test (containment heat-up), the calculated gas temperatures agree very well with measured values in the containment lower part (Fig. 10). Temperatures in the containment upper region (Figs. 7 and 8) are somewhat overpredicted (by about 20 K). Larger discrepancies occur only in the central region, mostly in compartments nos. 1707 and 1708 (Fig. 9), which are situated just below the steam source in compartment no. 1805.

In the test second phase (the injection of hydrogen, helium and steam up to the actuation of the external sprays), the gas temperatures in the containment are well predicted.



Sl. 9. *Temperatura plinov v srednjem delu vijačnega stopnišča (polne črte: meritve, črtkane črte: simulacija, t: čas, T: temperatura)*

Fig. 9. *Gas temperature in central part of hellical staircase (solid lines: measurements, dashed lines: simulation, t: time, T: temperature)*

V tretji fazi testa (delovanje zunanjih prh) so temperature plinov v zgornjem delu hrama (sl. 7, 8) nekoliko prenizke (približno za 20 K). V srednjem delu vijačnega stopnišča (sl. 9) so temperature prav tako prenizke (približno za 10 K). Temperature v spodnjem delu stopnišč (sl. 10) so dobro napovedane.

Razlike med izmerjenimi in izračunanimi temperaturami so najverjetneje posledica nepopolnosti pri modeliranju instrumentacijskega odvoda toplote in porazdelitve toplotnih struktur. Te vidike modeliranja je težko izboljšati zaradi nepopolnih informacij v viru [9].

2.4 Koncentracije plinov

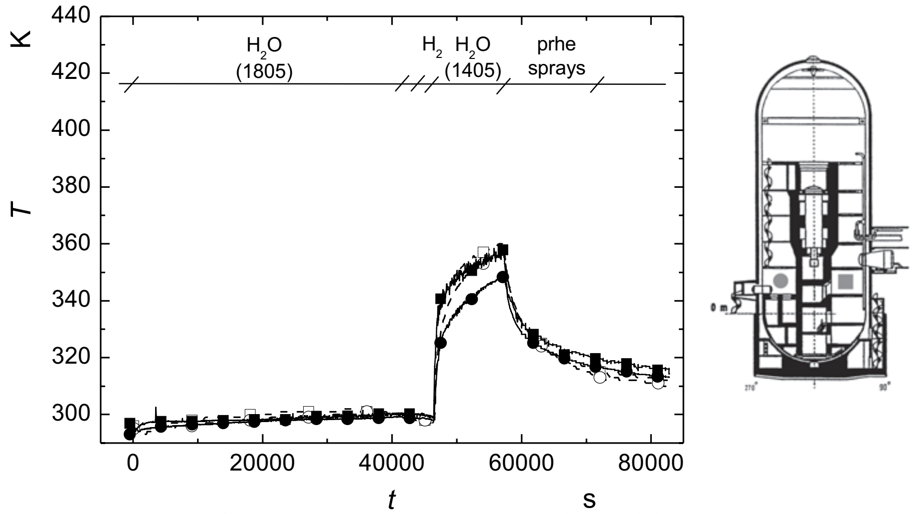
V fazi vbrizgavanja lahkih plinov so koncentracije vodika v zgornjem delu hrama (sl. 11 in 12) dobro napovedane. Po koncu te faze se vodik pretaka v zgornji del hrama. Simulacija napove razslojevanje atmosfere v kupoli (sl. 11). Po vklopu prh simulacija kakovostno dobro napove povečanje koncentracije vodika v zgornjih dveh nivojih kupole in zmanjšanje v spodnjem delu kupole. Največja napovedana koncentracija vodika v kupoli je približno za 0,4 vol. % prenizka. Koncentracije vodika v vseh nivojih kupole se hitreje izenačijo kakor pri preizkusu, verjetno zaradi predhodno nepopolne kakovostne napovedi razslojenosti atmosfere. Končna koncentracija vodika v kupoli je dobro napovedana.

In the test's third phase (the action of the external sprays), the gas temperatures in the containment upper part (Figs. 7 and 8) are somewhat too low (by about 20 K). In the central part of the hellical staircase (Fig. 9) the temperatures are also too low (by about 10 K). The temperatures in the lower part of the staircases (Fig. 10) are well predicted.

The discrepancies between the measured and calculated temperatures are most probably due to deficiencies in the modelling of the instrumentation heat removal and the distribution of heat structures. These aspects of the modelling are difficult to improve due to the incomplete information provided in Ref. [9].

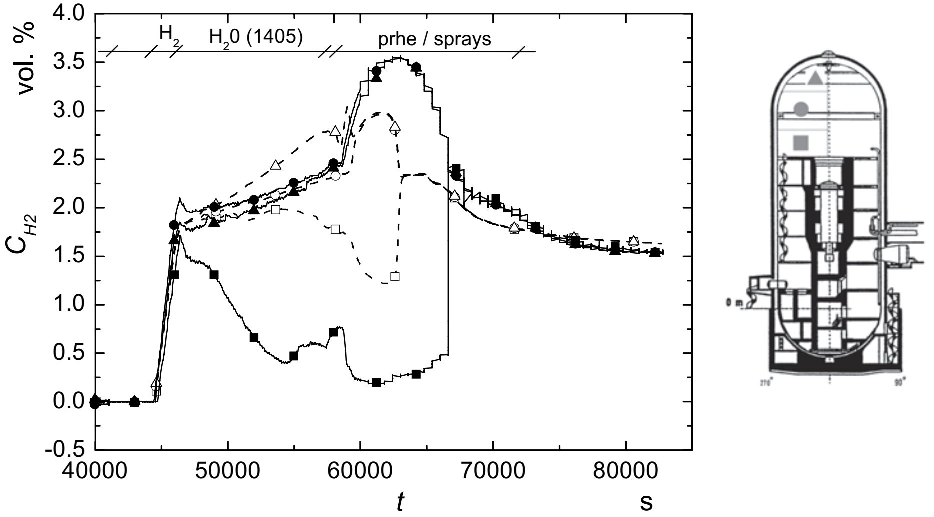
2.4 Gas concentration

In the light-gas injection phase, hydrogen concentrations in the containment upper parts (Figs. 11 and 12) are well predicted. After the end of this phase, hydrogen flows upwards to the containment upper part. The simulation predicts atmosphere stratification in the dome (Fig. 11). After the spray actuation, the simulation predicts qualitatively well the increase of the hydrogen concentration in the two upper levels of the dome and a decrease in the dome's lower level. The highest predicted hydrogen concentration in the dome is about 0.4 vol. % too low. Hydrogen concentrations in all levels of the dome even up faster than in the experiment probably because of the quantitatively imperfect prediction of the atmosphere stratification. The final hydrogen concentration in the dome is well predicted.



Sl. 10. *Temperatura plinov v spodnjem delu stopnišč (polne črte: meritve, črtkane črte: simulacija, t: čas, T: temperatura)*

Fig. 10. *Gas temperature in lower part of staircases (solid lines: measurements, dashed lines: simulation, t: time, T: temperature)*

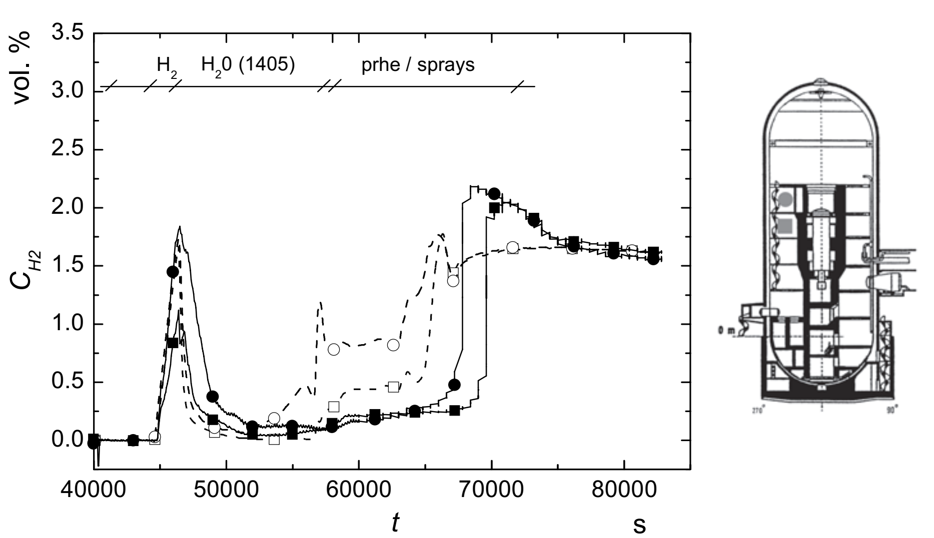


Sl. 11. *Koncentracija vodika v kupoli zadrževalnega hrama (polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)*

Fig. 11. *Hydrogen concentration in containment dome (solid lines: measurements, dashed lines: simulation, t: time, C: volumetric concentration)*

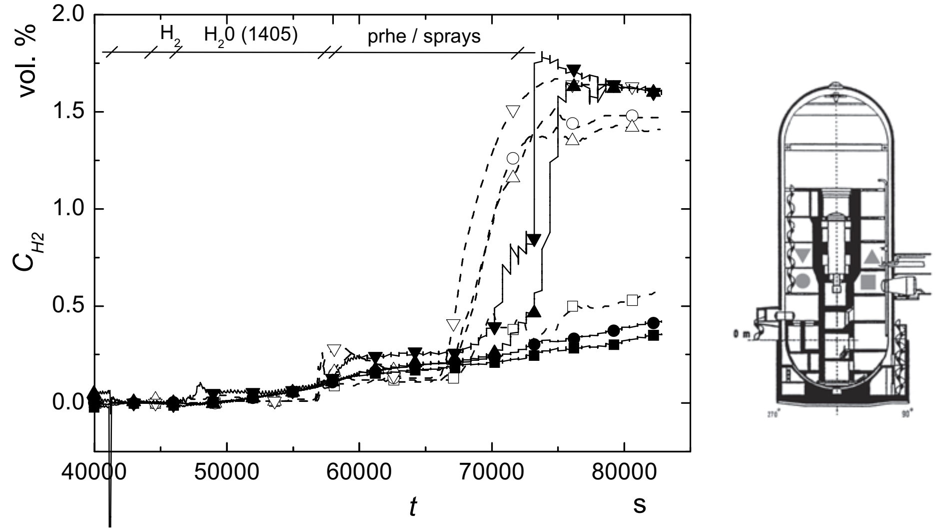
Končne koncentracije vodika v zgornjem delu vijačnega stopnišča so dobro napovedane (sl. 12). Koncentracije vodika v srednjem delu stopnišč (sl. 13) so v splošnem prav tako razmeroma dobro napovedane. Do večjega odstopanja pride le v celici št. 1611, pri kateri simulacija napove povečanje koncentracije vodika zaradi konvektivnih tokov, ki pri poskusu niso bili opaženi. V spodnjem delu navadnega stopnišča (sl. 14) so koncentracije vodika previsoke, verjetno zaradi prezgodnje izenačitve koncentracij v kupoli.

The final hydrogen concentrations in the hellical staircase upper parts are well predicted (Fig. 12). Hydrogen concentrations in the central part of the staircases (Fig. 13) are, in general, also relatively well predicted. A major discrepancy occurs only in cell no. 1611, where the simulation predicts an increase of the hydrogen concentration due to convective flows, which were not observed in the experiment. In the lower part of the normal staircase (Fig. 14), hydrogen concentrations are too high, probably because the concentrations in the dome even up to early.



Sl. 12. *Koncentracija vodika v zgornjem delu vijačnega stopnišča (polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)*

Fig. 12. *Hydrogen concentration in upper part of hellical staircase (solid lines: measurements, dashed lines: simulation, t: time, C: volumetric concentration)*

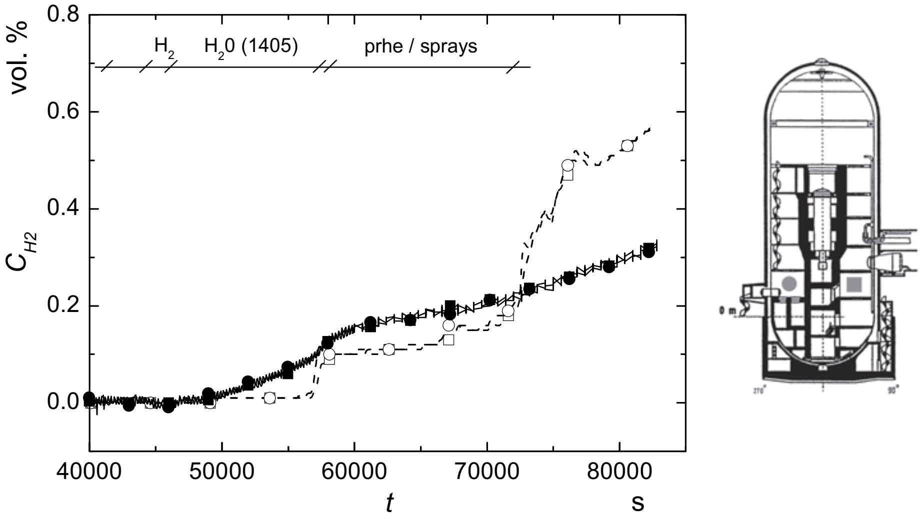


Sl. 13. *Koncentracija vodika v srednjem delu stopnišč (polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)*

Fig. 13. *Hydrogen concentration in central part of staircases (solid lines: measurements, dashed lines: simulation, t: time, C: volumetric concentration)*

V splošnem bi bila ocena ujemanja med rezultati poskusa in simulacije bolj popolna, če bi bile znane negotovosti obeh skupin rezultatov. Žal, negotovost rezultatov poskusa v dosegljivih dokumentih ni podana. Mogoč način za oceno negotovosti izračunanih rezultatov bi bila sistematična parametrična analiza s spreminjanjem začetnih in robnih pogojev. Tovrstni postopek je bil že uporabljen pri analizi negotovosti simulacij prehodnih pojavov v reaktorskem hladilnem sistemu [20].

In general, the comparison of the experimental and simulation results would be more complete if the uncertainties of both sets of results were known. Unfortunately, uncertainties of the experimental results are not provided in available documents. A possible way of estimating the uncertainty of the calculated results would be to perform systematic parametric analyses by varying the initial and boundary conditions. Such a procedure has already been applied in the uncertainty analysis of simulations of transients in the reactor coolant system [20].



Sl. 14. *Koncentracija vodika v spodnjem delu stopnišč*
(polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)
Fig. 14. *Hydrogen concentration in lower part of staircases*
(solid lines: measurements, dashed lines: simulation, t: time, C: volumetric concentration)

3 SKLEPI

Opisan je bil postopek z zgoščenimi parametri za modeliranje nehomogene večkomponentne atmosfere v večprostorskem zadrževalnem hramu jedrske elektrarne v nezgodnih razmerah. Kot ponazoritev je s termo-hidravličnim računalniškim programom CONTAIN bil simuliran test E11.2 “Porazdelitev vodika v tokovni zanki”, ki je bil izveden v integralni eksperimentalni napravi HDR v Nemčiji. Dobljeno je bilo dobro kakovostno ujemanje med izmerjenimi in izračunanimi rezultati, pri čemer so bile uporabljene identične vrednosti koeficientov tokovnih izgub in razmerij *A/L* (prerez tokovne poti / vztrajnostna dolžina) za vse tokovne poti. To podpira hipotezo, da so postopki z zgoščenimi parametri v bistvu uporabni za modeliranje nehomogene prehodne strukture atmosfere (v smislu temperature in sestave) v zadrževalnih hramih jedrskih elektrarn. Vsekakor bo treba razviti splošne smernice za tovrstne simulacije, ker je za dobro ujemanje med simuliranimi in eksperimentalnimi rezultati včasih še vedno treba nastaviti vrednosti nekaterih parametrov.

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[1] Razpad zaradi sevanja
[2] Izraz “celica” označuje prostor v *vhodnem modelu.*
[3] Izraz “predelek” označuje resnični prostor v *zadrževalnem hramu*.

3 CONCLUSIONS

A lumped-parameter approach for modelling the non-homogeneous multi-component atmosphere in a multi-compartment nuclear power plant containment during accident conditions was described. As an illustration, the atmosphere stratification test E11.2 “Hydrogen distribution in loop flow geometry”, which was performed in the integral experimental facility HDR in Germany, was simulated using the CONTAIN thermal-hydraulic computer code. A good qualitative agreement between the measured and calculated results was obtained, using identical values for the flow-loss coefficients and the ratios *A/L* (cross-section *vs.* inertial length) for all flow paths. This supports the hypothesis that, in principle, the lumped-parameter approach can be used for modelling the non-homogeneous transient atmosphere structure (in terms of temperature and composition) in nuclear power plant containments. However, general guidelines for these simulations need to be developed, as some parameters sometimes still need to be adjusted to obtain a good agreement between simulated and experimental results.

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[1] Decay due to radiation
[2] The term “cell” denotes a room in the *input model.*
[3] The term “compartment” denotes an actual room in the *containment*.

4 LITERATURA
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