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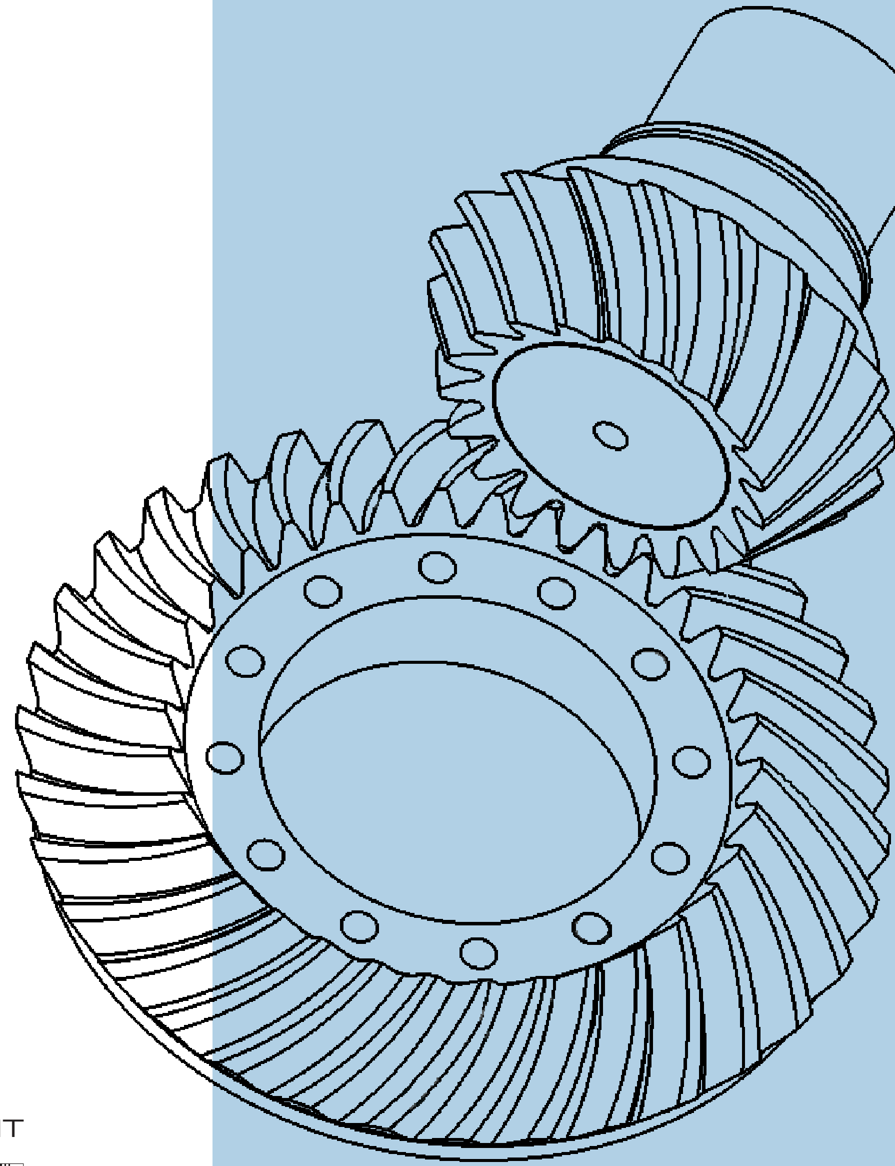

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Modeliranje razslojene atmosfere v eksperimentalni napravi jedrske elektrarne s popisom z zgoščenimi parametri

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]).

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 Opis eksperimentalne naprave HDR

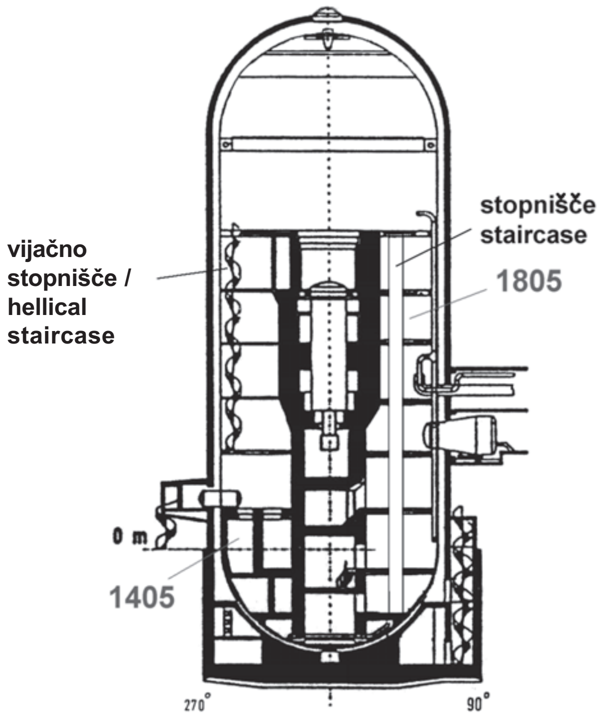
Zadrževalni hram integralne eksperimentalne naprave HDR ima krožni prerez s polkrogelno kupolo (sl. 1). Višina zadrževalnega hrama je 60 m, prosta prostornina pa približno 11300 m^3. Spodnji del hrama je razdeljen na 70 predelkov, medtem ko je prostorna kupola (približno 4800 m^3) nerazdeljena. Dve diametralno 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.

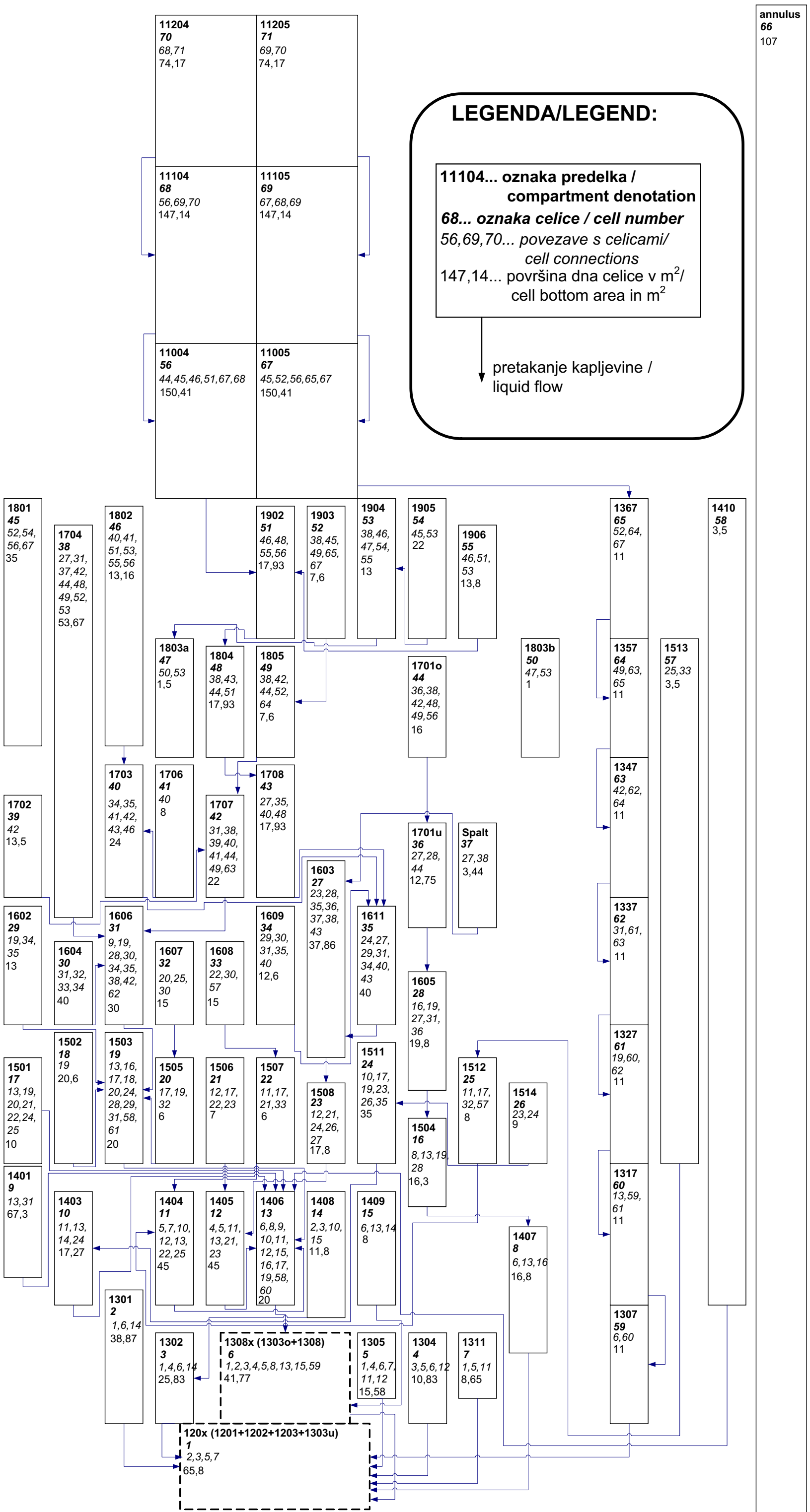
1.3 Description of the HDR experimental facility

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]:

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

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

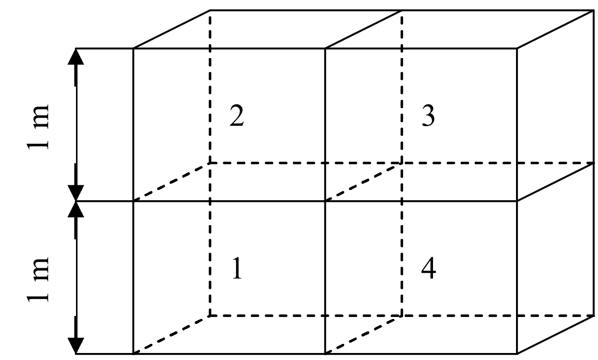
simulation is still determined by the code’s physical and numerical models, and is not artificially distorted by “tuning” the values of the coefficients. The flow of liquid was simulated by transferring to the next prescribed cell (see Fig. 2) all the liquid exceeding the maximum prescribed pool height 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:

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

- 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:

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

- za prisilno konvekcijo:

- for forced convection:

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

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.

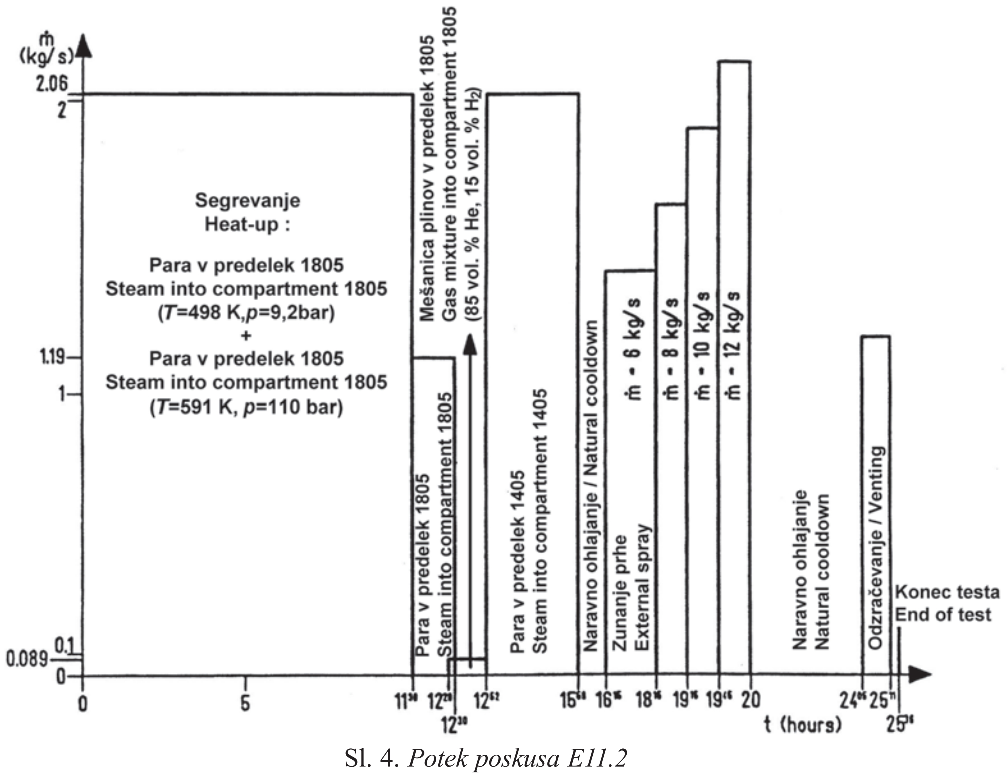
V vhodnem modelu sta upoštevana še dva dodatna ponora toplote: zunanje prhe in instrumentacijski odvod toplote iz hrama, do katerega je prihajalo zaradi meritev koncentracije vodika v

1.7 Initial and boundary conditions

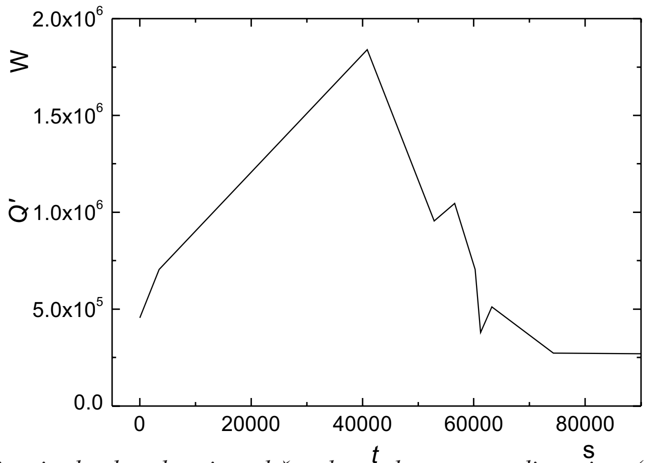
The initial pressure in all the cells was set to 101300 Pa. The initial temperatures (from 291 K to 339 K) and relative humidities (from 5.6 % to 100 %) were prescribed based on data from Ref. [9].

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]:

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

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.

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 REZULTATI IN RAZPRAVA

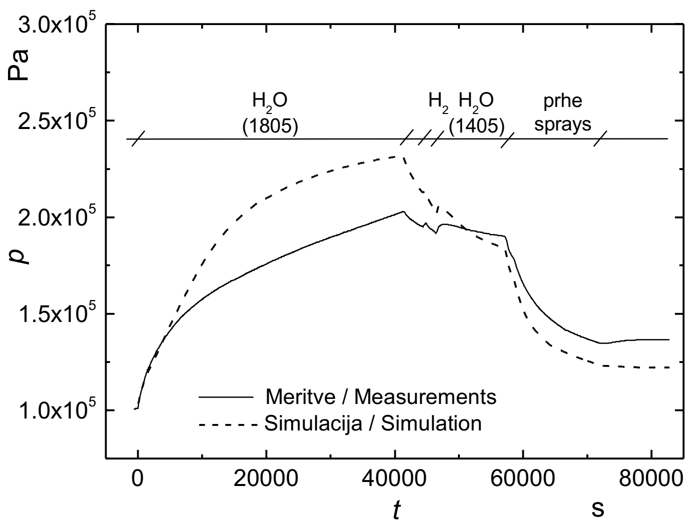
2 RESULTS AND DISCUSSION

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

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.

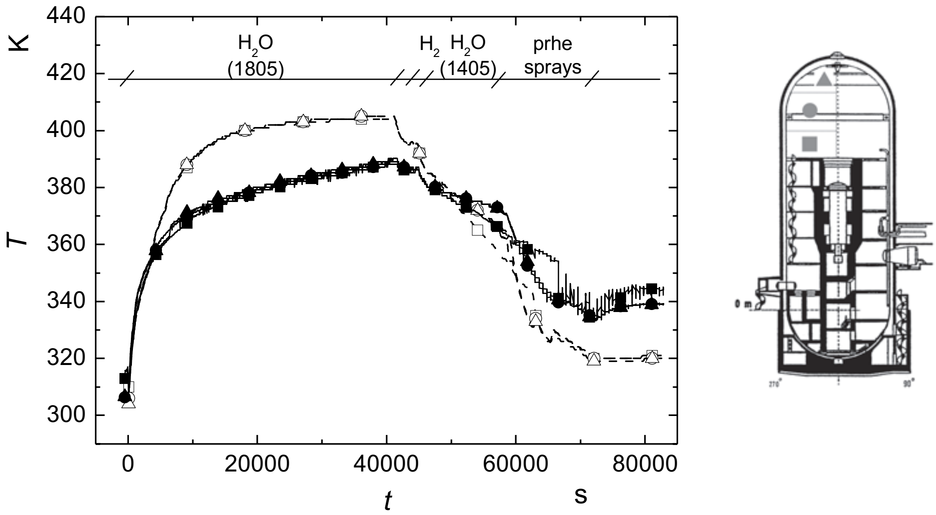
Začetno vbrizgavanje pare je povzročilo temperaturno razslojenost atmosfere (sl. 7 do 10) zaradi dvigovanja vroče pare. Vbrizgavanje lahkih plinov v temperaturno razslojeno atmosfero je povzročilo koncentracijsko razslojenost (sl. 11 do 14): vroče področje nad "zlomom" je bilo bogato z lahkimi plini (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

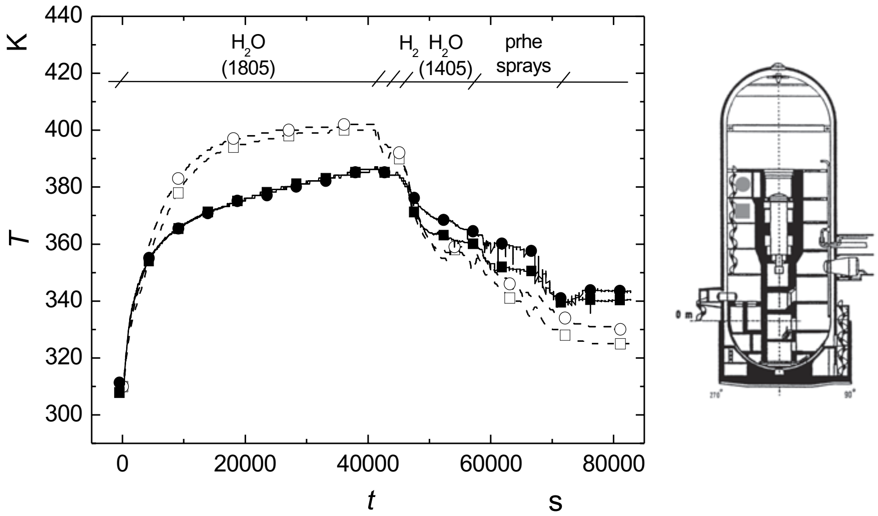
intermediate peak due to the injection of the light-gas mixture. After the second steam injection started, the pressure increased somewhat before slowly decreasing again. Following the actuation of the external sprays, the pressure dropped sharply. After the sprays stopped, the pressure increased somewhat 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).

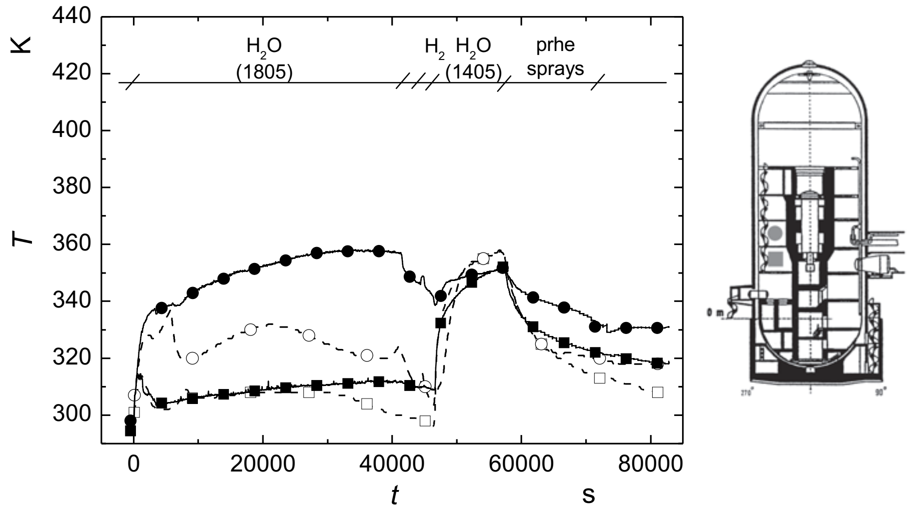
2.2 Pressure in the containment

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

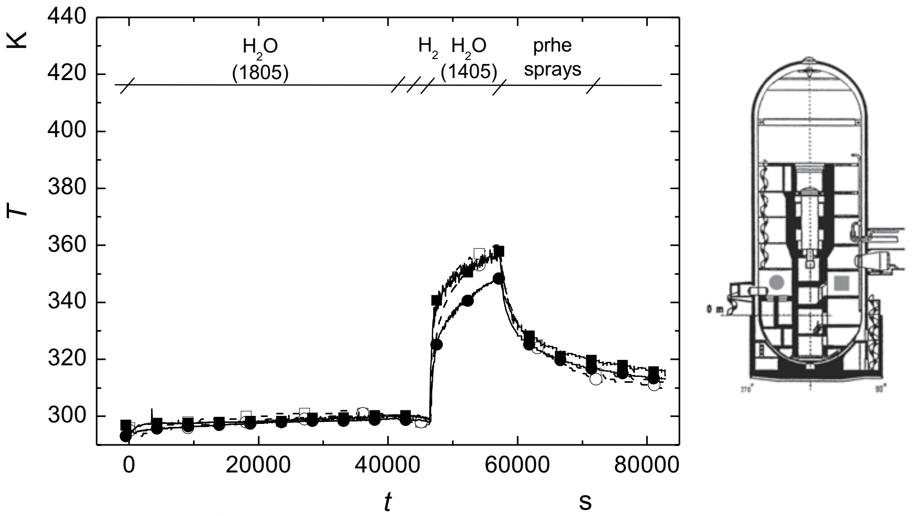
V fazi vbrizgavanja lahkih plinov so koncentracije vodika v zgornjem delu hrama (sl. 11 in 12) dobro napovedane. Po koncu te faze se vodik pretaka v zgornji del hrama. Simulacija napove razslojevanje atmosfere v kupoli (sl. 11). Po vklopu prh simulacija kakovostno dobro napove povečanje koncentracije 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.

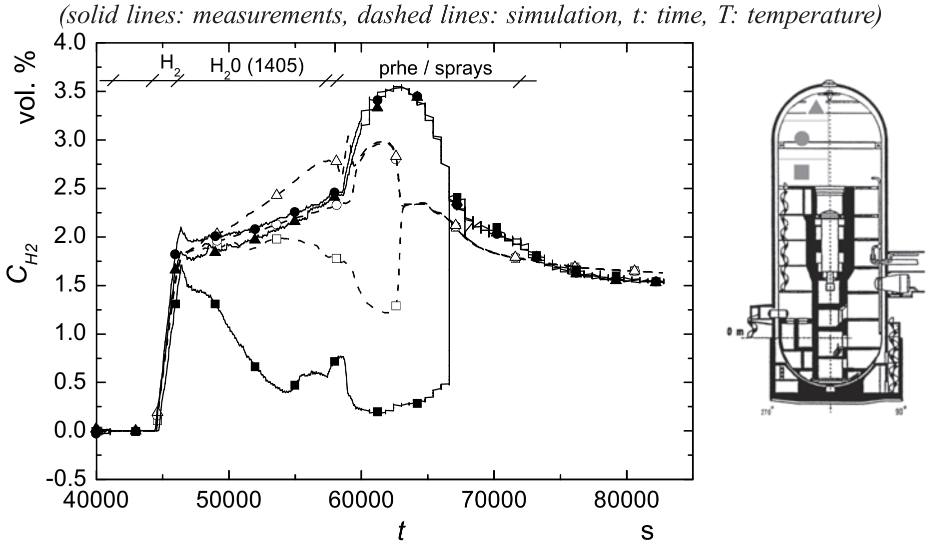
The discrepancies between the measured and calculated temperatures are most probably due to deficiencies in the modelling of the instrumentation heat removal and the distribution of heat structures. These aspects of the modelling are difficult to improve due to the incomplete information provided in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



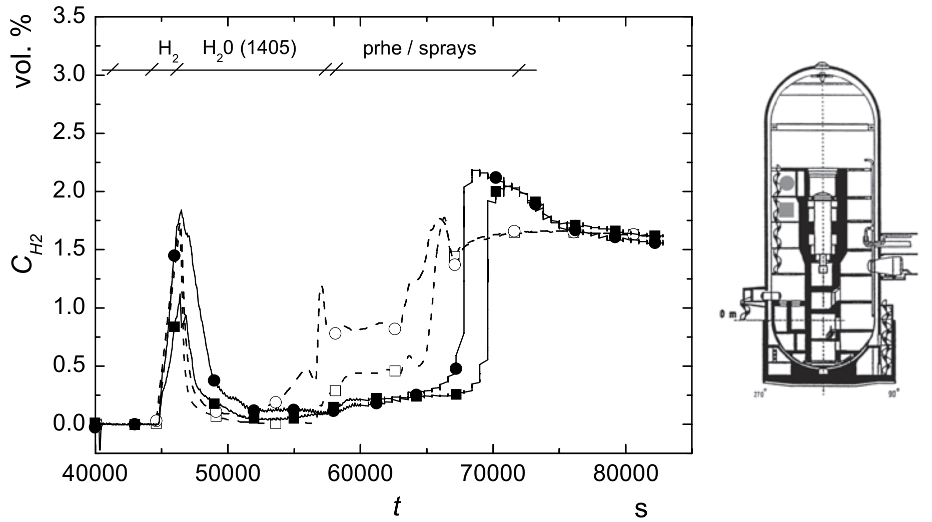
Sl. 10. *Temperatura plinov v spodnjem delu stopnišč*
(polne črte: meritve, črtkane črte: simulacija, t: čas, T: temperatura)
Fig. 10. *Gas temperature in lower part of staircases*
(solid lines: measurements, dashed lines: simulation, t: time, T: temperature)



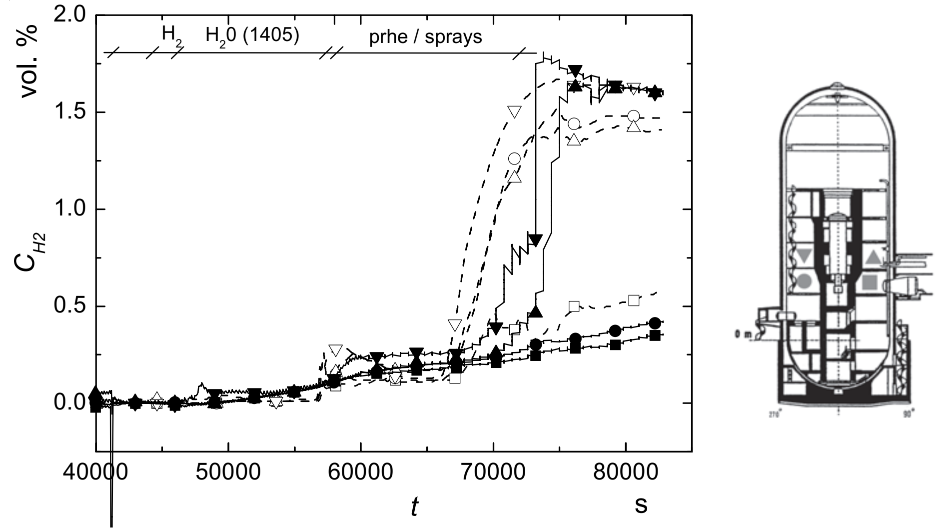
Sl. 11. *Koncentracija vodika v kupoli zadrževalnega hrama*
(polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)
Fig. 11. *Hydrogen concentration in containment dome*
(solid lines: measurements, dashed lines: simulation, t: time, C: volumetric concentration)

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.



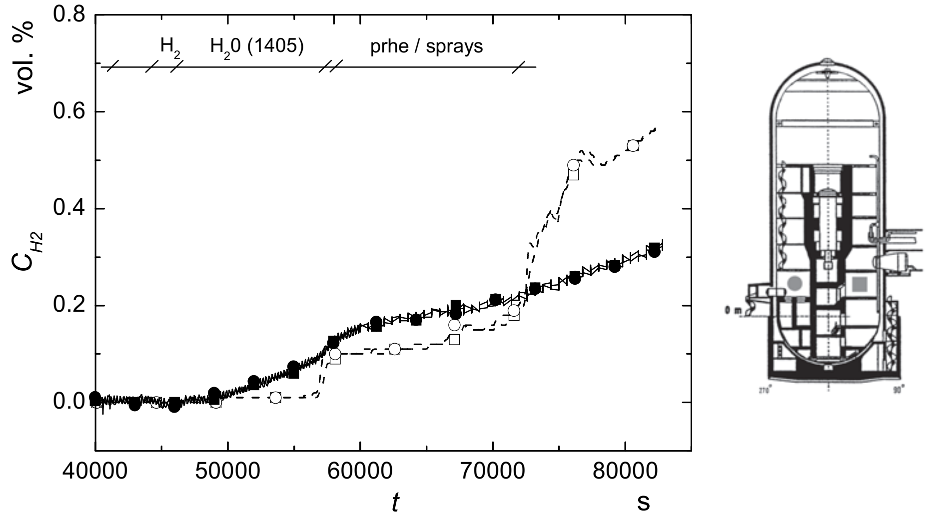
Sl. 12. *Koncentracija vodika v zgornjem delu vijačnega stopnišča*
(polne črte: meritve, črtkane črte: simulacija, t: čas, C: prostorninska koncentracija)
Fig. 12. *Hydrogen concentration in upper part of hellical staircase*
(solid lines: measurements, dashed lines: simulation, t: time, C: volumetric 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.

[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.

[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*.

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Analiza vpliva prometnega toka pešcev na prepustno zmožnost krožišča z uporabo diskretnih simulacij

An Analysis of the Influence of Pedestrians' Traffic Flow on the Capacity of a Roundabout Using the Discrete Simulation Method

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Podobno kakor v običajnih nesemaforiziranih križiščih lahko tudi pri krožiščih, v posebnih prometnih razmerah, prihaja do bistvenega zmanjšanja prepustnosti. V takih primerih je značilno, da je prometni tok pešcev in/ali kolesarjev pri prečkanju enega ali več krakov krožišča tako močan, da vpliva na polnjenje ali na praznjenje krožišča. Namen prispevka je ponazoriti, kako lahko uporaba diskretnih simulacij prispeva k odločitvi o izvedbi krožišča, oziroma ali bo krožišče primerno izpolnjevalo pogoj zmogljivosti ob pričakovanem prometnem toku pešcev in/ali kolesarjev. Predlagan je nov način obravnave problematike dimenzioniranja krožišč z vidika matematičnega modeliranja prometnih tokov z uporabo metode diskretnih simulacij, z upoštevanimi statistično ovrednotenimi vhodnimi podatki za prometni tok vozil in pešcev. Rezultati simulacij so uporabni pri določanju prepustnosti načrtovanih krožišč, ki bodo delovali v različnih prometnih okoliščinah. Predstavljen model izhaja iz sprejemljive časovne praznine v prometnem toku pešcev, ki jo uporabljajo motorna vozila za uvažanje in izvažanje iz krožišča, če upoštevamo, da imajo pešci prednost. Simulacijska analiza je preverjena na dejanskem primeru montažnega krožišča v Mariboru, na Koroški ulici, kjer so bile izvedene tudi potrebne meritve prometnega toka motornih vozil ter pešcev in kolesarjev. Postopek, prikazan v prispevku, predstavlja poleg znanstvenega postopka matematičnega modeliranja tudi praktično metodo za pomoč pri odločanju o smiselnosti izvedbe krožišča v primeru močnega toka pešcev in/ali kolesarjev.

(Ključne besede: krožišča, tokovi prometni, analize vplivov, modeli simulacijski)

Like with other non-traffic-lighted intersections, the capacity of roundabouts can be reduced by special traffic conditions. In such cases the pedestrian's and/or cyclist's traffic flow, crossing one or more roundabout arms, is the size that influences the roundabout filling or emptying. The purpose of this paper is to show how the use of discrete simulation methods contributes to the decision on implementing a roundabout, or to help decide if the roundabout is going to fulfil appropriately the condition of the expected flow of pedestrians and/or cyclists. A new approach is suggested for dimensioning roundabouts, with mathematical modelling of the traffic flows using the discrete simulation method, and considering the statistically evaluated entry data for vehicles' and pedestrians' traffic flows. The simulation results are useful when determining the capacity of foreseen and suggested roundabouts, which will function in different circumstances. The presented model derives from the expected time void in the vehicles' traffic flow, used by the pedestrians, assuming their right of way when joining the traffic. The simulation analysis was verified on a real example of a montage roundabout in Koroška Street in Maribor, where measurements of the motorised vehicles' traffic flow, and pedestrians' and cyclists' traffic flow were made. The procedure, shown in the paper, along with the scientific approach to mathematical modelling, presents a practical method, helpful when deciding whether to implement a roundabout in the case of heavy pedestrians' and/or cyclists' traffic flows.

(Keywords: roundabouts, traffic flow, influence analysis, simulation models)

0 UVOD

V krožiščih z enim voznim pasom v krožnem vozišču se lahko, zaradi močnega toka pešcev in/ali kolesarjev, pojavijo problemi s polnjenjem in praznjenjem krožišča. Vozila na uvozih in izvozih iz krožišča morajo pešcem in kolesarjem praviloma odstopiti prednost. Zaradi tega prihaja do motenj v prometnem toku motornih vozil, ki je prednostnem v smislu dimenzioniranja krožišča in njegove zmogljivosti in zaradi tega povzročenimi zastoji [1]. V primeru, da je tok motornih vozil, ki ga prečka tok pešcev in/ali kolesarjev, usmerjen proti uvozu, postane vprašljivo doseganje najmanjše zmogljivosti krožišča. V primeru, da je tok motornih vozil, ki ga prečka tok pešcev in/ali kolesarjev, usmerjen proti izvozu, prihaja do prekoračitve največje zmogljivosti krožišča [2]. Možnost nastanka blokade krožišča se lahko ugotavlja na več načinov. V preteklosti so različni avtorji ([4] in [5]) uporabljali različne načine izračuna zmogljivosti krožišč in različne načine določanja vpliva toka nemotoriziranih udeležencev na zmogljivost krožišča. Skupna lastnost vseh teh postopkov je obilica matematičnih izračunov [6] in poenostavitev, da bi izračun sploh bil mogoč. Zaradi tega so se takšni izračuni uporabljali le v izjemnih primerih. Med preprostejše metode, pri katerih se uporablja samo diagram ali ena enačba, sodijo nemška metoda za določanje vpliva pešcev [7] in nizozemska metoda za določanje vpliva kolesarjev [8] na prepustnost enopasovnega krožišča. Dandanes po svetu prevladujeta dve skupini metod za določanje zmogljivosti krožišč, s tem pa tudi vpliva toka pešcev in kolesarjev na zmanjšanje njihove zmogljivosti. V prvo skupino sodijo deterministične, v drugo skupino pa naključnostne metode.

V zadnjem času se vse bolj povečuje tudi pomen simulacijskih metod, za kar so zaslužni predvsem vedno bolj zmogljivi računalniki in velike možnosti ustvarjanja zapletenih matematičnih modelov, ki omogočajo dobro primerljivost rezultatov z dejanskimi razmerami. V prispevku predstavljen model izhaja iz sprejemljive časovne praznine v prometnem toku pešcev oziroma kolesarjev, ki jo uporabljajo motorna vozila za uvažanje in izvažanje iz krožišča, če upoštevamo, da imajo pešci oziroma kolesarji prednost. V predstavljenem modelu je obravnavan osamljen krak krožišča oziroma uvoza v krožišče brez vpliva krožečega toka v vozišču. Predpostavljena je enaka hitrost posameznih

0 INTRODUCTION

With one-lane roundabouts, problems with entering and exiting the roundabout can occur due to large traffic flows of pedestrians and/or cyclists. Vehicles on entries and exits should, as a rule, give priority to pedestrians and cyclists. For this reason, disturbances occur in the main vehicle flow, considered as a priority when dimensioning a roundabout intersection and its capacity for the resulting congestions [1]. When a flow of vehicles, traversed by pedestrians and/or cyclists, is oriented towards an entry, achieving the minimum capacity of the roundabout becomes questionable. When a flow of vehicles, traversed by pedestrians and/or cyclists, is oriented towards an exit, the maximum capacity gets exceeded [2]. The possibility of a roundabout blockage can occur in more ways. In the past, many authors ([4] and [5]) used different ways of calculating the capacity of roundabouts and different approaches for determining the influence of the flow of non-motorised traffic participants on the capacity of a roundabout. The common feature of all the approaches is an abundance of mathematical calculations [6] and simplifications to make the calculation possible in the first place. This is why this kind of calculation has been used in exceptional cases only. Among the simpler methods, where only a diagram or one equation are used, are the German method for determining the influence of pedestrians [7] and the Dutch method for determining the influence of cyclists [8] on the capacity of a one-lane roundabout. Nowadays, two groups of methods for determining the capacity of a roundabout, and the resulting influence of pedestrians' and cyclists' flow on the reduction of its capacity are dominant in the world. In the first group there are the deterministic methods, and in the second group are the stochastic methods.

Lately, the significance of simulation methods is also increasing, with the most credit going to increasingly capable computers and the numerous possibilities for creating complex mathematical models that enable good comparability of the results with the actual circumstances. The presented model derives from the expected time void in the pedestrians' traffic flow, used by the vehicles for entering and exiting the roundabout, assuming their right of way when joining the traffic. In the proposed model only a separate arm of the roundabout is considered, without the influence of a circular flow of motorised vehicles on the circulatory roadway. The equal velocity of the motorised vehicles, as well as for pedestrians is considered. The arrivals of motornih vozil kakor tudi enaka hitrost posameznih pešcev. Prihodi pešcev so obravnavani posamezno pešec za pešcem, v eni vrsti. Simulacijska analiza je uporabljena na dejanskem primeru montažnega krožišča v Mariboru, na Koroški ulici, kjer so bile izvedene tudi vse potrebne meritve. Postopek, prikazan v prispevku, je poleg znanstvenega načina matematičnega modeliranja tudi pripomoček za pomoč pri odločanju o primernosti izvedbe krožišča v primeru močnega toka pešcev in/ali kolesarjev.

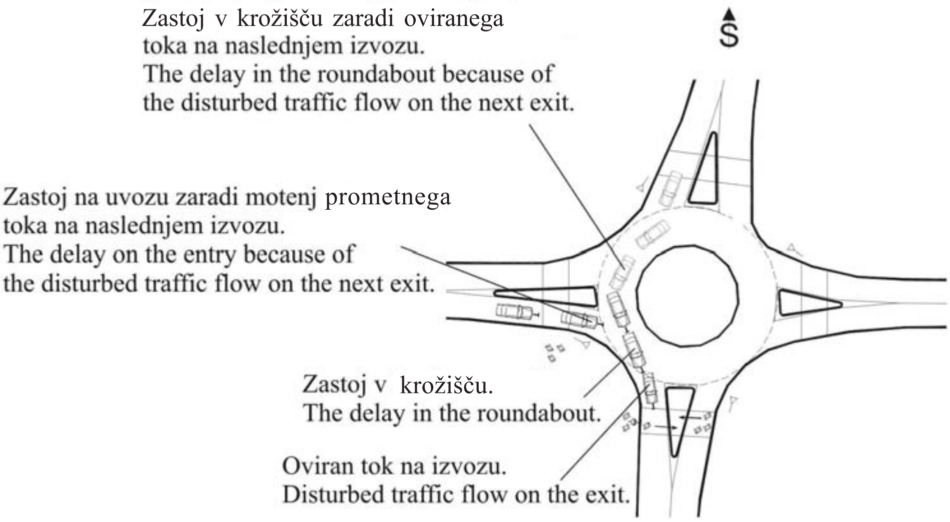
1 OPIS PROBLEMATIKE

V osnovi moramo, pri določanju zmanjšanja zmogljivosti krožišča zaradi močnega toka pešcev in/ali kolesarjev, ločiti dva primera. V prvem primeru prečni prometni tok pešcev sicer vpliva na prepustno zmožnost krožišča, toda krožišče deluje. V drugem primeru pa je vpliv pešcev in/ali kolesarjev tolikšen, da obstaja možnost, da nastajajo daljši zastoji pri uvozu in izvozu iz krožišča, ki pa se potem prenašajo na sosednje krake krožišča. Če je dolžina vozil v vrsti pri izvozu iz krožišča tako dolga, da doseže predhodni uvoz, prihaja do problemov zasedenosti krožišča in lahko pride do zastoja v celotnem krožišču. Navedena problema polnjenja in praznjenja krožišča v dejanskih razmerah se največkrat pojavita hkrati. V dejanskih razmerah je prav tako običajno, da močan tok pešcev prečka le enega od krakov krožišča, čeprav obstajajo tudi primeri, ko tok pešcev »seka« vse krake hkrati. V takšnih primerih pride do zastoja v krožišču prej. V nadaljevanju je, zaradi preprostejše razlage, obravnavan primer, ko močen tok pešcev prečka le en krak krožišča. Prednostni tok pešcev prečka (južni) krak krožišča (sl. 1). Časovni presledki med dvema zaporednima pešcema so zadostni, zato jih vozila na izvozu iz krožišča uporabljajo in nemoteno zapuščajo krožišče. Tok vozil pri izvozu iz krožišča je stabilen. S povečanjem jakosti toka pešcev prihaja do zmanjšanja časovnih presledkov med enotami tega prometnega toka. Občasno se pojavljajo tudi primeri, ko so posamezni časovni presledki med enotami toka pešcev krajši od sprejemljivih. V takšnih primerih vozilo čaka v niši med zunanjim robom krožišča in robom prehoda za pešce/kolesarje. Tok je še vedno stabilen, vendar občasno moten (oviran).

the pedestrians are supposed to be separate, one by one, in single file. The simulation analysis was verified on a real example of a montage roundabout in Koroška Street in Maribor, where all the necessary traffic-flow measurements were made. The procedure, shown in the paper, along with the scientific approach to mathematical modelling, presents an instrument that is helpful when deciding how reasonable it is to implement a roundabout in the case of strong traffic flows of pedestrians and/or cyclists.

1 DESCRIPTION OF THE PROBLEM

When defining the capacity reduction of roundabouts, two different samples can be distinguished because of large traffic flows of pedestrians and/or cyclists. In the first case, the traversed pedestrian’s and/or cyclist’s flow influenced the permeable capacity of the roundabout, but it still works. In second case, the influence of the pedestrian’s and/or cyclist’s traffic flow was of such size that bottlenecks on roundabout entry and exit are possible, which could also be extended to the adjacent roundabout arms. If the length of the vehicles in the queue is so long that it stretches back to the previous entry point, problems with occupation of the roundabout arise and a blockage of the entire roundabout can occur. The mentioned problems of entering and exiting a roundabout in real conditions usually happen simultaneously. In real circumstances it is also usual that those intensive pedestrian flows traverse only one arm of the roundabout, although in some cases the pedestrians’ flow “cuts” all the arms at once. In these cases the blockage of the roundabout occurs earlier. In the following is an example of when a strong pedestrian flow traverses only one arm, because of the easier explanation. The right-of-way pedestrian flow traverses the south arm of the roundabout (Figure 1). The time interspaces between two consecutive pedestrians are long enough; therefore, the vehicles exiting the roundabout use them and exit the roundabout undisturbed. The vehicle flow on the exit is stable in this case. With an increasing strength of pedestrian flow the time interspaces between the traffic-flow units are reduced. Situations occasionally occur when the individual time interspaces between the pedestrian flow units are shorter than acceptable. In these cases the vehicle waits in the waiting place between the outside edge of the circulatory roadway and the inside edge of the pedestrian crossing. The flow is still stable, but occasionally it is disturbed.



Sl. 1. *Nastanek zastoja v krožišču [3]*
Fig. 1. *Queue formation on a roundabout [3]*

Z nadaljnjim povečevanjem toka pešcev se razmere vedno bolj slabšajo, oziroma niša za čakanje pri izvozu iz krožišča postaja ves čas zasedena. Zaradi tega se vozila kopičijo na krožišču do predhodnega uvoza in onemogočajo uvoz vozil v krožišče. Prometni tok med južnim in zahodnim krakom krožišča je moten (sl. 1). V tem primeru je mogoče odvijanje prometnega toka le še na preostalih delih krožišča. V primeru, da je katero od vozil na preostalih treh uvozih usmerjeno proti zastojnemu izvozu, prihaja do zapolnitve še enega krožnega odseka (med zahodnim in severnim krakom – slika 1), kar povzroči zastoj tudi zahodnega kraka krožišča. Zastoj se prenaša od izvoza iz krožišča do prejšnjega (gledano v nasprotni smeri vožnje v krožišču) uvoza v krožišče in od tu zopet naprej na prejšnji izvoz. Celoten postopek se lahko ponavlja v nasprotni smeri vožnje do popolnega zastoja krožišča. V enopasovnem krožišču s prostorom za čakanje enega vozila v niši med prehodom za pešce in zunanjim robom krožišča se torej lahko v splošnem pojavijo trije primeri, in sicer:

- časovni presledki med posameznimi enotami prečnega toka pešcev so zadostni za prehod vozil, zato ni čakajočih vozil v niši;
- časovni presledki med posameznimi enotami prečnega toka pešcev so še vedno zadostni za prehod vozil, čeprav prihaja do čakanja vozil v niši;

With an additional increase in the pedestrian flow the conditions get worse and the waiting place on the exit of the roundabout becomes occupied all the time. For this reason the vehicles are congested on the circulatory roadway towards the preceding entry, thus preventing entry to the roundabout. The traffic flow between the south and the west arms is disturbed. In this case traffic flow is possible only on other parts of the circulatory roadway. In the case that one of the vehicles on the other three entries is directed towards the blocked exit, another circular segment gets filled (between the west and the north arms – Figure 1), which causes the blockage of the west arm of the roundabout. The blockage is transferred from an exit towards the preceding (opposite to the driving direction) entry to the roundabout and from here towards the preceding exit. The entire procedure can repeat itself in the direction opposite to the driving until the roundabout is completely blocked. In a one-lane roundabout with a waiting space for one vehicle in the waiting place between the pedestrian crossing and the outside edge of the circulatory roadway the following three situations can generally occur:

- time interspaces between the individual units of transverse pedestrian flow are sufficient for vehicle flow, and so there are no waiting vehicles in the waiting place;
- time interspaces between the individual units of transverse pedestrian flow are still sufficient for vehicle flow, although vehicles do wait in the waiting place;

- časovni presledki med posameznimi enotami prečnega toka pešcev so premajhni, niša je ves čas zasedena in vsako naslednje vozilo čaka na krožišču.

Kolikokrat se lahko pojavijo opisani primeri, kakšni so pogoji za nastanek opisanih primerov, kateri pogoji morajo biti izpolnjeni za nastanek zastoja enega kraka krožišča in pri kolikšni prometni obremenitvi pešcev ali motornega prometa se motnja iz enega kraka krožišča lahko prenese na sosednji krak, so vprašanja, katerih odgovori določajo vpliv toka pešcev na prepustno zmožnost, tj. zmogljivost enopasovnega krožišča. Očitno je, da tako zapletenih vplivov in medsebojnih delovanj različnih spremenljivk ni mogoče reševati brez uporabe ustreznih matematičnih modelov oziroma diskretnih simulacij prometnega toka motornih vozil, pešcev in/ali kolesarjev. V nadaljevanju so podana osnovna teoretična izhodišča za matematično analizo prometnega toka v obravnavanem krožišču.

2 TEORETIČNA IZHODIŠČA PRI ANALIZIRANJU PROMETNEGA TOKA V KROŽIŠČU

Pri načrtovanju krožišča nas v največji meri zanima njegova zmogljivost v odvisnosti od prometnega toka (*i*) motornih vozil ter (*ii*) pešcev in kolesarjev. Temeljno pravilo pri vsakem krožišču (izjema so semaforizirana krožišča) je, da imajo pešci in kolesarji prednost pred motornimi vozili. Pri določitvi zmogljivosti krožišča izhajamo iz skupne frekvence prometnega toka motornih vozil ter pešcev in kolesarjev, ki se križajo na posameznem kraku krožišča. Celotno zmogljivost (motornih vozil ter pešcev in kolesarjev) posameznega kraka krožišča lahko izrazimo z naslednjo poenostavljeno odvisnostjo, pri čemer je:

μ_1 – največja zmogljivost prometnega toka motornih vozil v izbrani časovni enoti,
μ_2 – največja zmogljivost prometnega toka pešcev in kolesarjev v izbrani časovni enoti,
λ_1 – dejanska zmogljivost prometnega toka motornih vozil z upoštevanjem pešcev in kolesarjev v izbrani časovni enoti,
λ_2 – dejanska zmogljivost prometnega toka pešcev in kolesarjev v izbrani časovni enoti.

- Izkoristek ρ_1 posameznega kraka krožišča za motorna vozila je enak naslednji odvisnosti:

- time interspaces between the individual units of transverse pedestrian flow are not large enough, the waiting place is occupied all the time and every next vehicle waits in the circulatory roadway.

How many times these situations occur, what are the conditions for the creation of these situations, what conditions have to be fulfilled for a blockage of one arm of the roundabout and at what traffic load of pedestrians or motorised traffic flow the disturbance is transferred from one to another arm are the questions, the answers to which determine the influence of the pedestrian flow on the capacity of a one-lane roundabout. It is obvious that such complex influences and mutual actions of different variables cannot be solved without appropriate mathematical models or discrete simulations of the motorised and non-motorised traffic flows. In the following, the basic theoretical backgrounds for the mathematical analysis of a traffic flow in a given roundabout are presented.

2 THEORETICAL BACKGROUNDS FOR ANALYSING THE TRAFFIC FLOW IN A ROUNDABOUT

When planning a roundabout, its capacity in relation to the traffic flow (i) of motorised vehicles and (ii) pedestrians and cyclists are the main interest. The general rule in every roundabout (roundabouts with traffic lights are an exception) is that pedestrians and cyclists have priority with regard to the motorised vehicles. When determining the capacity of a roundabout, the combined frequency of the traffic flow of vehicles, pedestrians and cyclists, crossing each other on an individual arm of a roundabout are derived. The total capacity (motorised vehicles, pedestrians and cyclists) in an individual arm of a roundabout can be presented with the following simplified relation dependence:

μ_1 – maximum capacity of a traffic flow of motorised vehicles in a given time period,
μ_2 – maximum capacity of a traffic flow of pedestrians and cyclists in a given time period,
λ_1 – actual capacity of a traffic flow of motorised vehicles, considering pedestrians and cyclists in a given time period,
λ_2 – actual capacity of a traffic flow of pedestrians and cyclists in a given time period.

- The utilisation rate ρ_1 of an individual arm of a roundabout for motorised vehicles is given by the following relation:

$$\rho_1 = \frac{\lambda_1}{\mu_1} \leq 1 \quad (1).$$

- Izkoristek ρ_2 posameznega kraka krožišča za pešce in kolesarje je enak naslednji odvisnosti:

- The utilisation rate ρ_2 of an individual roundabouts' arm for pedestrians and cyclists is given by the following relation:

$$\rho_2 = \frac{\lambda_2}{\mu_2} = 1 \quad \text{kjer je/where} \quad \lambda_2 = \mu_2 \quad (2).$$

S poenostavljeno odvisnostjo (2) smo pokazali, da je dejanska zmogljivost pešcev in kolesarjev, zaradi pogoja prednosti le-teh pred motornimi vozili, zmeraj enaka največji zmogljivosti. Drugačno odvisnost prikazuje izraz za zmogljivost motornih vozil (1), ki je močno odvisna od prometnega toka pešcev in kolesarjev. Pri analizi krožišča oziroma posameznih krakov krožišča želimo ugotoviti, pri katerem prometnem toku pešcev in kolesarjev je prepustnost motornih vozil še smotrna, da ne prihaja do prevelikih čakalnih dob (časov) in čakalnih vrst motornih vozil.

Prihode motornih vozil ter pešcev in kolesarjev v posamezne krake krožišča lahko obravnavamo kot sistem čakalne vrste z enim strežnim mestom [12]. Pri določitvi ustreznega sistema čakalne vrste izhajamo iz pogoja, da so prihodi motornih vozil porazdeljeni po Poissonovi statistični porazdelitvi. Prav tako upoštevamo, da je čas med dvema zaporednima prihodoma pešcev in kolesarjev podan po Poissonovi statistični porazdelitvi. Zaradi zveze med Poissonovo in eksponentno statistično porazdelitvijo je treba določiti naslednjo povezavo. Če je število prihodov motornih vozil ali pešcev in kolesarjev v določenem časovnem koraku t podano po Poissonovi porazdelitvi s povprečno stopnjo prihodov na časovno enoto enako λ in s srednjo vrednostjo $\lambda \cdot \tau$, potem so časi med prihodoma dveh zaporednih vozil ali pešcev in kolesarjev podani po *eksponentni* porazdelitvi s srednjo vrednostjo $1/\lambda$ [13].

M – se navezuje na Poissonovo porazdelitev števila prihodov motornih vozil pešcev in kolesarjev na časovno enoto,

D – navezuje se na stalno oz. deterministično porazdelitev časa, ki je potreben za vožnjo motornih vozil prek prehoda za pešce ter prehoda pešcev in kolesarjev na drugo stran vozišča,

1 – v sistemu je samo eno strežno mesto, ki se navezuje na prehod za pešce,

∞ – prihod v sistem je določen z neskončnim tokom motornih vozil ter pešcev in kolesarjev,

The simplified relation (2) presents the actual capacity of pedestrians and cyclists (due to the priority with regard to the motorised vehicles) that are always the same as the maximum capacity. A different relation is presented by the expression for the capacity of motorised vehicles (1), which strongly depends on the traffic flow of pedestrians and cyclists. When analysing a roundabout or individual arms of it, one has to establish at what traffic flow of pedestrians and cyclists the capacity of motorised vehicles is still reasonable, so that too long waiting periods and waiting lines of motorised vehicles do not occur.

The arrivals of motorised vehicles, pedestrians and cyclists into the individual arms of a roundabout can be treated as a system of a waiting line with one serving place [12]. When determining the appropriate system of the waiting line the basic condition, that the arrivals of motorised vehicles are distributed according to Poisson's statistical distribution, is taken into account. The condition that the time between two consecutive arrivals of pedestrians or cyclists is distributed according to Poisson's statistical distribution is also considered. Due to the connection between Poisson's and the exponent statistical distribution, the following relation has to be defined. If the number of arrivals of motorised vehicles, pedestrians or cyclists in a given time interval t is distributed according to Poisson's distribution with an average degree of arrivals in a time unit λ and a medium value $\lambda \cdot \tau$, then the times between the arrivals of two consecutive vehicles, pedestrians or cyclists, are distributed according to the exponent distribution with a medium value of $1/\lambda$ [13].

M – according to the Poisson's distribution of the number of arrivals of motorised vehicles, pedestrians and cyclists in a given time unit,

D – according to the constant or deterministic distribution of time, required for the driving of motorised vehicles by the pedestrian crossing and the crossing of pedestrians and cyclists to the other side of the roadway,

1 – only one serving station exists in the system, which is in connection to the pedestrian crossing,

∞ – arrival to the system is determined by an infinite flow of motorised vehicles, pedestrians and cyclists,

∞ – sistem omogoča neskončno mnogo voženj motornih vozil prek prehoda za pešce ter prehodov pešcev in kolesarjev na drugo stran vozišča,

FIFO – enota (motorno vozilo, pešec ali kolesar), ki pride v sistem prva, je tudi prva postrežena.

Sistem *M*/*D*/1/∞/∞/*FIFO* za prometni tok motornih vozil ter prometni tok pešcev in kolesarjev je za primer obravnavanega kraka krožišča prikazan na sliki 2.

Zaradi dveh neodvisnih prometnih tokov (motornih vozil ter pešcev in kolesarjev) pomeni posamezen krak krožišča skupek dveh neodvisnih sistemov čakalnih vrst, in sicer:

- *M*/*D*/1/∞/∞/*FIFO* za prometni tok motornih vozil in

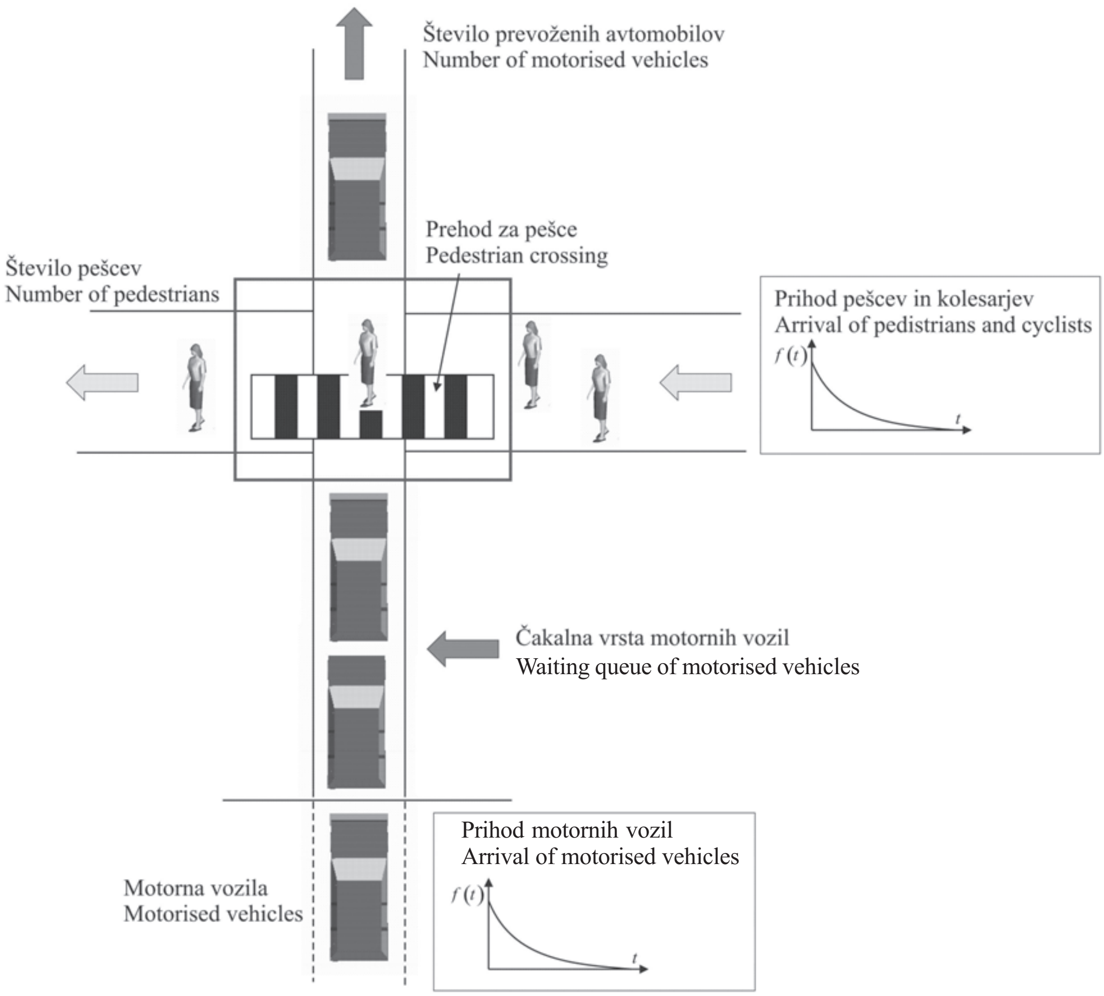
∞ – system enables infinite driving of motorised vehicles over the pedestrian crossing and the crossing of pedestrians and cyclists to the other side of the carriageway,

FIFO – *Unit (motorised vehicle, pedestrian or cyclist),* which when coming into the system first is served first.

The *M*/*D*/1/∞/∞/*FIFO* system for a traffic flow of motorised vehicles and the pedestrians' and cyclists' traffic flows is schematically shown in Figure 2 for the example of the roundabout arm in question.

Because of the two independent traffic flows (motorised vehicles, and pedestrians and cyclists), an individual arm in a roundabout presents a combination of two independent waiting-line systems:

- M/D/1/∞/∞/FIFO for the motorised vehicles' traffic flow,



Sl. 2. *Prikaz enega kraka krožišča v obliki sistema M/D/1/∞/∞/FIFO*
Fig. 2. *An individual roundabouts' arm in the form of the M/D/1/∞/∞/FIFO system*

- $M/D/1/\infty/\infty/FIFO$ za prometni tok pešcev in kolesarjev.

Medtem ko je prometni tok motornih vozil tipični sistem $M/D/1/\infty/\infty/FIFO$, je prometni tok pešcev in kolesarjev prilagojen sistem $M/D/1/\infty/\infty/FIFO$, saj v omenjenem sistemu nikoli ne pride do čakalnih dob in čakalne vrste. Omenjeno trditev lahko pojasnimo z dejstvom, da imajo v krožišču pešci in kolesarji v vsakem primeru prednost pred motornimi vozili. Zaradi zapletenosti in nedoločenosti sistema, bi sistem čakalnih vrst posameznega kraka krožišča in sistema čakalne vrste celotnega krožišča težko obravnavali analitično. Tako je mogoča rešitev problema uporaba metode diskretnih numeričnih simulacij, ki je predstavljena v nadaljevanju.

3 SIMULACIJA PROMETNEGA TOKA V DEJANSKEM KROŽIŠČU

Analiza prometnih tokov z uporabo diskretnih numeričnih simulacij pomeni uspešen način analize zahtevnejših nivojskih in večnivojskih križišč z vidika zmogljivosti ([9] do [11]). Glede na diskretne modele in način prometnega dogajanja lahko, v splošnem, simulacijske metode razdelimo v dve osnovni skupini, in sicer na (*i*) makroskopske in (*ii*) mikroskopske modele. Makroskopski modeli združujejo vozila in sama potovanja po skupinah, pri čemer se prometni tok kaže kot statistični model, medtem ko rezultat predstavlja povprečje v določenem času. Pri makroskopskih modelih je poudarek na samih povezavah, križišča so v modelu poenostavljena. Makroskopski modeli so, nasprotno od mikroskopskih modelov, osredotočeni na dolgo dobo načrtovanja. Z mikroskopskimi modeli »opisujemo« vsako posamezno vozilo, pešca, kolesarja itn. s stvarnimi lastnostmi (izmere, hitrosti, pospeški itn.). Mikroskopski modeli se uporabljajo za analize prometnih tokov v kratki načrtovalni dobi.

Glede na zapletenost analitičnega modela krožišča in uporabnosti diskretne simulacijske tehnike, smo za analizo zmogljivosti krožišča uporabili diskretne numerične simulacije. V tem prispevku smo za analizo krožišča uporabili programsko orodje AutoMod [14], ki se uporablja predvsem za izvajanje diskretnih numeričnih simulacij sistemov notranje logistike [15] ter vseh drugih logističnih diskretnih sistemov. Le-ta omogoča uporabniku zanesljivo orodje pri načrtovanju ali

- M/D/1/∞/∞/FIFO for the pedestrians' and cyclists' traffic flow.

While the motorised vehicles' traffic flow represents a typical M/D/1/∞/∞/FIFO system, the pedestrians' and cyclists' traffic flow system M/D/1/∞/∞/FIFO is modified, since in the mentioned system the waiting periods and the waiting line never occur. This assertion can be explained by the fact that in a roundabout pedestrians and cyclists have priority over the motorised vehicles. Because of the complexity and non-determination of the system, the waiting line system of an individual arm of a roundabout and the waiting line system of the entire roundabout is problematic for an analytical treatment. Therefore, a possible solution to the problem is the use of the discrete numeric simulations method, which is presented in the following section.

3 SIMULATION OF THE TRAFFIC FLOW IN A REAL ROUNDABOUT

The analysis of traffic flows using discrete numeric simulations represents a successful way of analysing more complex crossroads and intersections from the point of capacity determination ([9] to [11]). According to discrete models and the way of action in traffic, simulation methods can be, generally, divided in two groups: (i) macroscopic and (ii) microscopic models. Macroscopic models combine vehicles and travelling among groups, and the traffic flow is represented by a statistical model; the result is presented as an average value after a certain time. With macroscopic models the emphasis is on the links themselves, the intersections are simplified in the model. Macroscopic models are, unlike microscopic models, focused on a long-term planning period. With a microscopic model every individual vehicle, pedestrian, cyclist, etc., can be described with real characteristics (dimensions, velocities, accelerations, etc.). Microscopic models are used for traffic-flow analyses in a short-term planning period.

Considering the complexity of the analytical model of a roundabout and the usage of a discrete simulation technique, discrete numeric simulations for the analysis of the capacity of a roundabout were used. In the proposed contribution the program code AutoMod [14] was used for the analysis of a roundabout. AutoMod [14] is used mostly for implementing discrete numeric simulations of internal logistic systems and all other logistic discrete systems. It offers the user a reliable tool for planning or reconstructing rekonstrukciji zapletenih in medsebojno odvisnih sistemov. Programsko orodje deluje v opravilnem sistemu Windows XP in je sestavljeno iz okolja, kjer modeliramo izbran sistem (predprocesor) in modul za izvedbo simulacije. Programsko orodje je sestavljeno iz posameznih programskih modulov, ki sestavljajo celoto programskega orodja AutoMod [14]. Pri modeliranju poljubnega sistema uporabljamo že vgrajene elemente (zvezni transporterji, avtomatizirana transportna vozila itn.), ki pomenijo določene sklope v izbranem postopku. Le-tem v vhodni datoteki (ang. *Source file*) z vpisom programske kode določimo lastnosti, ki ustrezajo dejanskemu stanju ter jih med seboj ustrezno povežemo. Z ukaznimi vrsticami določimo izvajanje simulacije ter analiziramo uspešnost in učinkovitost sistema.

V nadaljevanju so prikazani koraki simulacije in analize prometnega toka motornih vozil na montažnem trikrakem enopasovnem krožišču z močnim prometnim tokom pešcev in kolesarjev, na Koroški ulici v Mariboru (sl. 8). Izhajali smo iz dejanskih geometrijskih podatkov (sl. 9), kakor tudi vzorca prometnega toka pešcev in motornih vozil za vse krake križišča in prehode za pešce, ki smo ga izvedli s štetjem prometa in statistično ovrednotili dobljene podatke.

3.1 Vhodni podatki za izdelavo mikrosimulacijskega modela – analiza dejanskega stanja prometnih tokov, opravljena s štetjem prometa

Pri izdelavi simulacijskega modela za montažno trikrako enopasovno krožišče (sl. 3) smo upoštevali dejansko geometrijsko obliko krožišča (sl. 4) in hitrostne značilnice vozil in pešcev (pregl. 1).

Za potrebe analize je bilo opravljeno 15-urno štetje (6^{00} do 21^{00}), na vseh krakih križišča, ločeno za promet motornih vozil ter promet pešcev in kolesarjev (slika 4). V prispevku prikazujemo rezultate štetja motornega prometa (preglednica 2) in prometa pešcev ter kolesarjev (preglednica 2) na kraku A – smer “Stari most”, na kraku B – smer Koroška c. vzhod (Kolosej) ter kraku C – smer Koroška c., ki so predmet obravnave pričujočega prispevka.

Na podlagi štetja prometnega toka motornih vozil ter pešcev in kolesarjev za vse cestne krake A, B in C montažnega krožišča na Koroški ulici v Mariboru smo dobljene podatke statistično

complex and inter-dependent systems [15]. The program code works in the Windows XP operating system and is constructed by the environment, where the chosen system is modelled (pre-processor) and a module for the starting of the simulation. The programming tool consists of individual programming modules that construct the programming tool AutoMod [14] as an integrity. When modelling a general system, already built-in elements (connection transporters, automates transport vehicles, etc.) that represent certain complexes in the chosen process, can be used. In the source file characteristics, which suit to the real situation and connect them appropriately, are determined. With the help of command lines the implementation of the simulation is determined and based on the acquired results of simulations the success and the efficiency of the system is analysed.

In the continuation steps of the simulation and the analysis of the motorised vehicles’ traffic flow on a montage three-armed, one-lane roundabout with strong pedestrians’ and cyclists’ traffic flow on Koroška Street in Maribor (Figure 3) are shown. The actual geometrical data are derived from Figure 4 and from a sample of pedestrians’ and motorised vehicles’ flows for all the arms of the roundabout and pedestrian crossings, gathered by counting traffic and statistically evaluating the acquired data.

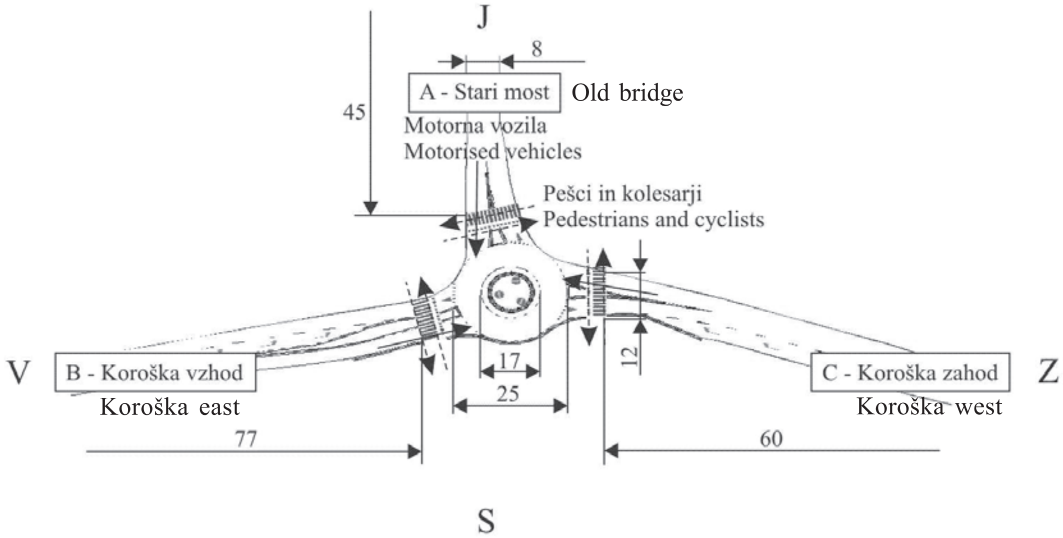
3.1 Input data for constructing a micro-simulation model – an analysis of the actual situation of traffic flows performed by counting traffic

When constructing a simulation model for a montage three-armed, one-lane roundabout (Figure 3) the actual geometry of the roundabout (Figure 4) and the velocity characteristics of vehicles and pedestrians (Table 1) were considered.

A 15-hour (6^{00} to 21^{00}) count was performed for the requirements of the analysis, on all the intersections’ arms, separately for the motorised vehicle traffic and the pedestrian and cyclist traffic (Figure 4). The results of the motorised-vehicle traffic count (Table 2) and the pedestrian/cyclist traffic count (Table 2) on the Arm A – direction “old bridge”, on the Arm B – direction Koroška Street east (Coloseum) and on the Arm C – direction Koroška Street, that are treated in this work were presented.

The acquired data was statistically evaluated, based on the traffic count of motorised vehicles and the pedestrians and cyclists for all the roads’ arms A, B and C of the montage roundabout on the Koroška Street in

Sl. 3. *Montažno trikrako, enopasovno krožišče na Koroški ulici v Mariboru*
Fig. 3. *Montage three-armed, one-lane roundabout on Koroška Street in Maribor*



Sl. 4. *Geometrijska oblika obravnavanega krožišča (razdalje so v metrih)*
Fig. 4. *Geometry of the treated roundabout (distances are in meters)*

ovrednotili. V preglednici 2 so podrobneje prikazani podatki za posamezno konično uro, ki se navezujejo na prometni tok motornih vozil ter pešcev in kolesarjev na posameznih krakih krožišča A, B in C (slika 4). Izračunani so tudi povprečni časi med prihodoma dveh zaporednih vozil ($t = 1/\lambda$). Primer: število prihodov vozil v časovnem koraku 5 minut (300 s) je 43, porazdeljeno po Poissonovi statistični porazdelitvi, s povprečno stopnjo prihodov na časovno enoto λ = 43:300 in s srednjo vrednostjo $t \cdot \lambda$ = 43 MV; tako je povprečni čas med prihodoma dveh zaporednih vozil porazdeljen po eksponentni porazdelitvi s srednjo vrednostjo $1/\lambda$ = 6,98 sekund.

Maribor. In Table 2 the data for an individual rush-hour are presented, and they are connecting to the traffic flows of motorised vehicles, pedestrians and cyclists on the individual arms A, B and C of the roundabout (Figure 4). Additional, average times between two arrivals of successive motor vehicles are calculated ($t=1/\lambda$). Case: the number of motor-vehicle arrivals within a time interval of 5 minutes (300 s) is 43, distributed as a Poisson statistical distribution, with the average degree of arrivals per time unit λ=43:300 and with the medium value of $t \cdot \lambda$=43 MV; the average time between two arrivals of successive motor vehicles can be then determined using an exponential distribution with the medium value $1/\lambda$ = 6.98 seconds.

Preglednica 1. *Geometrijski in kinematični vhodni podatki*
Table 1. *Geometrical and kinematic input data*

Geometrijski vhodni podatki ***Geometrical input data***	
Zunanji premer krožišča Outside diameter of the roundabout	25 m
Notranji premer krožišča Inside diameter of the roundabout	17 m
Širina voznega pasu Width of the road	4 m
Širina prehoda za pešce Width of the pedestrian crossing	5 m
Dolžina vpadnice (izbrana) Length of entrance road (chosen)	Krak/Arm A – 45 m, Krak/Arm B – 77 m, Krak /Arm C – 60 m.
Dolžina prehoda za pešce Length of pedestrian crossing	12 m

Kinematični vhodni podatki ***Kinematics input data***	
Pospešek a_{MV1} motornega vozila na uvozu Acceleration a_{MV1} of a motorised vehicle on the entry	1 m/s^2
Hitrost v_{MV1} motornega vozila na kraku (vpadnici) Velocity v_{MV1} of a motorised vehicle on the arm	40 km/h
Hitrost v_{MV2} motornega vozila v bližini prehoda za pešce Velocity v_{MV2} of a motorised vehicle near the pedestrians' crossing	20 km/h
Pospešek a_{PK} pešca in kolesarja Acceleration a_{PK} of a pedestrian and a cyclist	0,3 m/s^2
Hitrost v_{PK} pešca in kolesarja Velocity v_{PK} of a pedestrian and a cyclist	5 km/h

S štetjem pridobljeni podatki so vhodni podatki za prometni tok motornih vozil ter pešcev in kolesarjev v simulacijskem modelu. Ker so bile meritve izvedene v obliki štetja v posameznem kraku krožišča, predpostavljamo, da se prometni tok motornih vozil ter pešcev in kolesarjev ujema s Poissonovo porazdelitvijo. V tem primeru so časi med prihodoma dveh zaporednih motornih vozil ter pešcev in kolesarjev podani po *eksponentni* porazdelitvi. Za konkretni primer kraka A v časovnem koraku od 10^{10} do 10^{15} obsega prometni tok motornih vozil 43 enot, kar pomeni, da v krak A prihajajo motorna vozila v povprečju vsakih 6,98 sekunde, porazdeljena po *eksponentni* statistični porazdelitvi.

Experimentally acquired input data represent the input data for the traffic flow of motorised vehicles, pedestrians and cyclists in a simulation model. Since the measurements were taken in the form of counting on an individual arm of the roundabout, the presumption has been made that the traffic flow of motorised vehicles, pedestrians and cyclists matches with Poisson's statistical distribution. In this case the times between the arrivals of two consecutive motorised vehicles, pedestrians and cyclists are distributed according to the exponent distribution. For example, on arm A in the time interval from 10^{10} to 10^{15} the traffic flow of motorised vehicles consists of 43 units, which means that motorised vehicles arrive into the arm A on average every 6.98 seconds, and are distributed according to the exponent statistical distribution.

3.2 Mikrosimulacijski model krožišča

Na podlagi obravnavanega krožišča na Koroški ulici v Mariboru smo izdelali simulacijski model krožišča (sl. 5). Simulacijski model je v

3.2 Micro-simulation model of a roundabout

Based on the treated roundabout in Koroška Street in Maribor a simulation model was created (Figure 5). The simulation model in the programming

Preglednica 2. *Meritve MV ter P in K za posamezno konično uro*
Table 2. *Measurements of MV, P and C for an individual rush-hour*

Časovni korak (minute) Time interval (minutes)	**Krak A Arm A**		**Krak B Arm B**		**Krak C Arm C**	
	Konična ura Rush-hour 10^{10} do/to 11^{10}		Konična ura Rush-hour 14^{50} do/to 15^{50}		Konična ura Rush-hour 14^{30} do/to 15^{30}	
	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)
00^{00} do/to 05^{00}	43 (6,98)	6 (50,00)	58 (5,17)	44 (6,82)	53 (5,66)	48 (6,25)
05^{00} do/to 10^{00}	37 (8,11)	6 (50,00)	51 (5,88)	53 (5,66)	63 (4,76)	39 (7,69)
10^{00} do/to 15^{00}	62 (4,84)	14 (21,43)	69 (4,35)	47 (6,38)	73 (4,11)	28 (10,71)
15^{00} do/to 20^{00}	64 (4,69)	10 (30,00)	56 (5,36)	49 (6,12)	64 (4,69)	28 (10,71)
20^{00} do/to 25^{00}	58 (5,17)	9 (33,33)	57 (5,26)	33 (9,09)	51 (5,88)	18 (16,67)
25^{00} do/to 30^{00}	79 (3,80)	9 (33,33)	63 (4,76)	51 (5,88)	73 (4,11)	37 (8,11)
30^{00} do/to 35^{00}	43 (6,98)	8 (37,50)	57 (5,26)	42 (7,14)	63 (4,76)	46 (6,52)
35^{00} do/to 40^{00}	53 (5,66)	9 (33,33)	55 (5,45)	39 (7,69)	47 (6,38)	42 (7,14)
40^{00} do/to 45^{00}	63 (4,76)	10 (30,00)	49 (6,12)	43 (6,98)	46 (6,52)	81 (3,70)
45^{00} do/to 50^{00}	68 (4,41)	10 (30,00)	61 (4,92)	47 (6,38)	64 (4,69)	36 (8,33)
50^{00} do/to 55^{00}	53 (5,66)	10 (30,00)	55 (5,45)	29 (10,34)	58 (5,17)	54 (5,56)
55^{00} do/to 60^{00}	48 (6,25)	4 (75,00)	73 (4,11)	38 (7,89)	67 (4,48)	36 (8,33)

programskem orodju AutoMod [13] ponazorjen z zveznimi transporterji, po katerih poteka prometni tok motornih vozil ter pešcev in kolesarjev. Pri izdelavi simulacijskega modela smo izhajali iz dejanskih geometrijskih podatkov in kinematičnih veličin (preglednica 1), kakor tudi iz vzorca toka pešcev in motornih vozil za vse krake krožišča in prehode za pešce (preglednica 2).

Delovanje simulacijskega modela krmili programska koda (sl. 7 (a) in (b)), ki sledi algoritmu poteka na sliki 6.

Simulacija se prične s postopkom, ki na podlagi določenih funkcij v programski kodi zažene delovanje krožišča. Del primera prihoda motornih vozil v krak A, v programski kodi orodja AutoMod [14], je prikazan na sliki 7 (a) za prihod motornih vozil in 7 (b) za izvedbo pogoja o prednosti pešcev in kolesarjev.

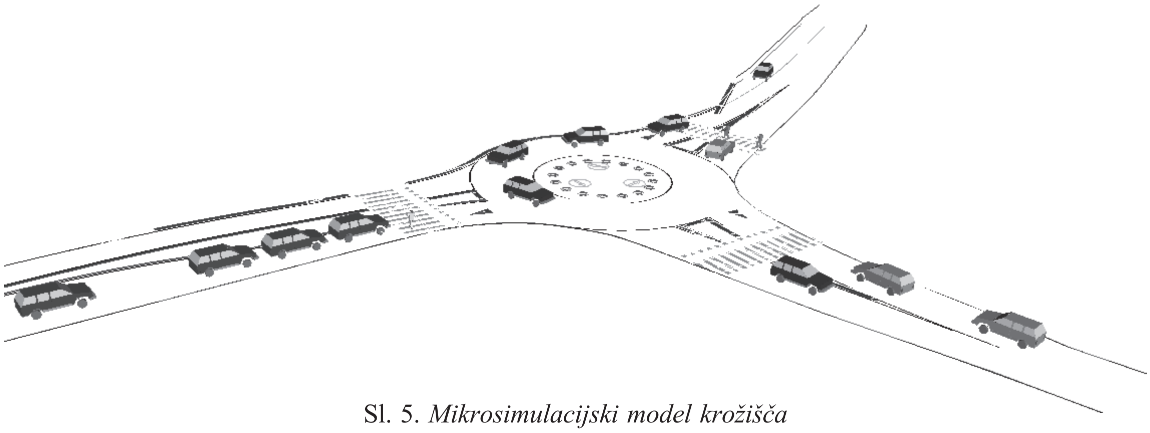
Ko je vrednost funkcije »*inicirati začetek izvajanja simulacije*« enaka »je enako«, se začne izvajati postopek »*p_stari_most_avtomobili*«. Postopek je sestavljen iz projektnih spremenljivk

tool AutoMod [14] is illustrated with connection transporters, on which the motorised vehicles', pedestrians' and cyclists' traffic flow is moving. The simulation model was created from the actual geometrical data and the kinematics values (Table 1), as well as from a sample of traffic flow of pedestrians and motorised vehicles on all the roundabout's arms and all the pedestrian crossings (Table 2).

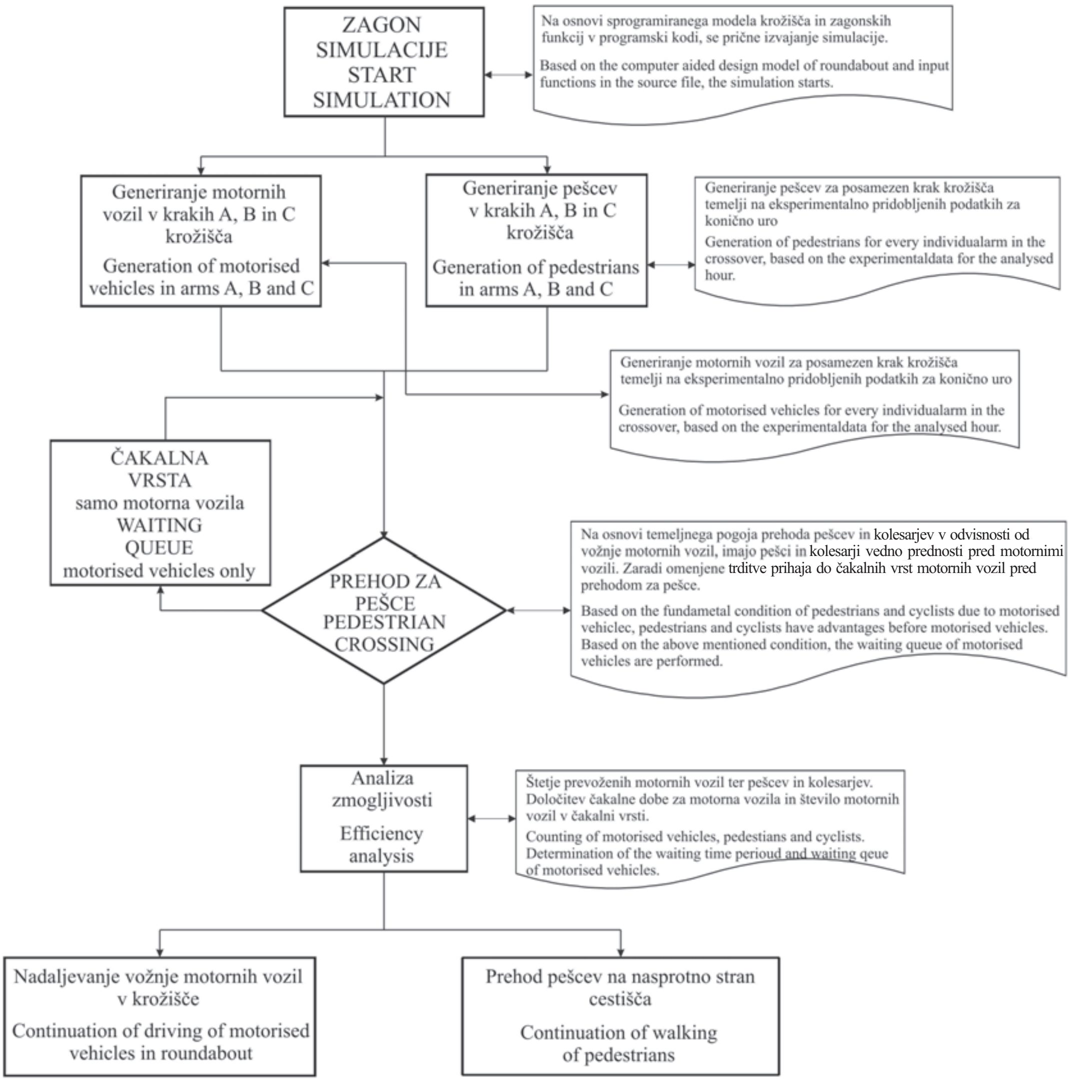
The operation of the simulation model is governed by a program code (Figure 7 (a) and (b)), following the algorithm of the course in Figure 6.

The simulation begins with a process that is based on determined functions in the program code that start the operation of a roundabout. An example of generating the arrival of motorised vehicles into the arm A in the AutoMod [14] programming tool is shown in Figure 7 (a) and in Figure 7 (b) for the implementation of the condition of pedestrians' and cyclists' priority.

When the function »begin model initialization function« equals »true«, the process »p_old_bridge_vehicles« begins. The process consists of project variables and individual program



Sl. 5. *Mikrosimulacijski model krožišča*
Fig. 5. *Micro-simulation model of a roundabout*



Sl. 6. *Algoritem poteka delovanja simulacijskega modela krožišča*
Fig. 6. *Algorithm of the course of operating the simulation model of a roundabout*

```
begin model initialization function
        create 1 load of type L_dummy_1 to p_stari_most_avtomobili
        return true
end


begin p_stari_most_avtomobili arriving procedure
while 1=1 do
        begin
                set V_set_1 to 1
                print "V_set_zacetni_1 = " V_set_1 to message

        while 1=1 do
        begin
                if V_set_1 <= 43 then wait for exponential 6.98
                else
                if V_set_1 <= 79 then wait for exponential 8.11
                else
                if V_set_1 <= 141 then wait for exponential 4.84
                .
                .
                .

        clone 1 load to p_vkrozisce_starimost_avtomobili nlt L_stari_most_avtomobili
                set V_set_1 = V_set_1 + 1
                print "V_set_1 = " V_set_1 to message
                if V_set_1 = 1000 then
                        begin
                                print "Ran out of data" to message
                                terminate
                        end
                end
        end
end
```

(a)

```
begin p_vkrozisce_starimost_avtomobili arriving procedure
        move into conv:sta_1
        inc V_stevilo_avtomobilov by 1

        set A_INSYSTEM to ac
        print "Stevilo avtomobilov = " V_stevilo_avtomobilov to message
        print "A_INSYSTEM = " A_INSYSTEM to message
        travel to conv:sta_2
        travel to conv:sta_3

        if B_block_1 current claims <> 0 then begin
                wait to be ordered on Ol_WaitForPath_1
        end

        travel to conv:sta_4

        decrement V_stevilo_avtomobilov by 1
        set A_cakalni_cas to (ac - A_INSYSTEM)
        set V_cakalni_cas to A_cakalni_cas

        print V_stevilo_avtomobilov to "ZAST.txt"
        print V_cakalni_cas to "TIME.txt"

        print "Trenutno stevilo avtomobilov pred prehodom = " V_stevilo_avtomobilov to message
        print "Cakalni cas avtomobila = " A_cakalni_cas to message

        inc V_stevilo_prevozenih_avtomobilov by 1
        print "Stevilo prevozenih avtomobilov = " V_stevilo_prevozenih_avtomobilov to message

        send to p_izkrozisca_kolosej

end
```

(b)

Sl. 7. *Primer programske kode: (a) za prihod motornih vozil - krak A (b) za izvedbo pogoja o prednosti pešcev in kolesarjev*

Fig. 7. *An example of the program code: (a) for generating motorised vehicles into arm A (b) for the implementation of the condition of pedestrians' and cyclists' priority*

in posameznih programskih zank, ki simulirajo prihod motornih vozil v odvisnosti od povprečne vrednosti prihoda v posameznem časovnem koraku petih minut in predpisane statistične porazdelitve. Simulacija se ustavi po preteku predpisanega časa, tj. ene ure. Dotok preostalega prometnega toka motornih vozil ter pešcev in kolesarjev je programirano podobno, glede na eksperimentalno pridobljene vrednosti, predstavljene v preglednici 2. Upoštevali smo, da so prihodi motornih vozil ter pešcev in kolesarjev neenakomerni, zato smo za dotok uporabili *eksponentno* statistično porazdelitev. Pri izdelavi glavne programske logike krožišča smo izhajali iz splošno veljavnega pogoja, da imajo pešci in kolesarji zmeraj prednost pred motornimi vozili.

Algoritem (sl. 6) pri prihodu motornega vozila do obravnavanega prehoda za pešce preveri, ali je na prehodu za pešce že pešec ali kolesar. V primeru, da je na prehodu za pešce pešec ali kolesar »*B_trenutna zahteva pogoja "omejitev" - zapore <> 0*«, se motorno vozilo nemudoma ustavi in čaka, da pešec zapusti prehod »*čakaj na vrstni red Ol_čakaj na pot_1*«. Kadar je prometni tok pešcev

loops that simulate the arrival of motorised vehicles depending on the average arrival value in an individual time interval of 5 minutes and the directed statistical distribution. After the defined time interval, i.e., one hour, the simulation is stopped. Generating of the rest of the traffic flow of motorised vehicles, pedestrians and cyclists is programmed similarly, according to the experimentally acquired values, presented in Table 2. It is presumed that the arrivals of the motorised vehicles, pedestrians and cyclists are uneven, so the exponent statistical distribution has been used for generating the traffic flow. When creating the main program logic of a roundabout the general valid condition was presumed, that pedestrians and cyclists have priority with regard to the motorised vehicles.

The algorithm (Figure 6) for the arrival of a motorised vehicle to the considered pedestrian crossing verifies whether there is already a pedestrian or a cyclist on the pedestrian crossing or not. In the case that there is a pedestrian or a cyclist on the pedestrian crossing »*B_block_1 current claims <> 0*«, the motorised vehicle immediately stops and waits until the pedestrian leaves the crossing »*wait to be ordered on Ol_waithForPath_1*«. When the pedestrians' or cyin kolesarjev močno izrazit, prihaja do čakalnih vrst motornih vozil (sl. 8 (a) in (b)).

V trenutku, ko je prehod za pešce sproščen »*B_trenutna zahteva pogoja "omejitev" - zapore = 0*«, nadaljujejo motorna vozila po zaporedju FIFO svojo vožnjo. Vožnja motornih vozil poteka neovirano tako dolgo, dokler se na prehodu ne pojavi naslednji pešec ali kolesar, ki ponovno »ustavi« vožnjo motornih vozil.

Za vsako prevoženo motorno vozilo, pešca in kolesarja zapisuje algoritem (slika 6) osnovne podatke »*V_cakalni_cas* in *V_stevilo_avtomobilov*«, in sicer: število prevoženih motornih vozil ter število prehodov pešcev in kolesarjev, koliko časa je bilo posamezno motorno vozilo na izbranem kraku krožišča (čakalna doba) in ali je bilo posamezno motorno vozilo v čakalni vrsti.

Na podlagi simulacijske analize želimo ugotoviti, ali je glede na eksperimentalno izmerjene podatke zmogljivost krožišča v posameznih krakih še sprejemljiva v odvisnosti od (*i*) čakalne dobe in (*ii*) čakalne vrste motornih vozil pred prehodom za pešce.

3.3 Analiza rezultatov mikrosimulacije krožišča

Rezultati opravljene analize za določitev čakalne dobe in čakalne vrste motornih vozil v odvisnosti od prometnega toka pešcev in kolesarjev podajajo poglavitne sklepe, ki so predstavljeni v diagramih (a do f) na sliki 9. Simulacijska analiza je bila izvedena na podlagi znanih geometrijskih veličin krožišča in izbranih kinematičnih veličin za motorna vozila ter pešce in kolesarje.

clists' flow is extremely strong, waiting lines of motorised vehicles occur (Figure 8 (a) and (b)).

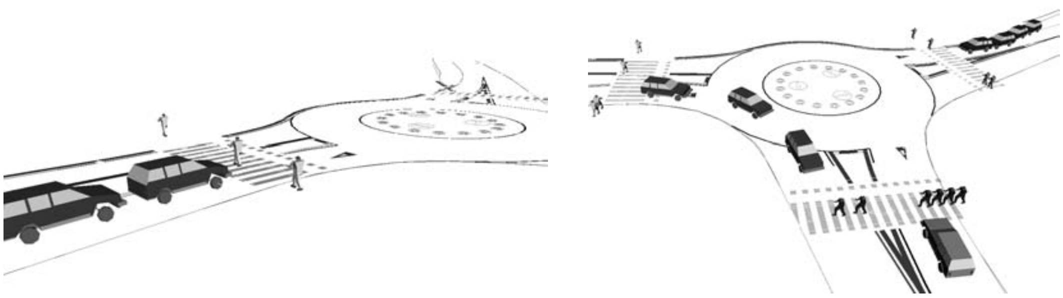
The moment the pedestrian crossing is free »*B_block_1 current claims = 0*«, motorised vehicles continue with driving in the FIFO consequence according to their drive. The driving of motorised vehicles takes place until the next pedestrian or cyclist appears on the crossing, which again stops the driving of the motorised vehicles.

For every passing motorised vehicle, pedestrian or a cyclist the algorithm registers (Figure 6) the basic information »*V_waiting_time in V_number_of motorised vehicles*« as follows: the number of passing motorised vehicles and the number of pedestrians' or cyclists' crossings in the roundabout, how long an individual motorised vehicle has been in the chosen arm of the roundabout (the waiting period) and if an individual motorised vehicle has been in a queue (waiting line).

The main goal of the simulation analysis is to establish the capacity of the roundabout on individual arms depending on (*i*) the waiting period and (*ii*) if the waiting line of motorised vehicles in front of a pedestrian crossing is still acceptable, according to the experimentally measured information.

3.3 An analysis of the results of the micro-simulation of a roundabout

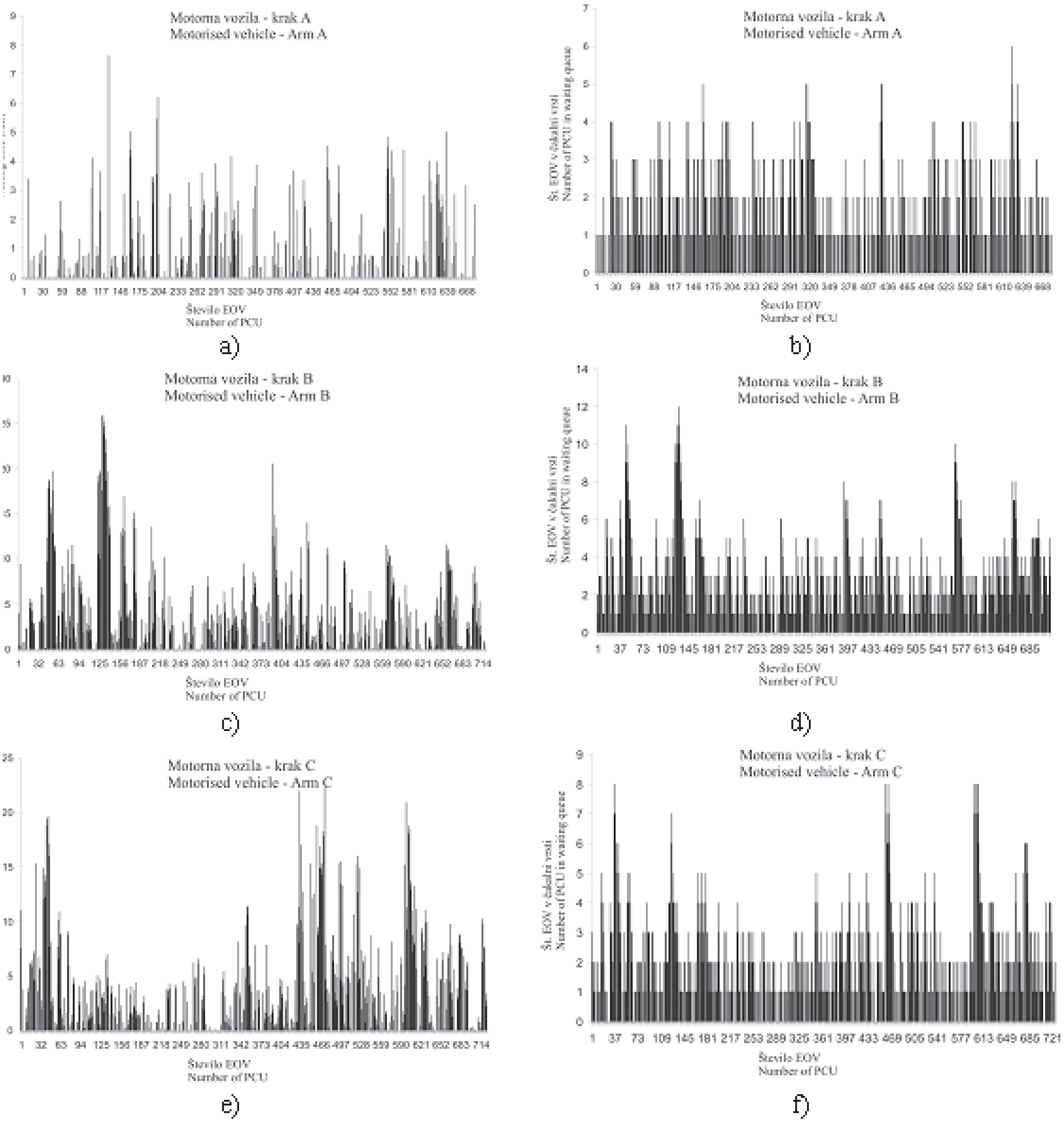
The results of the performed analysis for determining the waiting period and the waiting line of motorised vehicles depending on the pedestrians' and cyclists' traffic flows give basic conclusions, presented in the diagrams (a to f) in Figure 9. The simulation analysis was performed based on the geometrical values of a roundabout and the kinematics values for motorised



(a) (b)

Sl. 8. *Primer čakalne vrste motornih vozil zaradi toka pešcev*

Fig. 8. *An example of a waiting line of motorised vehicles because of pedestrians' flow*



Sl. 9. *Rezultati analize prometnega toka motornih vozil z vidika čakalne dobe (a, c, e) ter čakalne vrste (b, d, f) v odvisnosti od prometnega toka pešcev in kolesarjev*

Fig. 9. *The results of the analysis of the traffic flow of the motorised vehicles considering the waiting period (a, c, e) and the waiting line (b, d, f) depending on the pedestrians' and cyclists' traffic flows*

Na sliki 9 lahko vidimo porazdelitev čakalne dobe (a, c, e) in čakalne vrste (b, d, f) motornih vozil v krožišču. Rezultati analize kažejo, da se število prevoženih motornih vozil ter število prehodov pešcev in kolesarjev, glede na izbrano konično uro, zelo dobro ujemata z eksperimentalno pridobljenimi podatki (preglednica 3).

Glede na porazdelitev čakalne dobe (sl. 9 a, c in e) za motorna vozila, lahko vidimo

The distribution of the waiting period (a, c, e) and the waiting line (b, d, f) of motorised vehicles in a roundabout is presented in Figure 9. The results of the analysis show that the number of passing motorised vehicles and the number of passing pedestrians and cyclists, according to the selected rush-hour, matches well with the experimentally gathered results (Table 3).

According to the waiting-period distribution (Figures 9 a, c and e) for motorised vehicles, proporsorazmerno majhne vrednosti za posamezne krake križišča. Opazimo lahko, da so čakalni časi v kraku A najkrajši, saj je v omenjenem kraku pretok pešcev in kolesarjev najmanjši (krak A leži na južnem delu križišča in ponazarja del Starega mostu). Glede na sorazmerno večji pretok pešcev in kolesarjev v krakih B in C, so posledično čakalne dobe večje, vendar ne presegajo največjega čakalnega časa 35 sekund.

V odvisnosti od čakalnih vrst (slika 9 b, d in f) za motorna vozila lahko opazimo sorazmerno majhne vrste. Zopet se pojavljajo najmanjše čakalne vrste v kraku A (največ 6 motornih vozil), sledi krak C (največ 10 motornih vozil) in krak B (največ 11 motornih vozil). Poudariti je treba, da se pojavijo čakalne vrste, poleg zastoja v križišču zaradi vpliva pešcev in kolesarjev, tudi zaradi prometnega toka motornih vozil z *eksponentno* statistično porazdelitvijo. Slednje pomeni, da se lahko v poljubnem kraku hkrati pojavi večje število motornih vozil, ki v odvisnosti od obremenitve v križišču povzročijo zastoj in posledično čakalno vrsto.

tionally low values for the individual arms of the roundabout are obvious. The waiting times in arm A are the shortest, since in the mentioned arm the pedestrians' and cyclists' flows are the smallest (arm A is located in the south part of the roundabout and represents a part of the Old bridge). According to the proportionally larger flow of pedestrians and cyclists in the arms B and C, consequentially the waiting periods are longer, but do not exceed the maximum waiting time of 35 seconds.

Due to the waiting lines (Figures 9 b, d and f) for motorised vehicles, proportionally smaller queues can be seen. Again, the smallest waiting lines occur in the arm A (a maximum of 6 motorised vehicles), the next is arm C (a maximum of 10 motorised vehicles) and the arm B is last (a maximum of 11 motorised vehicles). It should be emphasized that waiting lines (next to the roundabout blockage due to pedestrians' and cyclists' flows) occur due to the traffic flow of motorised vehicles with an exponent statistical distribution as well. This means that in any optional arm of the roundabout there can be a larger number of motorised vehicles, which depending on the traffic load in the roundabout cause congestion and consequently a waiting line.

4 SKLEPI

V tem prispevku je analiziran vpliv prometnega toka pešcev na prepustno zmožnost, tj. zmogljivost enopasovnega križišča z uporabo diskretnih numeričnih simulacij. Najpomembnejši cilj opravljene analize je bil ugotoviti resnične parametre, ki so kasneje uporabljeni pri določanju vpliva toka pešcev na zmogljivost načrtovanega križišča.

V prvem vsebinskem sklopu prispevka so predstavljena glavna teoretična izhodišča pri analiziranju prometnega toka motornih vozil ter pešcev in kolesarjev v križišču. V križiščih je tok pešcev prednosten, zato mu vozila na uvozih/

4 CONCLUSIONS

The influence of the pedestrians' traffic flow, i.e., the capacity of a one-lane roundabout using discrete numeric simulations is presented. The most important goal of the performed analysis was to establish the real parameters that were later used for determining the influence of pedestrians' traffic flow on the capacity of the foreseen roundabout.

In the first part of the present work the main theoretical background for the analysis of traffic flow of motorised vehicles, pedestrians and cyclists in a roundabout is presented. Since in roundabouts the pedestrian traffic flow has priority, the vehicles on

Preglednica 3. *Primerjava rezultatov meritev in simulacijske analize*
Table 3. *Comparison of the results of measuring and the simulation analysis*

	Krak A Arm A		Krak B Arm B		Krak C Arm C	
	MV	P in K P and C	MV	P in K P and C	MV	P in K P and C
Meritve Measuring	671	105	704	515	722	493
Simulacija Simulation	683	100	719	513	725	492
Odstopek Discrepancy	-1,79 %	4,76 %	-2,13 %	0,39 %	-0,42 %	0,20 %

izvozih morajo odstopiti prednost. Pri tem prihaja do motenj pri uvažanju/izvažanju toka motornih vozil, tok motornih vozil je oviran. Bolj, ko je tok motornih vozil oviran, manjša je prepustna zmožnost krožišča. V primeru, da so ovirani tokovi na uvozu v krožišče, se lahko zgodi, da ni dosežena niti najmanjša zmogljivost. V primeru, da so ovirani tokovi na izvozu iz krožišča, se lahko zgodi, da je presežena največja zmogljivost. V dejanskih razmerah sta uvozni in izvozni tok ovirana hkrati, zastoji se prenašajo s kraka na krak, v smeri gibanja urnega kazalca. V prispevku je pri analizi vpliva toka pešcev na prepustno zmožnost krožišča uporabljeno matematično modeliranje prometnih tokov z uporabo metode diskretnih simulacij, upoštevaje statistično ovrednotene vhodne podatke za prometna toka motornih vozil in pešcev.

Analitični model posameznega kraka krožišča je predstavljen s teorijo čakalnih vrst. Pomanjkljivost omenjene teorije je v omejenosti na poenostavljene modele, medtem ko je predstavljeni model krožišča s številnimi medsebojnimi odvisnostmi motornih vozil ter pešcev in kolesarjev preveč zapleten. Analitični modeli zaradi poenostavitev ne zagotavljajo dovolj velike natančnosti in so samo približek dejanskemu stanju. Zaradi omenjene pomanjkljivosti smo uporabili tehniko diskretnih numeričnih simulacij.

V drugem vsebinskem sklopu je predstavljena diskretna numerična simulacija s simulacijskim modelom krožišča. Simulacijski model krožišča je splošen, kar pomeni da ga lahko razširimo za vsako posamezno izvedbo, glede na izbrane geometrijske in kinematične veličine. Matematični model izhaja iz zakonitosti sprejemljivih časovnih praznin v prometnem toku pešcev, ki jih uporabljajo vozila za uvažanje/izvažanje iz krožišča. Za definiranje prometnega toka motornih vozil ter pešcev in kolesarjev smo uporabili dejanske vhodne podatke za vse cestne krake in prehode za pešce, ki smo jih dobili s štetjem prometa na Koroški ulici v Mariboru. Ugotovili smo, da se rezultati meritev in simulacijske analize dobro ujemajo, kar pomeni, da so rezultati simulacijske analize dobra napoved za ovrednotenje čakalne dobe in čakalnih vrst motornih vozil v posameznem kraku krožišča. Glede na porazdelitev čakalne dobe in posledično čakalnih vrst v odvisnosti od števila prevoženih motornih vozil, lahko vidimo, da so

entries/exits have to give way to pedestrians. During this disturbances to the entering/exiting of motorised vehicles occur, and the motorised vehicles' flow is disturbed. The more disturbed the motorized vehicles' flow is, the lower is the capacity of the roundabout. In the case the flows towards an entry to the roundabout are disturbed, the minimum capacity is not reached. In the case the flows towards an exit from the roundabout are disturbed, the maximum capacity can get exceeded. In real conditions, the entering and the exiting motorised traffic flows are disturbed simultaneously, and the congestions are transferred from arm to arm, in a clockwise direction. For this purpose, the mathematical modelling of traffic flows with the use of discrete simulations has been used for the analysis of the influence of pedestrians' flow on the capacity of the roundabout, considering the statistically evaluated input data for the motorised vehicles' and pedestrians' traffic flows.

The analytical model of an individual arm of a roundabout is presented with the waiting-line (queue) theory. The drawback of the mentioned theory is in its limitations with simplified models, while the presented model of a roundabout, with many mutual dependencies between the motorised vehicles, pedestrians and cyclists is too complex. Due to simplifications, the analytical models do not ensure sufficient accuracy and present only an approximation of the actual situation. Because of these drawbacks the discrete numerical simulations technique was used.

In the second part, a discrete numerical simulation of a roundabout is presented. The simulation model of a roundabout is general, which means it can be extended for every individual implementation, according to the chosen geometrical and kinematics sizes. The mathematical model derives from legalities of acceptable time voids in the pedestrians' traffic flow, used by the vehicles for entering/exiting a roundabout. For a determination of the traffic flow of motorised vehicles, pedestrians and cyclists the real input data for all the roundabout's arms and pedestrian crossings, acquired by the traffic counting on Koroška Street in Maribor were used. The results of the measurements and simulation analyses match well, which means that the simulation analysis results give a good prediction for the evaluation of the waiting period and the waiting lines of motorized vehicles in an individual arm of the roundabout. According to the waiting-period distribution and consequentially the waiting lines depending on the number of motorised vehicles one can determine that the waiting periods and the queue of motorized vehičakalni časi in vrste motornih vozil sorazmerno majhne. Ugotovljeno odvisnost lahko komentiramo z dejstvom, da bi načrtovano krožišče ustrezalo načrtovani zmogljivosti in ne bi prihajalo do čezmernih čakalnih časov in čakalnih vrst motornih vozil.

Simulacijski model, prikazan v prispevku, ni le znanstveni postopek matematičnega modeliranja krožišč, temveč pomeni tudi praktično metodo pri odločanju o smiselnosti izvedbe krožišča v primeru velikega števila pešcev.

V nadaljnjih raziskavah bi bilo primerno dograditi prvotni preprosti model za celotni krak krožišča, vključno z vplivom krožečega toka na krožišču, predvideti različne hitrosti pešcev in njihov prihod v večjem številu vrst.

cles are proportionally low. The established dependency can be commented with the fact that the foreseen roundabout is going to suit the expected capacity and excessive waiting periods and waiting lines of motorized vehicles will not occur.

However, the simulation model presented in this paper does not only present a scientific approach to mathematical modelling of roundabouts, but also presents a practical method for deciding on the suitability of introducing a roundabout in the case of a large number of pedestrians.

For future research it would be sensible to upgrade the present simple model for all the arms of a roundabout, including the influence of the circular flow on the circular roadway, considering different pedestrian speeds and their arrival in more than single file.

5 OZNAKE
5 SYMBOLS

dejanska zmogljivost prometnega toka motornih vozil ter pešcev in kolesarjev	λ	actual capacity of traffic flow of motorized vehicles, pedestrians and cyclists
največja zmogljivost prometnega toka motornih vozil ter pešcev in kolesarjev	μ	maximum capacity of traffic flow of motorized vehicles, pedestrians and cyclists
izkoristek posameznega kraka krožišča	ρ	utilization rate an individual arm of a roundabout intersection
časovni korak	t	time interval
porazdelitvena funkcija	$F(t)$	distributional function,
gostota verjetnosti	$f(t)$	probability density,
Poissonova porazdelitev števila prihodov motornih vozil, pešcev in kolesarjev na časovno enoto	M	Poisson's distribution of the number of arrivals of motorized vehicles, pedestrians and cyclists in a time unit,
stalnica oz. deterministična porazdelitev časa, ki je potreben za vožnjo motornih vozil mimo prehoda za pešce ter prehoda pešcev in kolesarjev	D	constant or deterministic distribution of the time, required for driving of motorized vehicles by pedestrians' crossing and the pedestrians' and cyclists' crossing,
število strežnih mest v sistemu čakalne vrste (v našem primeru se navezuje na prehod za pešce)	s	number of serving stations in a waiting line system (in our case regarding the pedestrians' crossing),
prihod v sistem je določen z neskončnim tokom motornih vozil ter pešcev in kolesarjev	∞	arrival to the system is determined by an infinite flow of motorized vehicles, pedestrians and cyclists,
sistem omogoča neskončno mnogo voženj motornih vozil preko prehoda za pešce ter prehodov pešcev in kolesarjev na drugo stran cestišča	∞	system enables infinite number of driving of motorized vehicles over a pedestrian crossing and pedestrians' and cyclists' crossings to the other side of the road,
enota (motorno vozilo, pešec ali kolesar), ki pride v sistem prva, je tudi prva postrežena	$FIFO$	unit (motorized vehicle, pedestrian or cyclist) that comes first into the system is first served,
hitrost motornega vozila na vpadnici	v_{MV1}	velocity of a motorized vehicle on an entrance road,
hitrost motornega vozila v bližini peš-cone	v_{MV2}	velocity of a motorized vehicle near a walking-zone,

hitrost pešca in kolesarja	v_{PK}	velocity of pedestrian and cyclist,
pospeševanje motornega vozila na vpadnici	a_{MV1}	acceleration of a motorized vehicle on an entrance road,
pospeševanje pešca in kolesarja	a_{PK}	acceleration of pedestrian and cyclist,
enota motornega vozila	EOV/ PCU	personal car unit
motorna vozila	MV	motorised vehicles
pešci	P	pedestrians
kolesarji	K/C	cyclists

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Model požara ob prometni nesreči v bližini jedrske elektrarne

Model of an Accident-Induced Fire around a Nuclear Power Plant

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Prispevek obravnava obnašanje požara oz. dimnega oblaka na odprtem prostoru. Prispevek temelji na analizi vira požara ter širjenja dimnega oblaka v okolico. Za simulacijo je uporabljen računalniški program FDS (Fire Dynamics Simulator). Model računske dinamike fluidov uporablja metodo simulacije velikih vrtincev za računanje dinamike gibanja zgorevalnih ostankov v okolici. Vir požara je postavljen v okolico nevarne zgradbe, v prispevku je predpostavljena okolica elektrarne Krško. Prispevek prikazuje kratko ozadje modela FDS ter začetne in robne pogoje, uporabljene pri modelu. Predstavljena je analiza izhodnih podatkov in predstavljana kakovost rezultatov. Prispevek podaja tudi nekatere popravke modela FDS, ki imajo pomemben vpliv na rezultate.

(Ključne besede: varnost protipožarna, analize varnostne, modeli, koncentracija dima, območje nevarna)

The basic aim of this paper is to research the relevant features of the control and management of an outdoor fire event and its influence on the safety of the surrounding area. The work is based on an analytical study of the fire's origin, its development and spread. A computer program called FDS (Fire Dynamic Simulator) is used in the work to simulate the fire's behaviour. A program based on the CFD (Computational Fluid Dynamic) model using the LES (Large Eddie Simulation) is used to calculate the fire's development and the spread of the combustion products in the environment. The fire's source is located in the vicinity of a hazardous plant, e.g., a power or chemical plant. The article presents the brief background of the FDS computer program and the initial and boundary conditions used in the mathematical model. The output data is discussed and the validity of the results is checked. The work also presents some corrections to the physical model used and its validation by experimental data, which influences the quality of results. The obtained results were discussed and compared with the Fire Safety Analysis report included in the Probabilistic Safety Assessment of the Krško nuclear power plant.

(Keywords: fire safety, safety analysis, models, smoke concentrations, hazardous range)

0 UVOD

Požarno inženirstvo in požarna znanost sta prepleteni interdisciplinarni področji, ki obsegata širok obseg fizikalnih pojavov. To so predvsem hidrodinamika, prenos snovi in toplote, zgorevanje, toksičnost, obnašanje materialov pri povišanih temperaturah in drugo.

Uporaba računske dinamike fluidov (RDF) pridobiva pomen z vse hitrejšim razvojem računalnikov. Čeprav obstajajo izkustveni modeli, ki so računsko bistveno hitrejši od modelov RDF, se ti pri analizah požarov manj uporabljajo.

Pri modelih RDF se rešitve parcialnih diferencialnih enačb (PDE) računajo z numeričnimi

0 INTRODUCTION

Fire-fighting engineering and fire science are very complex interdisciplinary fields that include a wide spectrum of physical phenomena. These include hydrodynamics, heat transfer, mass transfer, combustion, toxicity, the response of construction to high temperatures, and others.

The use of CFD (Computational Fluid Dynamics) models acquires significance with the development of computer-hardware resources. Other lumped and empirical methods exist that are faster in terms of computation, but are usually much too conservative and do not allow accurate analyses.

Fire Field Models (CFD-Computational Fluid metodami. PDE opisujejo fizikalne postopke in se rešujejo v trorazsežnem prostoru. Ker požarni modeli štejejo veliko fizikalnih pojavov, postane interakcija med njimi zelo zahtevna in zahteva uporabo računalnika. Opisani model požara predstavlja obnašanje požara na odprtem oziroma razvoj dimnega oblaka. Za simulacijo je bil uporabljen program FDS, ki je zasnovan na turbulentnem modelu velikih vrtincev. Disipacijski pojavi se v modelu računajo z (nič enačbenim) modelom Smagorinskega. Prispevek prikazuje, da je natančnost rezultatov zelo odvisna od pravilne predpostavke začetnih in robnih pogojev in zadostne gostote numerične mreže. Zaradi razmeroma velike geometrijske oblike se je po več simulacijah izkazala potreba po zmanjšanju stalnice Smagorinskega, kakor je bila privzeta v programu FDS.

Predstavljeni model v prispevku predpostavlja kraj požara v okolici elektrarne Krško.

Dynamics models) use numerical methods to solve the governing equations. Differential equations that describe the physical processes are solved in three-dimensions including continuity, momentum and energy equations. The FDS uses the LES (Large Eddy Simulation) for turbulence modelling where dissipation processes are modelled using a (zero equation) Smagorinsky model [6]. The work shows that simulation results depend significantly on the correct definition of the initial and boundary conditions and an appropriate numerical grid density. Because of the large geometry and the larger grid cells than usually used in FDS calculations, the turbulence model needs to be validated with experimental data.

The model presented in the paper assumes the computational domain and geometry located in the surroundings of the Krško nuclear power plant in Slovenia.

1 OZADJE PROGRAMSKE KODE

Poglavje na kratko opisuje matematične modele in numerične metode, ki jih uporablja program FDS.

1 PROGRAM CODE BACKGROUND

This section briefly describes the mathematical models and the numerical methods used in the program code.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho Z) + \nabla \cdot \rho Z \mathbf{u} = \nabla \cdot \rho D \nabla Z \tag{2}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \frac{1}{2}\nabla|\mathbf{u}|^2 - \mathbf{u}\times\omega\right) + \nabla\tilde{p} = (\rho - \rho_\infty)\mathbf{g} + \nabla\cdot\tau \tag{3}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) = \dot{q}_c''' - \nabla\cdot\mathbf{q}_R + \nabla\cdot k\nabla T \tag{4}$$

1.1 Termo-hidrodinamični model

V splošnem je gibanje tekočine mogoče opisati z enačbami prenosa mase, gibalne količine in energije. V modelu FDS je uvedena dodatna ohranitvena enačba, ki opisuje ohranitev masnega deleža komponent dodanih toku. Običajno so dodane komponente zgorevalni ostanki v zmesi dima, za katere nas zanima difuzija v prostoru.

Pri tem so: ρ gostota, $\mathbf{u}$ hitrostni vektor, Z mešalno razmerje, T temperatura in D molekularna difuzivnost. $\tilde{p}$ pomeni tlačne motnje, τ tenzor viskoznih napetosti ter k toplotno difuzivnost, $\dot{q}_c'''$ in $\nabla\cdot\mathbf{q}_R$ pomenita vira toplote kemične reakcije in sevanja [1].

Ker model predpostavlja tok tekočine pri majhnih Machovih številih, se okoliški tlak računa

1.1 Thermo-hydrodynamic model

The fluid flow is modelled by solving the basic conservation equations. These are the conservation of mass, the conservation of mixture fraction, the conservation of momentum and the conservation of energy using the low-Mach-number form of the Navier-Stokes equations.

Where ρ is a density, $\mathbf{u}$ is a velocity vector, Z is the mixture fraction, T is the temperature and D is a molecular diffusivity. $\tilde{p}$ is the perturbation pressure, τ is the viscosity stress tensor and k is the thermal conductivity. $\dot{q}_c'''$ and $\nabla\cdot\mathbf{q}_R$ are the source terms of the chemical reaction and radiation, respectively [1].

Because the model assumes low-Mach-number flows, the pressure p_o is approximated to be po plinski enačbi, ki izloči tlačne valove:

an average value and replaces the total pressure to filter out acoustic waves:

$$p_0 = \rho TR \sum (Y_i / M_i) \quad (5).$$

Enačba stanja je zapisana v splošni obliki za zmes, pri kateri je gostota skupna gostota zmesi in R plinska stalnica zmesi.

Zelo pomembna poenostavitev v modelu je uvedba izraza za celotni tlak v gibalni enačbi:

R is the general ideal gas constant and Y_i and M_i are the species mass fraction and molecular weight. In the case of an open space, p_o is a constant value.

A very important approximation in the model is the following substitution in the momentum equation:

$$\nabla \mathcal{H} \approx \frac{1}{2} \nabla |\mathbf{u}|^2 + \frac{1}{\rho} \nabla \tilde{p} \quad (6).$$

Če izračunamo divergenco celotnega tlaka in zanemarimo člen $(1/\rho)\nabla\tilde{p}$, ki predstavlja zanemarljiv del vira vrtinčnosti, dobimo eliptično parcialno diferencialno enačbo za celotni tlak. Enačba je v programu FDS rešljiva z neposredno metodo, ki uporablja hitro Fourierjevo preslikavo [1]. Končna oblika gibalne enačbe dobi obliko:

This approximation is equivalent to neglecting the baroclinic torque $(1/\rho)\nabla\tilde{p}$ that is a small source of vorticity compared to buoyancy [6]. The value of $\mathcal{H}$ is solved by taking the divergence of the momentum equation, using the equation of state and solving the resulting Poisson equation by a fast, direct method. The final form of the momentum equation becomes:

$$\frac{\partial \mathbf{u}}{\partial t} - \mathbf{u} \times \omega + \nabla \mathcal{H} = \frac{1}{\rho}\left((\rho - \rho_\infty) g + \nabla \cdot \tau \right) \quad (7).$$

FDS uporablja diskretizacijsko metodo končnih razlik. Prostorski odvodi so poenostavljeni s sredinsko shemo drugega reda, časovni odvodi pa po izrecni shemi napoved in popravek ([1], [8] in [10]).

The FDS uses rectangular grid elements, where all the spatial derivatives are approximated by second-order central differences and the flow variables are updated in time using an explicit second-order predictor-corrector scheme ([1], [8] and [10]).

1.2 Zgorevalni model

FDS uporablja tako imenovani model mešalnih razmerij, pri katerem je zgorevanje nadzorovano z mešalnim razmerjem kisika in goriva. Iz tega izhaja, da lahko vse reaktante in ostanke v reakciji definiramo z mešalnim razmerjem Z(x,t). Krajevni delež sproščene toplote se izračuna iz krajevne porabe kisika na površini plamena. Pri tem upoštevamo, da je količina sproščene toplote odvisna le od količine porabljenega kisika, ne pa od količine razpoložljivega goriva. Sproščena toplota na enoto površine je izračunana po naslednji enačbi:

1.2 Combustion model

The combustion model is based on the assumption that the combustion is mixing-controlled. This implies that all the species of interest can be described in terms of the mixture fraction Z(x,t). The heat from the reaction of fuel and oxygen is released along an infinitely thin sheet where Z takes on its stoichiometric value, as determined by the solution of the transport equation for Z. The heat release rate per unit area of flame surface is defined using the following equation:

$$\dot{q}'' = \Delta H_0 \left. \frac{dY_O}{dZ} \right|_{Z<Z_f} (\rho D) \nabla Z \cdot \mathbf{n} \quad (8),$$

ΔH_0 je delež sproščene toplote na ponor mase (masni tok $\dot{m}_O'''$) kisika, Y_O je masni delež kisika ter **n** smerni vektor.

Razmerja stanje koncentracij se računajo za kemično reakcijo (zgorevanje) med heptanom in kisikom $11\,O_2 + C_7H_{16} \rightarrow 7\,CO_2 + 8\,H_2O$, kateri je

ΔH_0 is the energy released per unit mass of oxygen consumed $\dot{m}_O'''$, Y_O is the mass fraction of oxygen and **n** is the outward-facing unit normal vector.

The state relations are calculated for a stoichiometric reaction $11\,O_2 + C_7H_{16} \rightarrow 7\,CO_2 + 8\,H_2O$, which represents the Heptane combustion reaction.

dodano 0,11 masnega deleža sajastih delcev v ostankih.

Zgornji način računanja toplotnega toka pride v poštev, ko sta požar oziroma gorišče primerno zajeta z numerično mrežo. Kako dobro je gorišče požara preračunano lahko ocenimo z brezrazsežnim izrazom $D^* / \delta x$, kjer je D^* značilna dolžinska lestvica za povezave velikosti plamena požara (Heskestad 1995).

In addition, the reaction assumes that a 0.11 mass fraction of fuel is converted into soot particles.

In the case when a coarse mesh is used the fire is not adequately resolved. The quality parameter to compute the fire source is an non dimensional $D^* / \delta x$, where D^* is a characteristic fire diameter (Heskestad 1995).

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}} \qquad (9).$$

Pri požarnih scenarijih, kjer je D^* majhen v primerjavi z realnim premerom požara, in/ali je gostota numerične mreže majhna, pogoj zgorevalne površine $Z = Z_f$ izračuna nižjo višino plamena, kot je realna. Ugotovljeno je, da se doseže boljše rezultate, v kolikor se pri grobi mreži spremeni vrednost Z v področju zgorevanja. Prednost aproksimacije je, da se s tem poleg gostote numerične mreže upošteva tudi velikost gorišča. Nadaljnja razlaga modela je opisana v [6].

For a fire scenario where D^* is small relative to the physical diameter of the fire, and/or the numerical grid is relatively coarse, the stoichiometric surface $Z = Z_f$ will underestimate the observed flame height. It has been found that a good estimation of resolving the coarse-grid-defined fire is to change the value of Z in the combustion region. The benefit of this is that it provides a quantifiable measure for the grid resolution that takes into account not only the size of the grid cells, but also the size of the fire. Further explains can be found in [6].

1.3 Sevalni model

Ker se pri gorenju pojavljajo visoke temperature in se oddana toplota zaradi sevanja zvišuje s četrto potenco temperature, pomeni sevanje kot zapleten pojav pomemben delež prenosa toplote [3]. Bolj uporabna veličina kakor oddana sevalna toplota E je sevalna intenziteta ali sevalna jakost I. Sevalna jakost je definirana kot delež oddane toplote pri valovni dolžini l v smeri (q,j) na enoto sevalne površine, pravokotne na to smer. Ker v modelu obravnavamo ovire in odprtine kot črna telesa, je sevalna jakost odvisna le od valovne dolžine sevanja in temperature. Črnim telesom, ki uporabljajo tak približek, pravimo difuzni sevalniki.

1.3 Thermal radiation model

Because of high temperatures occur during the fire and the radiative heat increases with forth power of temperature, the radiation presents an important heat transfer share [3]. The radiative intensity I is a much useful unit than the emitted radiation heat E. The radiation intensity is defined as the emitted heat, at particular wave length l in (q,j) directions the surface, perpendicular to the radiation direction. Because the model assumes obstructions and openings as black bodies, the radiation intensity depends only on radiation wave length and temperature. Those black bodies are called diffusive emitters.

2 GEOMETRIJSKA OBLIKA IN ZASNOVA MODELA

2.1 Geometrijska oblika modela

Slika 1 prikazuje geometrijo računske domene, kjer telesa na desni strani predstavljajo zgradbe jedrske elektrarne. Objekti so oštevilčeni in opisani v preglednici 1.

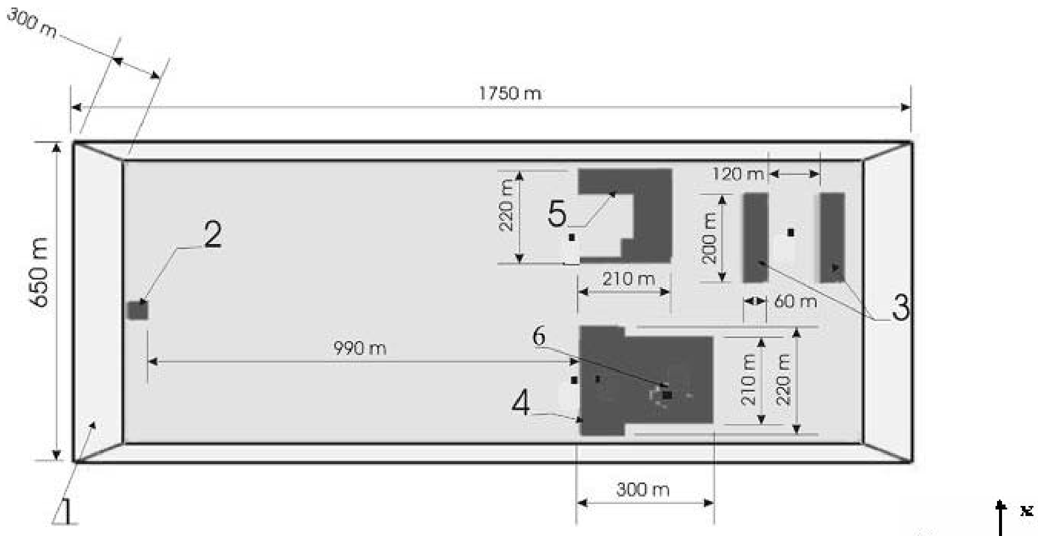
Uporabljena je neenakomerna kartezična mreža z 170 × 180 × 50 računskimi točkami v smereh x, y in z. Simulacija je zahtevala približno 70 ur računskega časa na osebnem računalniku 2,5 MHz.

2 GEOMETRY AND MODEL DEFINITION

2.1.Geometry of the model

Figure 1 shows the geometry of the computational domain where the objects located on the right-hand side represent the buildings of the power plant. The objects are numbered and specified in Table 1.

A non-uniform Cartesian grid was used with 170 × 180 × 50 cells in the x, y and z coordinates, respectively. The simulation takes approximately 70 hours on a 2.5-MHz PC. The compression between the



Sl. 1. *Geometrijska oblika modela*
Fig. 1. *Geometry of the model*

Mreža je zgoščena v okolici gorišča, in sicer med 0 in 50 metri za 40 odstotkov. Zgostitev mrežne celice v smeri *y* zmanjša na okoli 2 m. Z gostejšo mrežo v vse smeri bi rezultati bili natančnejši, vendar bi zahtevali veliko daljši računski čas.

y coordinate 0 m and 50 m is 40%, which means that the compressed grid cells have a *y* coordinate length of approximately 2 m. Better results would be obtained with a denser grid, but the long computation time and hardware resources limit such simulations.

2.2 Overitev kode FDS

Programska koda FDS uporablja nič-enačbeni turbulentni model, ki temelji na zamisli turbulentne viskoznosti. Model turbulentne viskoznosti je model Smagorinskega. Model izhaja iz Kolmogorovove $k^{-5/3}$ kaskadne teorije. Turbulentna viskoznost, računana z modelom Smagorinskega, je odvisna od značilne dolžinske lestvice, tenzorja deformacijskih hitrosti in stalnice Smagorinskega. Zaradi te konstante ne more biti model splošno uporabljen. V primeru obsežne geometrijske oblike, kakršna je predstavljena v prispevku, je treba stalnico spremeniti. Privzeta vrednosti v program FDS je 0,2.

2.2 FDS code validation

The FDS program code uses a zero-equation turbulent model based on a turbulent viscosity approach. The model is known as the Smagorinsky model, which is derived from the Kolmogorov $k^{-5/3}$ cascade theory. The turbulent viscosity calculated using the Smagorinsky model depends on the characteristic length scale, a velocity deformation tensor and the Smagorinsky constant. Because of the constant, the model cannot be applied for universal use. In the case of a large geometry, as presented in the paper, the constant needs revision. The default value used in the FDS code is 0.2.

Preglednica 1. *Lastnosti modeliranih zgradb*
Table 1. *Properties of the modelled elements*

Št./No.	Ime/Name	Lastnosti/Properties	Velikost/Size
1	Odprtina/VENT	VEL[2] = 9 m/s in/or 2 m/s	650 m × 300 m
2	Goreča luža/Pool burner	HRRUPA[1] = 2900 kW/m^2	8 m × 8 m
3	Hladilni stolpi/Cooling towers	profil/relief	200 m × 60 m × 30 m
4	Reaktorska zgradba/Reactor building	profil/relief	240 m × 300 m × 60 m
5	Upravna zgradba/ Administration building	profil/relief	220 m × 210 m × 20 m
6	Turbinska zgradba/Turbine building	profil/relief	40 m × 40 m × 80 m

[1]- Sproščena toplota na enoto površine / Heat Release Rate Per Unit Area
[2]- Začetni hitrostni profil / Initial velocity potential profile

Septembra 1994 je podjetje Alaskan Clean Seas izvedlo požarno vajo v Prudhoevem zalivu na Aljaski. Izvedeni so bili trije testi, s katerimi so želeli preveriti uspešnost gašenja z nekaterimi novimi postopki. Na testu 2 je gorelo 12,2 m^3 nafte v posodi z izmero 8 × 8 m. Zaznavala za merjenje koncentracije so bila postavljena na različnih oddaljenostih, pretežno v smeri vetra. Izmerjeni rezultati so primerjani s simulacijo modela FDS. Ena od primerjav je prikazana na sliki 2. Slika 2 prikazuje primerjavo podatkov, izmerjenih na kraju 1500 metrov od požara na višini 1 meter [4].

Izračunani rezultati koncentracij, dobljeni s spremenjeno stalnico Smagorinskega, se dobro ujemajo s preizkusnimi po redu velikosti. Znano je, da je difuzivnost večja na grobi numerični mreži zaradi povezave s turbulentno viskoznostjo. V okolici požara bi tako prihajalo do velike disipacije energije, ki bi izhajala iz numerične napake. Zato zgorevalni model vključuje izkustveni model, ki določi velikost plamena in s tem reakcijsko površino. V preostalem delu domene, ker se koncentracije računajo z difuzijsko enačbo, je difuzivnost prevelika. Z zmanjšanjem stalnice Smagorinskega dosežemo optimalno difuzivnost, ki se kaže pri kakovosti rezultatov.

2.3 Začetni in robni pogoji

Začetni pogoji

Temperature vseh površin so enake temperaturi okolice 20 °C. Hitrosti na vseh površinah so enake nič, razen na levi pokončni steni, označeni

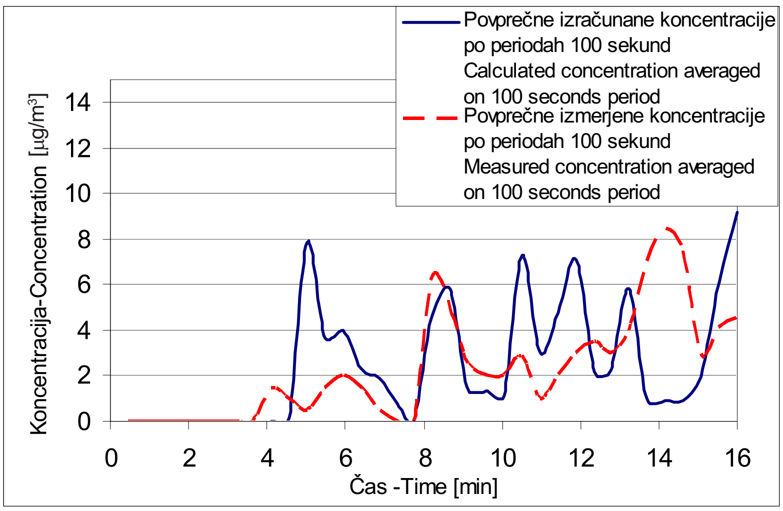
The validation of the model is made using the experimental data obtained from the ‘’Alaskan Clean Seas’’ experiment, conducted in the Prudhoe Bay in Alaska in September, 1994. In the Test 2, 12.2 m^3 of crude oil was ignited in a pool of 8 × 8 meters. The smoke-concentration measurement sensors were located at different distances, mainly in the direction where the wind was blowing. The obtained results from the FDS simulation were compared with the experimental data in different locations. Figure 2 shows the comparison of data for a measurement point located 1500 meters from the fire source at a height of 1 metre [4].

The obtained results of the calculated concentration that conform well to the experimental data in terms of order of magnitude were obtained with a correction of the Smagorinsky constant in the FDS turbulent model. It is known that the diffusivity is large on the coarse grid because it is related to the Smagorinsky viscosity. Close to the fire source the loss of the energy is limited by the enhanced combustion model. The change of the constant in the turbulent model tunes the sub-grid scale model for the specific case of study.

2.3 Initial and boundary conditions

Initial conditions

The temperatures of the numbered object surfaces (Fig. 1) are equal to the environmental temperature of 20^{o}C. The velocity components at any



Sl. 2. *Primerjava povprečnih vrednosti koncentracij po periodah 100 sekund*
Fig. 2. *Comparison of averaged concentration on 100 seconds periods*

z **1** (Sl. 1). Na steni **1** je predpisan začetni hitrostni profil, ki je definiran z enačbo:

domain boundary are assumed to be zero except at the wall **1** (Fig. 1), with a prescribed initial velocity profile:

$$v = v_0 \left(\frac{z}{10} \right)^{0.15} ; \; z = 0 \; ... \; 300 \text{ m} \qquad (10).$$

Požar je definiran z virom toplote na enoto površine luže. Sproščena toplota ne enoto površine gorišča je 2900 kW/m^2. Vrednost pomeni sproščeno toploto pri zgorevanju nafte na površini luže 64 m^2 [2]. Vrednosti so validirane v [9]. Da bi se približali realnemu stanju, je predpisan tudi začetni navpični temperaturni gradient v domeni, in sicer 0,0025 ^{o}C/m.

Začetni pogoji sevalnega modela obravnavajo vse stene in odprtine kot črna telesa in zgorevalni model upošteva hladno stanje goriva - nafte.

Robni pogoji

Robni pogoji zunanjih pokončnih površin in strešna površina domene so definirani kot odprti, razen leve stene **1** na sliki 1, ki ima predpisano začetno hitrost. Odprte površine domene modela imajo v sevalnem modelu predpisano emisivnost nič, kar pomeni črno telo. Jakost sevanja na stenah računamo za črna telesa.

Objekti v domeni imajo majhen vpliv na rezultate simulacije, predvsem na koncentracijo dima v okolici teh objektov. Ti objekti pa s toplotnega stališča, predvsem toplotnega sevanja, nimajo vpliva saj so izbrani za inertna telesa.

3 REZULTATI

Izvedeni sta dve simulaciji širjenja dimnega oblaka v okolici elektrarne Krško. Prva obravnava hitrost vetra 9 m/s, druga pa 2 m/s. Najbolj pomemben rezultat je vsekakor koncentracija dima v okolici elektrarne. Ker so sajasti delci pri zgorevanju nafte najbolj opazen ostanek, ki ima najdaljšo dobo trajanja v obliki aerosola, so v rezultatih prikazane izračunane koncentracije saj v zraku. Koncentracije preostalih zgorevalnih ostankov predpostavljamo kot manj problematične, predvsem zaradi velike razdalje med goriščem in zgradbami.

Koncentracije sajastih delcev imajo naslednje lastnosti [10]:
- pri koncentraciji sajastih delcev pod 100 μg/m^3 je območje varno tudi brez uporabe zaščitnih sredstev;
- pri koncentraciji delcev nad 250 μg/m^3 je oteženo

The fire is defined as an energy and mass source. The energy release rate per unit area is 2900 kW/m^2. The value represents a heat release rate of the combustion of crude oil in a pool of 64 m^2 surface [2]. The value is obtained with experimental data and validated in [9]. Also, a temperature profile is defined. The temperature gradient is 0.0025^{o}C/m and decreases with height.

The initial thermal radiation intensities depend on the initial temperatures in the domain, the radiation spectra of black walls and on the absorption coefficients.

Boundary conditions

The boundary conditions of the domain borders are defined as open, except for wall **1** (Fig. 1), which uses an initial velocity profile. Open boundary conditions represent an energy and mass sink. A thermal radiation model assumes the boundary of the domain to be black objects.

Obstacles located inside the domain have some effect on the simulation results, particularly on soot concentrations observed near these objects. However, the objects do not have any thermal, particularly radiative, contribution because they are chosen to be inert ones.

3 SIMULATION RESULTS

Two simulations of fire spread around the Krško power plant have been performed. The first assumes a wind velocity of 9 m/s, the second of 2 m/s. The results of interest are the concentrations of smoke, particles labelled as PM10, in the power-plant surroundings. Because smoke particulates (soot) have the longest ‘life time’ as an aerosol, the results presented just show the soot concentrations. The concentrations of the other combustion products are assumed not to be dangerous at a long distance from the fire source, because of the very low concentration.

The soot concentrations of interest have the following characteristics [10]:
- the area with a concentration below 100 μg/m^3 is safe without the use of respirators;
- at concentrations above 250 μg/m^3 normal

normalno dihanje in sposobnost za delo ter odzivnosti človeka se poslabšajo;
- večja ogroženost se pojavi pri koncentracijah okoli 1000 $\mu g/m^3$ ([4] in [12]).

Slika 3 prikazuje koncentracijo dima pri hitrosti vetra 9 m/s. Po 1000 sekundah dimni oblak prepotuje celotno dolžino domene. S časovnim povprečenjem rezultatov po periodah 100 sekund se majhni vrtinci filtrirajo iz rezultatov, s čemer je slika lažje predstavljiva. Rezultati prikazujejo, da je koncentracija saj v okolici zgradb elektrarne okoli 60 $\mu g/m^3$ do 250 $\mu g/m^3$. V primerjavi s prej omenjenimi nivoji koncentracije je območje relativno varno. Rezultati pa kljub temu nakazujejo , da se zaradi turbulence toka pojavijo lokalne in kratkotrajne povišane koncentracije.

Drugače je pri manjši hitrosti vetra. Slika 4 prikazuje razvoj dimnega oblaka pri hitrosti vetra 2 m/s. Pri hitrosti vetra 2 m/s je opazen zanimiv pojav.

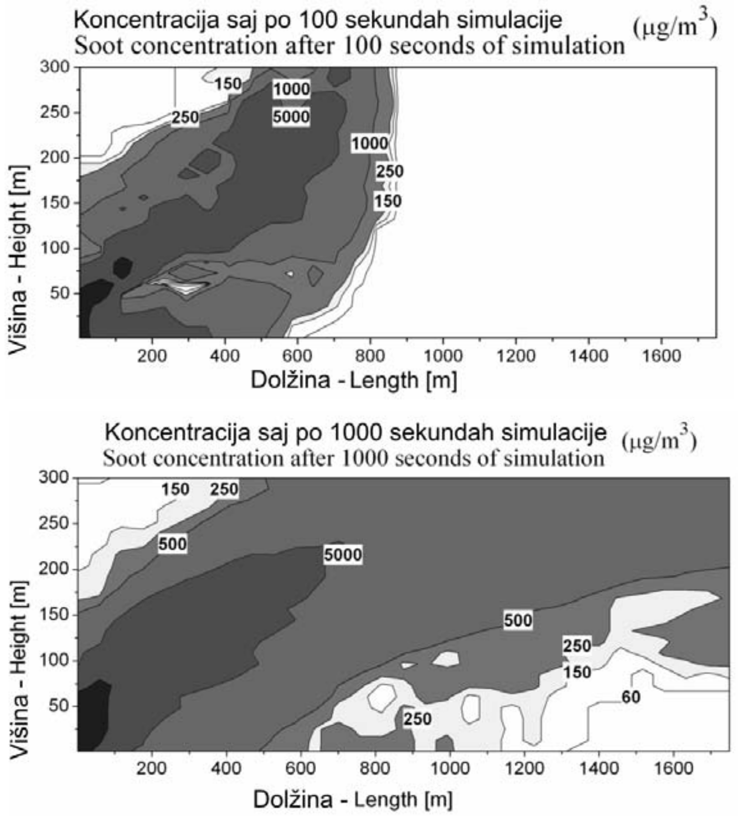
Slika 4 prikazuje bistveno drugačne razmere. Koncentracije saj so dva do tri krat višje. Opazi se zanimiv pojav: po 1000 sekundah simulacije se jedro

respiration is more difficult, but health is not threatened.
- concentrations of soot above 1000 $\mu g/m^3$ are considered to be the highest allowed ([4] and [12]).

Figure 3 shows the soot concentration at a wind speed of 9 m/s. After 1000 seconds the smoke cloud reaches through the entire length of the domain. Averaging the results over a time period of 100 seconds, the small vortices are filtered out of the plot. The results show that soot concentrations from 60 $\mu g/m^3$ to 250 $\mu g/m^3$ are reached in the surroundings of the power plant. Referring to the concentration levels mentioned above, the zone is relatively safe. However, local and short-term elevated concentrations could appear because of the turbulence flow. Such vortices especially develop around power-plant buildings.

A different scenario develops at the lower wind speed. Figure 4 shows the simulation results at a wind speed of 2 m/s.

Figure 4 shows a different picture than Figure 3. The soot concentrations are two to three times higher. An interesting phenomenon occurs: after 1000



Sl. 3. *Polje koncentracij saj po srednjem prerezu po 100 sekundah in 1000 sekundah simulacije pri hitrosti vetra 9 m/s*

Fig. 3. *Soot concentration field at wind speed 9 m/s after 100 and 1000 seconds of simulation*

dimnega oblaka pomika praktično navpično navzgor. Polje koncentracij, ki polni domeno z dimom, nastaja iz vrtincev, ki se formirajo v okolici jedra toka. Začetna stopnja takega vrtinca je prikazana na sliki 4 po 100 sekundah simulacije in je označen z detajlom A. Z razvojem dimnega oblaka nastaja veliko število podobnih vrtincev in oblikujejo dimno polje, ki se pomika v smeri z vetrom.

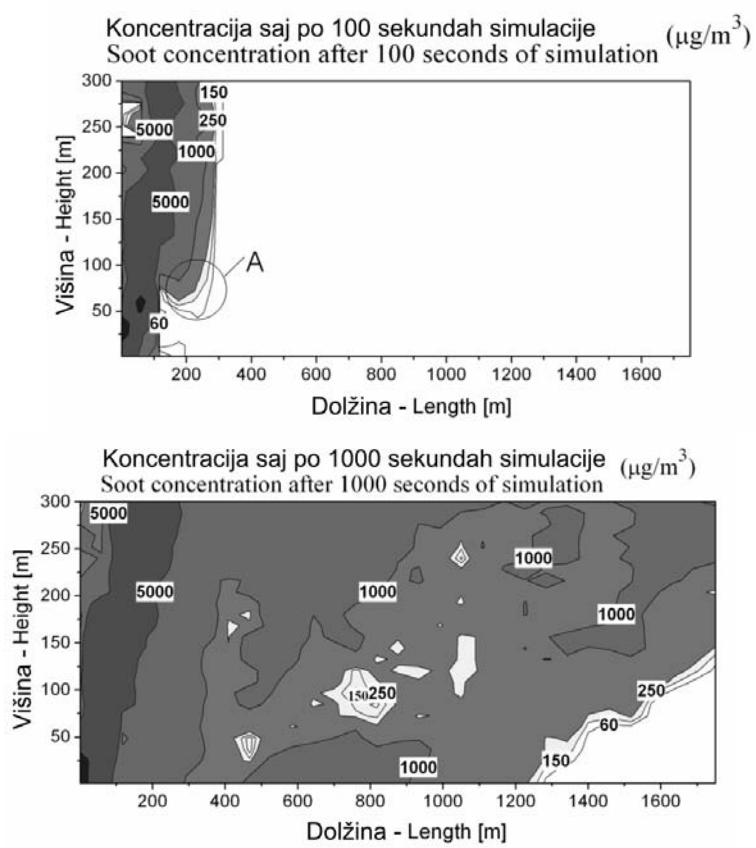
3.1 Izguba podatkov zaradi odprtih robnih pogojev

Obe simulaciji prikazujeta, da večji del dimnega oblaka ni zajet v domeni simulacije in "uide" prek mej domene, pretežno zgornje. Lastnost gostega dima je, da se po ohladitvi ponovno spusti na tla. To pomeni predvsem, da je analiza zgornjih plasti dimnega oblaka potrebna. Najmanjša potrebna višina je ocenjena na 500 metrov, pri čemer je zajet večji del oblaka. Simulacija prikazuje, da se dimni oblak na oddaljenosti 1500

seconds of simulation the core of the smoke cloud takes an almost vertical direction. The concentration field that fills the remaining part of the domain comes from vortices formation in the smoke core surroundings. Such an eddy is shown in Figure 4 after 100 seconds of simulation, labelled as detail A. During a smoke cloud's formation many such eddies form a smoke field that is pushed in the wind direction.

3.1 Analyses of open boundary condition effect on data loss

Both the simulations show that a large part of the smoke cloud escapes, especially from the upper boundaries. A characteristic of the high-density soot is the slump after it is cooled down at higher levels. This means that the smoke cloud should be analysed at its maximum level and its upper part should be included in the computational domain. The minimum necessary height of the domain to capture the whole cloud was found to be 500 meters. The simulation results show



Sl. 4. *Polje koncentracij saj za srednji prerez po 100 sekundah in 1000 sekundah simulacije pri hitrosti vetra 2 m/s*

Fig. 4. *Soot concentration field at wind speed 2 m/s after 100 and 1000 seconds of simulation*

metrov ne spusti in da je še vedno pod vplivom vzgona. Videti je tudi, da se koncentracije bistveno ne razlikujejo od modela z višino 300 metrov, kar prikazuje slika 5.

that the cloud does not slump down at the distance where the power plant is located and the concentrations are not significantly different from those in the simulation with the 300-metre domain height, Figure 5.

3.2 Kratek pregled požarne varnostne analize elektrarne Krško za požar na odprtem prostoru

3.2 Consideration of Probabilistic Safety Assessment for external fire event

Predstavljena deterministična varnostna analiza predstavlja nadgradnjo Verjetnostne varnostne analize - Požarne varnostne analize jedrske elektrarne Krško, ki deterministične analize ne obravnava. Po Verjetnostni varnostni analizi je opisani požarni scenarij na prostem obravnavan kot ostali zunanji dogodek. Po analizi je doprinos požara na prostem na skupno verjetnost poškodbe sredice reaktorja manj kot 1E-7 na leto, kar je tudi razlog, da se ne opravljajo nadaljnje analize.V primeru notranjega požara pa je ogroženost sredice zaradi ogroženosti nadzorne sobe ocenjena z verjetnostjo dogodka 1.2E-5 na leto z upoštevanjem požarnega varnostnega sistema. Največji prispevek k temu pomeni zapustitev nadzorne sobe ([5] in [6]).

Če je nadzorna soba neprimerna za bivanje, je treba nadzorno sobo zapustiti le po izvedbi potrebnih opravil, ki zagotavljajo varno delovanje reaktorja. V primeru kontaminirane okolice (požar, klor itn.) klimatizacija nadzorne sobe preide na obtok s filtri, v katerih je aktivno oglje za čiščenje zraka. Če to ne zadošča, si operaterji v izmeni nadenejo dihalne aparate.

The presented deterministic fire safety analysis should represent an upgrade of the PSA - Probabilistic Safety Assessment of Krško nuclear power plant - Fire Safety Analysis, although it does not consider the deterministic analyses. The external fire event that we described is defined as the Other External Event by PSA. The probability contribution of an external fire to the total core damage is less than 1E-7 per year. That is why no other special analyses are required. In the case of an internal fire, the fire area core damage frequency contribution for the power plant control room is 1.2 E-5 per year, considering a fire safety system. This contribution comes mostly from the control-room abandonment scenario ([5] and [6]).

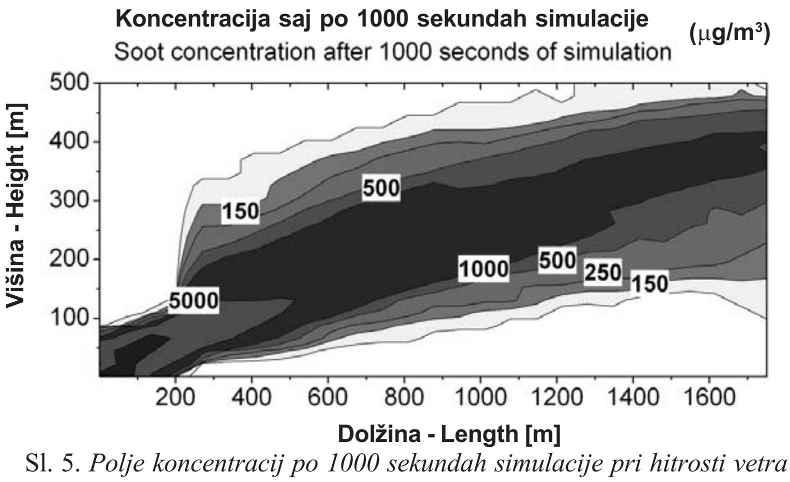
In the case of uninhabitable conditions in the control room, abandonment should occur only after performing actions necessary to ensure the safety of the reactor. These actions include the start of the control-room charcoal cleanup system. The probability that such an accident as we described could occur is very low.

4 SKLEP

4 CONCLUSION

Prispevek opisuje način modeliranja dinamike požara s postopki računske dinamike tekočin, ki

The paper presents a fire modelling approach with computational fluid dynamics, based on Navier-



Sl. 5. *Polje koncentracij po 1000 sekundah simulacije pri hitrosti vetra 9 m/s*
Fig. 5. *Soot concentration field at wind speed 9 m/s after 1000 seconds of simulation*

slonijo na Navier-Stokesovih enačbah, prirejenih za majhna Machova števila. Turbulentni tok sem modeliral z metodo velikih vrtincev LES, ki uporablja model turbulentne viskoznosti Smagorinskega za modeliranje prenosa energije iz velikih na majhne strukture toka. Opisan je uporabljeni model zgorevanja ter model prenosa toplote s sevanjem. Predstavljeni sta dve simulacij širjenja dimnega oblaka v okolici elektrarne Krško in izračunane so koncentracije dimnih delcev po izdelanem modelu.

Sklepni odgovor na začetno vprašanje ali je v primeru požara na odprtem, kakršen je predpostavljen v modelu ''Krško'', ogroženo delovanje elektrarne. Iz rezultatov svoje simulacije in pregleda varnostne analize elektrarne Krško ugotavljam, da nadzorna soba ne bi bila prizadeta s povišano koncentracijo dima pri uporabi filtrov v prezračevalnem sistemu, kakor jih predpisuje varnostno poročilo. V primeru nepravilnega delovanja prezračevalnega sistema se možnost prodora dima v nadzorno sobo nekoliko poveča. V vsakem primeru pa je najdaljši mogoči čas ogroženosti največ toliko, kolikor znaša čas zgorevanja luže nafte ob prometni nesreči s cisterno z gorivom.

Stokes equation, arranged for low Mach number. The turbulent flow is modelled with Large Eddy Simulation LES that uses the Smagorinsky model to simulate the energy transfer from the large structure of flow to the sub-grid scales. The combustion and radiation heat transfer models are presented. Two simulations of fire spread and smoke in the surrounding of Krško nuclear power plant are discussed and the dynamics of soot concentrations are analysed.

The answer to the initial question about the safety operation of the power plant during the outdoor fire event, as presented in the model "Krško" should be: From the results of the simulation and the review of the Krško power plant safety analyses is found, that the control room would not be affected with the excessive smoke concentration under the regular use of filters in the ventilation system, as prescribed with the safety report. The risk increases if the ventilation system is not working properly. In any case the longest time of threat is equal to the burnout time of the fuel pool released from the tank lorry.

5 OZNAKE
5 SYMBOLS

gostota	ρ	kg/m^3	density
tenzor viskozne napetosti	τ	kg/ms^2	viscous stress tensor
molekularna difuzivnost	D	m^2/s	diffusivity
gravitacijski pospešek	$\mathbf{g}$	m/s^2	acceleration due to gravity
višina	h	m	height
zgorevalna toplota	h_c	J/kg	heat of combustion
uparjalna toplota	h_v	J/kg	heat of vaporization
masni tok	$\dot{m}$	kg/s	mass flux
tlak	p	Pa	pressure
temperatura	T	K	temperature
sevalna jakost	I	W/m^2	radiation intensity
plinska konstanta	R	J/kgK	ideal gas constant
masni delež	Y	-	mass fraction
toplotni tok	$\dot{q}$	W	heat flux
mešalno razmerje	Z	-	mixture fraction
temperaturna prevodnost	k	m^2/s	thermal diffusivity
vektor hitrosti	u	m/s	velocity vector
enotni vektor	$\mathbf{n}$		unit vector
vrtinčnost	ω		vorticity vector

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Uporaba neobičajnih nevronskih mrež za ovrednotenje okoljskih vidikov modeliranja

The Application of an Atypical Neural Network when Quantifying the Modeling of Environmental Aspects

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(University of Podgorica, Podgorica)

Prispevek podaja novo metodo, ki bazira na nevronski mreži, in je vpeljana v fazi ocenjevanja okoljskega vidika. Metoda naj bi zagotovila zadostno objektivnost in natančnost v ocenjevanju vplivov na okolje za vse oblike organizacij in temelji na specifičnosti dosegljivih matematičnih modelov, uporabljenih pri že certificiranih organizacijah v Srbiji in Črni Gori.

(Ključne besede: mreže nevronalne, zaščita okolja, vidiki okoljski, vplivi okolja, vrednotenje)

This paper looks at the environmental aspects' quantification phase, *where a new method based on a neural network was initiated. The method should provide sufficient objectivity and accuracy in the assessment of environmental impacts for all types of organization, and it is based on the specificity of available mathematical models used by certified organizations in Serbia & Montenegro.*

(Keywords: neural networks, environmental protection, environmental aspect, environmental impact, quantification)

0 INTRODUCTORY REMARKS

Implementation of the environmental protection management system according to the ISO 14000 series standards is very arduous work and demands the validation of the following:

- Specificity of the company
- Specificity of the locality
- Validation of the standard's requests
- Validation of the legal regulations

The aspects and impacts on the environment represent the most significant request of the standard and the procedure of environmental protection in general, where further compliance with the requests of the standard does not lead to the complete fulfillment of assigned goals, if it is not defined in details at this point, and in this way the whole work on environmental protection of one organization can be put into question. Concerning the great importance of 4.3.1 requests, the arbitrariness and insufficient accuracy in the approach protected by the standard, represents a stimulus for the investigation toward the quantification of environmental impacts by using scientific methods and work techniques. In particular, the ISO 14004 standard, article 4.3.1.5 justified by the argument "significance is a relative concept: it cannot be defined in absolute terms" gives organizations complete freedom in relation to these problematics. The purpose, to find possibilities for a determination of the unique approach for all organizations in the quantification of environmental impacts, due to the diversity of data and given result, the application of neural networks represents the basis for this paper.

1 ENVIRONMENTAL ASPECTS

Aspects of the environment represent a complex field, and also one of the most demanding articles of standards, considering that the efficiency of environmental protection management depends exactly on the substantial and fundamental respect of this request.

The essence of EMS lies in good identification and quantification of the environmental impacts, considering that from there the indicators of environmental protection efficiency originate, whose measurement serves for the determination of the fulfillment level of the appointed general and special goals of the organization and

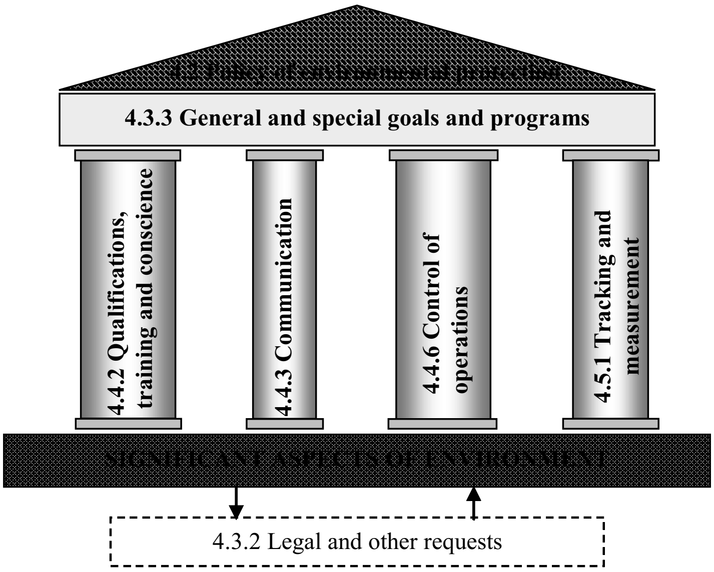

Fig. 1. *Articles of the standard, based on significant environmental aspects*

evaluation of the system itself. Most of the key articles are based on a knowledge of the significant environmental aspects, such as those presented in Figure 1, while other standard articles stand in certain correlation with them, although they are not entirely dependent on them.

This topic was elaborated in both versions of the standard (ISO 14001:1996 and ISO 14001:2004) under the same title "Environmental aspects" and the same article 4.3.1.

As for the standard ISO 14004, the difference is obvious because ISO 14004:2004 goes more in-depth with the identification processes and the significance of aspects and environmental impacts. The fact that five sub-articles were formulated within the article "Environmental aspects" in ISO 14004:2004, where the guidelines and recommendations had been given, shows what value this new standard attributes to this request (Figure 2). Through an analysis of 4.3.1 and part of the aspects' significance and the environmental impacts evaluation in the standard ISO 14004, too much freedom of choice can be left for the organizations observed:

- methodology
- significance criterion
- criteria ranking
- limited values of significance

In accordance with this, certification institutions do not enter into the evaluation methodology selected by the organization either. They only analyze the final results and evaluate the way of monitoring and rehabilitation of the

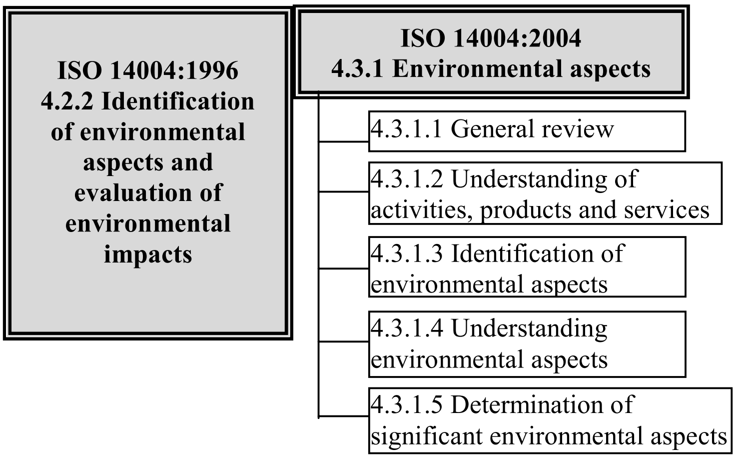

Fig. 2. *Structure fact "Environmental aspects" in standards ISO 14004:1996 and ISO 14004:2004*

Table 1. *Comparison II (A and C)*

	C	**A**	
VOLUME	1	1.2	**C** (significant) **A** (insignificant) **84**
	2	3	
	3	4	
	4	5, 6	
	5	7, 8	
PROBABILITY	1	1, 2	**A** (significant) **C** (insignificant) **0**
	2	3, 4	
IMPACT SEVERITY	1	1	
	2	2	
	3	3	
Influence on public opinion	1	1	
	2		
	3		

significant aspects‘ consequences. Therefore, this leaves too much room for manipulation with data on which the whole environmental protection management system relies, and the system should be determined to the greatest possible extent. Namely, based on the available data from three certified organizations (A, B and C) in Serbia and Montenegro that are related to the chosen mathematical model and the evaluations of the environmental aspects, a worrying reduction in the number of significant impacts can be seen, depending on the applied verified model, and which cannot be justified by the different activities of the organizations. A comparative analysis was realized through programming in the JAVA programming language, software package JDK 1.2.2. (Java Development Kit) in the available text editor JCreator 3.50. In order to carry out a comparison of the applied methodology in these organizations, first of all it was necessary to make an adjustment of the evaluation and the selected criteria (e.g., Table 1 for organizations A and C). A comparison was realized for all three organizations, such as follows:

1. Comparison I (organization A and organization B)
2. Comparison II (A and C), Table 1
3. Comparison III (organization B and organization C)

- EVALUATION OF ORGANIZATION A

ENVIRONMENTAL ASPECTS: SIGNIFICANCE EVALUATION CRITERIA

Environmental aspects: volume

Environmental aspect volume	**Criteria description**	**Evaluation**
Immediate environment	The consequences of the environmental aspect are limited to the immediate environment of the place of its emergence.	1
Work premises level	The consequences of the environmental aspect are limited to the work premises in which it emerged.	2
Department level	The consequences of the environmental aspect are limited to the department in which it emerged.	3
Operation level	The consequences of the environmental aspect are limited to the operation level in which it emerged.	4
Industrial complex level	The consequences of the environmental aspect are limited to the industrial complex level.	5
Municipal level	The consequences of the environmental aspect are limited to the municipal level.	6
Regional level	The consequences of the environmental aspect include more municipalities.	7
International level	The consequences of the environmental aspect are extended over the state borders.	8

Environmental aspect: emergence frequency

Frequency	Criteria description	Evaluation
Small	The environmental aspect emerges only under extreme working conditions (explosion, fire etc.).	1
Medium	The environmental aspect can emerge only under unusual working conditions (power-supply discontinuation, equipment breakdown, irrelevant executor, malicious damage etc.)	2
Big	The environmental aspect can emerge if the executor is negligent, unskilled or the equipment is not maintained.	3
Very big	The environmental aspect emerges under normal working conditions.	4

Environmental aspect: consequences severity

Severity	Criteria description	Evaluation
Minor	There are no measurable environmental consequences.	1
Medium	The measured presence of matters which are not dangerous matters, or their influence on the environment is not known.	2
Big	• Presence of dangerous matters measured in quantities higher than permitted by law. • Lack of information.	3

▪ EVALUATION OF ORGANIZATION C

Public opinion
- Small impact (1 point) – Loss of reputation of local character, short-term effect.
- Medium impact (2 points) – Loss of reputation of local character, long-term effect.
- Big impact (3 points) – Loss of reputation of regional or wider character, long-term effect.

Severity of impact
- Small impact (1 point) – Impact on the environment with insignificant influence on human beings, flora and fauna.
- Medium impact (3 points) – Impact on the environment with a harmful effect on human beings‘ health and/or a temporary impact on flora and fauna.
- Big impact (3 points) – Impact on the environment posing a direct threat to human lives and long-term and/or permanent consequences for the flora and fauna.

Probability of impact
- Small probability (1 point) – If the aspect does not have an impact on the environment in the course of technological process realization, but there is a possibility due to failing to keep to technological technical measures of protection, the impact may have an effect.
- Big probability (2 points) – If the aspect has a continuous impact on the environment in the course of technological process realization.

Intensity of impact
- **for waste**

Intensity of impact	Quantity
1	to 0.1 t / year
2	from 0.1 t / year to 0.5 t / year
3	from 0.5 t / year to 1 t / year
4	from 1 t / year to 5 t / year
5	over 5 t/ year

- **for discharges into water / emissions into air**

Intensity of impact	Quantity
1	to 1 m^3 / year
2	1–5 m^3 / year
3	5–10 m^3 / year
4	10–100 m^3 / year
5	over 100 m^3 / year

Intensity of the impact on the environment of organization C is analogous with the environmental aspect volume of organization A.

To overcome the stated non-uniformities of certain methodologies but still to adopt their specificities and gained results, we approached the production of a program for the evaluation of the environmental impacts through the application of a neural network. The aim was to establish a model with as little as possible subjectivity in the individual evaluation so as to avoid possible manipulations with the results.

2 FEED-FORWARD BACK-PROPAGATION NEURAL NETWORK

The feed-forward back-propagation neural network is most commonly applied in practice because of its simplicity as well as for the wide spectrum of problems it can solve (shape recognition, robot and vehicle management, figure classification, knowledge processing and the other different problems of shape analysis). Considering that the input data available in a certain problem are grouped, and that the exact response is known for every input, a feed-forward back-propagation neural network is the simplest and best solution for the choice of network.

The feed-forward back-propagation neural network belongs to a group of networks that have the following characteristics:

- number of layers: multi-layer
- architecture: layered
- training: statically supervised
- direction of information flow: non-recurrent
- kind of data: discrete static

The feed-forward back-propagation is an abbreviation of ”back error propagation”, which is translated as the propagation of an error backwards. It is a network with two or more layers; therefore, it has at least one hidden layer, and most commonly networks with completely linked layers are used (Fig. 3).

The linear function of the input interaction is represented by the expression:

$$n_j = \sum p_{ij} \cdot W_{ij}; \quad i = 0,...R \qquad (1),$$

where p_{ij} is an input signal of j units and W_{ij} is the weight coefficient of the relation that links units i and j.

The neuron threshold in this case is represented by a constant input p_{oj}=1 and a weight W_{oj}. The output signal of the same neuron is:

$$a_j = f(n_j) \qquad (2).$$

When the network is excited with a signal = $(p_1,...pi_R)$ its response will be $a = (a_1,...a_S)$, so during the learning process the difference between the real ”a” and the desired response ”o” should be minimized, and the error function can be represented by:

$$\varepsilon = \frac{\sum (o_j - a_j)^2}{2} \qquad (3),$$

$j = 1,\ldots S$ – the counter of the output signals

The feed-forward back-propagation neural network has two phases in the procedure of training, as follows:

- phase (propagation) forward
- phase (propagation) backward

During first propagation (forward), the computation of all the neuron responses is performed starting from the first, until the last layer, based on

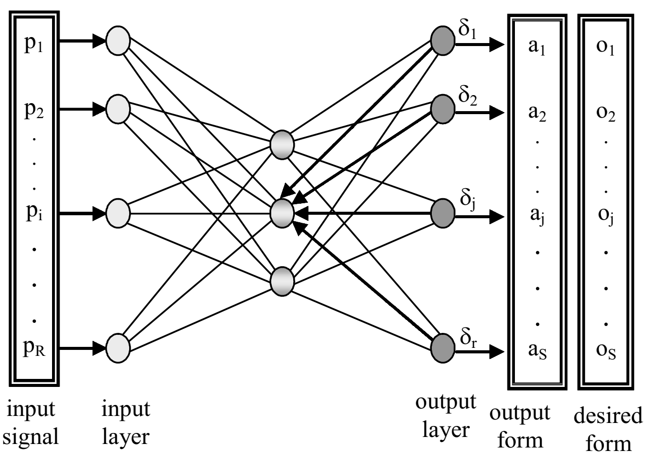

Fig. 3. *Two propagation steps of the back-propagation neural network*

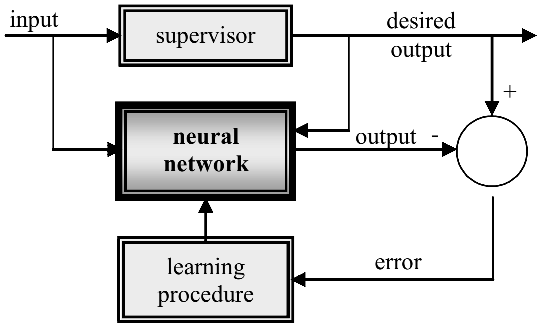

Fig. 4. *Supervised (offline) learning*

the input signals that are presented to the network. All the weight coefficients are calculated during this phase.

The second propagation (backward) implies the correction of weight coefficients based on the calculated error that is gained as a difference between the real and desired responses. This phase is only finished when the correction of the weight coefficients for all the neurons in all the layers is done.

The statically supervised training of the back-propagation neural network is represented in Figure 4.

After the neural network is trained, the testing of the model by the simulation (test) sample can begin.

For the feed-forward back-propagation network type, in the Matlab software package it is possible to chose the following parameters:
1. Training function
2. Adoption learning function
3. Network performance function
4. Number of neuron layers
5. Number of neurons in layer
6. Transfer function

within the window "Create New Network" represented in Figure 5.

The choice of the training function is of great significance for providing the speed of learning for the given network, i.e., the algorithm. It is difficult to answer in advance the question as to which function will give the best results for the given problem, because there are several factors on which it depends (the number of training samples of the training set, the expected accuracy, the number of neurons in the network, etc.)

The Trainlm network training function, which updates the weight and bias values according to the Lovenberg-Marquardt optimization, gave the best results as regards the concrete problem.

Immediately following the training-function selection, it is placed at the user's disposal to select an adoption learning function that is related to the manner of the calculation of the weight coefficients change, and which can have a big impact on the speed of convergence and size of the error for certain network and training-function selection.

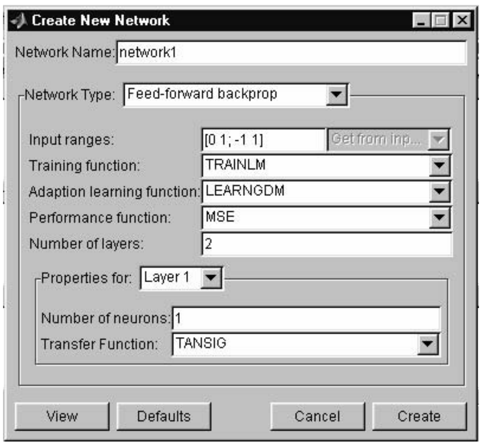

Fig. 5. *Choice of back-propagation neural-network performances*

The Network Performance Function for the network characteristics' modification is related to the manner of the error-function calculation. When the network is stimulated by the input signal $p = (p_{1,} p_{2,....} p_R)$ its response will be $a = (a_{1,} a_{2,....} a_n)$, so that in the learning procedure the difference between this response and the required one should be minimized $o = (o_{1,} o_{2,....} o_s)$. Depending on the manner of the error-function definition there are software proposals to calculate it in three ways:
1. ¨mse¨ - (Mean-squared error)
2. ¨msereg¨ - (Mean-squared error with regularization)
3. ¨sse¨ - (Sum-squared error)

There are three options offered for the selection of the transfer, i.e., activation function, so there is one linear and two sigmoid functions:
1. purelin (linear transfer function)
2. logsig (logarithmic sigmoid transfer function)
3. tansig (tangential sigmoid transfer function)

It is considered that the tansig function produces the best results in terms of the biggest number of concrete problems, and for that reason when selecting the transfer functions in the framework of the window, ¨Create new network¨ it is set as the ¨default¨.

Apart from these basic characteristics of neural networks, which are related first of all to the procedure of the training, it is necessary to define two more network parameters:
- the number of layers,
- the number of neurons in each of the layers.

The selection of the number of epochs is done following the selection of these parameters and starts the network training. The obtained output value for the defined synaptic weights and input values is brought to the network entry in order to make a potential correction of the mentioned coefficients and obtain the final output with a certain accuracy in the framework of the defined number of epochs. Obtaining the output once for all the input values and one set of placed weight coefficients represents an iteration, which is known as an epoch in the terminology of neural networks.

3 BACK-PROPAGATION NEURAL NETWORK (MEDIUM AIR)

Previously the significance of the request 4.3.1 was indicated, so in that respect the arbitrariness and the insufficient preciseness in the procedure of quantification of the aspects and impacts on the environment favored by the standard ISO 14000 encouraged us to initiate research in this field on the basis of scientific methods and techniques. The objective of the research was to try to define, exactly in this part of analysis, the regularity in the quantification of the environmental impacts on the basis of data obtained from organizations that are certified in accordance with the requirements of standard ISO 14001, and to perform the application and checking on a new as well as certified organization by means of a generalization of the obtained results.

Taking into account that there is a very small number of certified organizations in Serbia and Montenegro in accordance with the standard ISO 14000 (28 in total) the first idea was to create a neural network on the basis of due diligence from all the organizations, which would then be trained to evaluate the significance of the impact in the new organization on the basis of such a large amount of input–output information and the different mathematic models. The data sought from the organizations were related to the register of all the identified aspects and the impacts on the environment and to their evaluation of the significance according to their own mathematical models. The organizations independently created and adjusted the mathematic models for the evaluation of the significance of the impact and the aspects on the environment to their criteria for meeting the requirements of the ISO 14001 standards.

However, due to impossibility of a cooperation with a larger number of organizations, data from four organizations were collected, so the training of the neural network was performed on the basis of data from three organizations, and the data from the fourth organization were used for the simulation of the model. Having in mind that in the course of due diligence from the certified organizations, the fields of activities of which are completely different, they bound themselves to respect the principle of absolute discretion and not to use any names or any organization's identity anywhere, we will use in the following text the letters A, B and C for the organizations, and the data will be analyzed to work out the new model, and D will be the letter for the organization whose data will be used for the simulation of the work of the model. As a lot of different data is in question (2184 impacts in total), pursuant to the recommendation of the standards we approached the classification

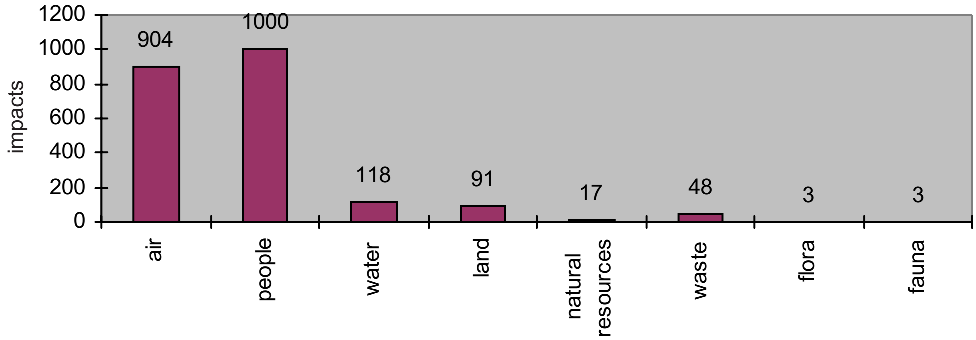

Fig. 6. *Diagram of impacts number division according to the mediums of the effect*

according to the medium on which the observed impacts have an effect:

- Air
- People
- Water
- Land
- Natural resources
- Waste
- Flora
- Fauna

The data schedule presented in Figure 6 is obtained by this procedure

As evaluations for all the three organizations (A, B and C) were obtained on the basis of different methodologies (mathematical models) it is necessary to perform a normalization of the input data in relation to the organization with the highest range of evaluations in order to harmonize the evaluation differences. The biggest range of evaluations is in organization A in relation to the criterion "Environmental Impact Volume", so that the evaluation is taken as a maximum, also for other organizations, and the relation of the evaluations among the criteria within the organizations, characteristic for its own mathematical model, aimed at a preservation of their particular quality, is kept in this process.

The procedure which will be presented for medium air, for which 904 inputs were obtained, is applied to other mediums, except for flora, fauna, waste and natural resources because the number of data in relation to flora, fauna and natural resources is very small, and as regards waste it is obtained from only one organization. Therefore, these impacts were not further considered, due to impossibility of obtaining real results.

The output values of the network (the final evaluation of the significance of impacts) are normalized in relation to the limitations set by the software package Matlab, and they are related to the allowed output width (-1, 1) so that all the

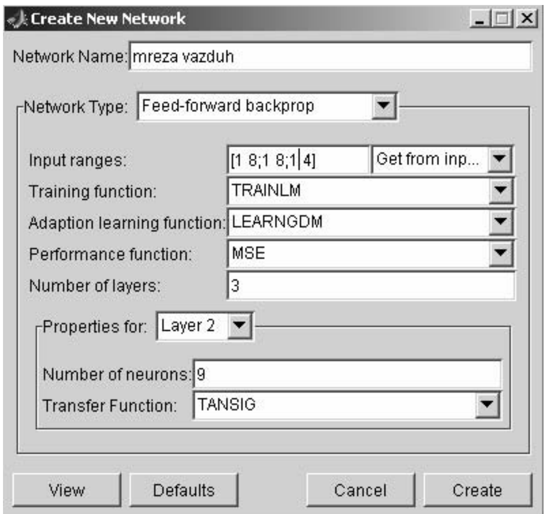

Fig. 7a. *Performances of neural network*

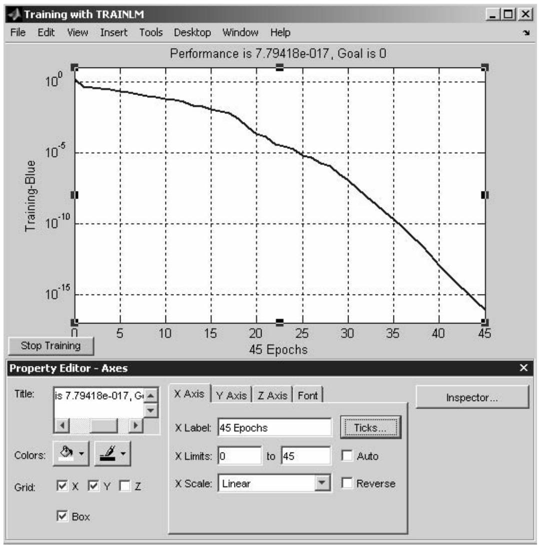

Fig. 7b. *Convergence of neural network*

significant impacts according to our own mathematical models were evaluated by evaluation 1 and those insignificant by -1. The performance of the selected back-propagation neural network for medium air is given in Figure 7a, and its convergence diagram, which defines speed and accuracy of training, in Figure 7b.

The appearance of the selected neural network with three layers, out of which the first two each have nine neurons, and the last output according to the rule 1 is presented in Figure 8.

After the results derived in this way, with a relatively fast convergence and a high accuracy, the model was tested with data from organization D, and produced results that completely coincided with the mathematical model of organization D, chosen from the four available models (models of organizations A, B, C and D) to serve as the reference model. The appearance of the basic window in Matlab with the results of the network training and the simulation for the medium air is given in Figure 9.

Analogously with the previously defined procedure, we approached the neural-network creation and training for the medium people. The network that gave the best output results for the included evaluations of this environmental impact is the network with the characteristics given in Figure 10

The appearance of the selected neural network with three layers, out of which the first two have got 12 neurons and the last output 1, is presented in Figure 11

The accuracy of the network output for these performances is accomplished with 10^{-15} in a total of 29 epochs. The appearance of the convergence diagram of the created neural network for the influence on the health of people is presented in Figure 12.

The network is tested analogously with the pervious procedure for the medium air using the data from organization D. The results of the simulation

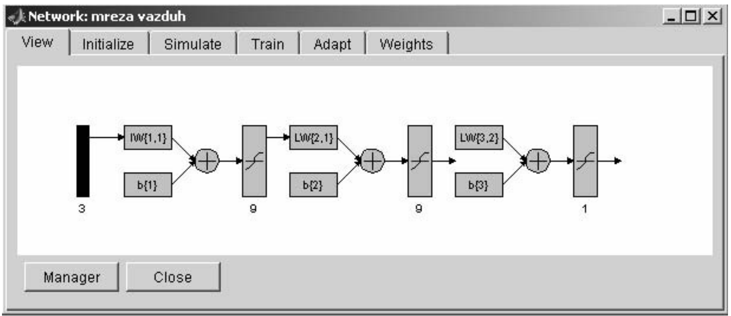

Fig. 8. *Appearance of the neural network (air)*

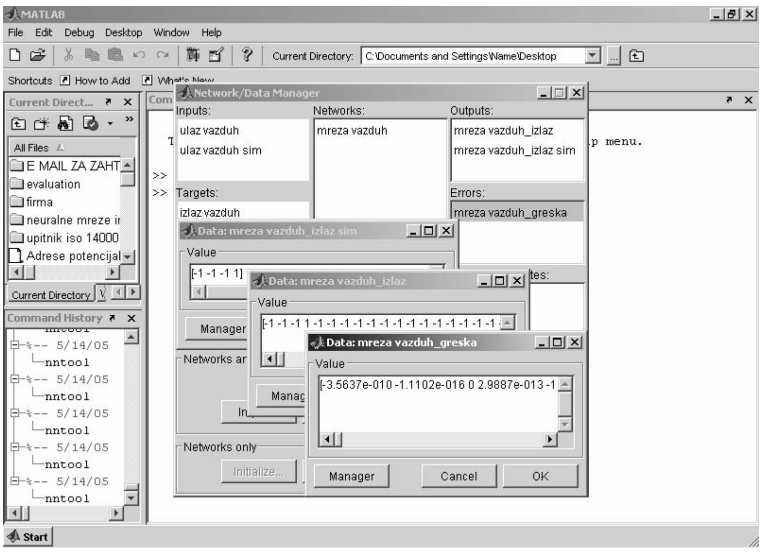

Fig. 9. *Appearance of the basic window with results of the network training and simulation (air)*

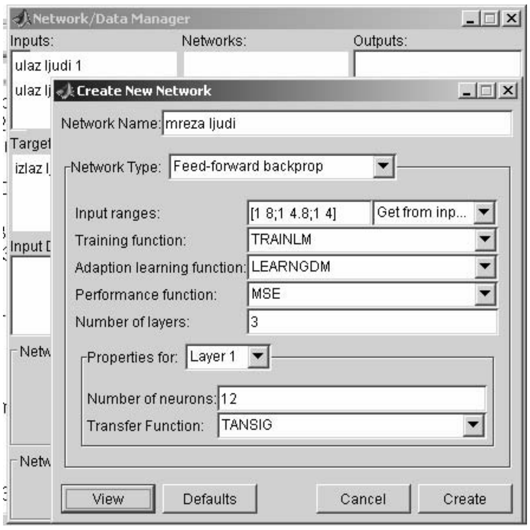

Fig. 10. *Performances of neural network (people)*

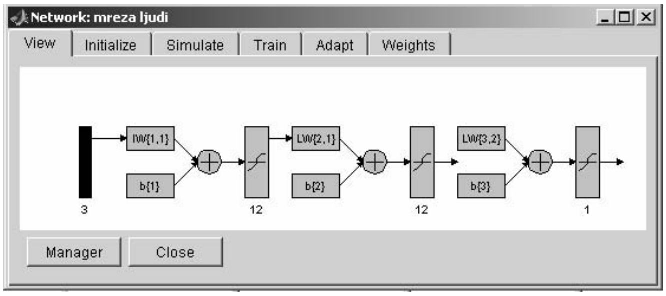

Fig. 11. *Appearance of neural network (people)*

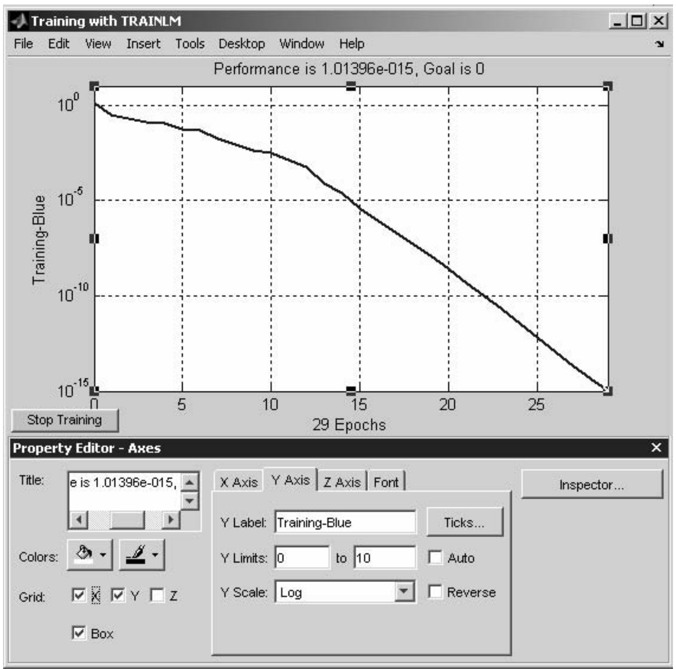

Fig. 12. *Diagram of convergence of neural network (people)*

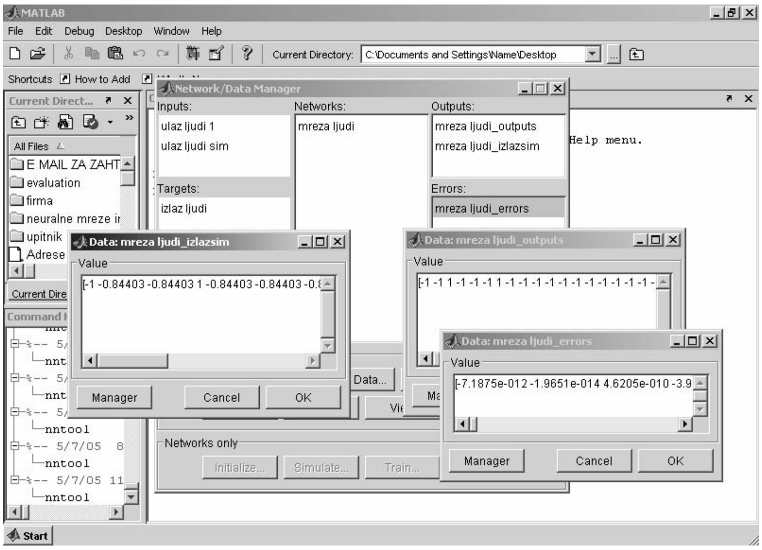

Fig. 13. *Appearance of the basic window with results of network training and simulation (people)*

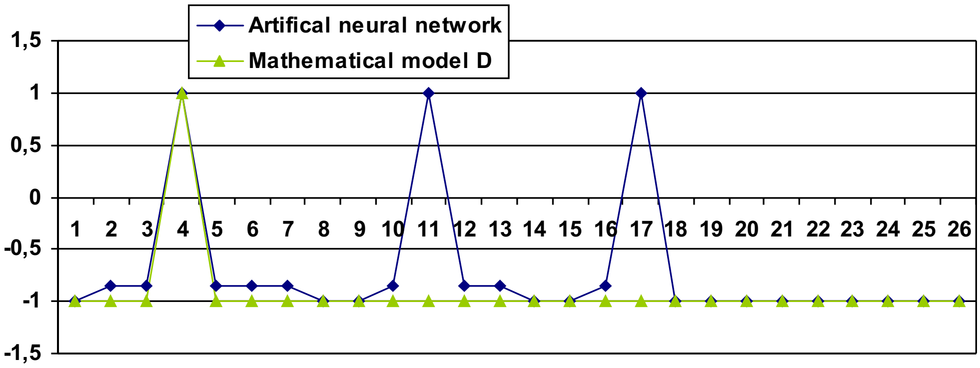

Fig. 14. *Comparative analyses of the results for medium people*

are presented in the Figure 13 within the window "Data: mreza ljudi_izlazsim", and a certain deviation can be observed when compared to the data obtained by the methodology of organization D.

A comparative analysis of the results obtained by the neural network and the mathematical model of organization D are given in the diagram in Figure 14

The difference in the results obtained by the application of these two different models is the impact for 11 and 17. However, by an analysis of the mathematic model of organization D it can be seen that the impacts 11 and 17 belong to the limiting value that is not included as significant for the given model while the neural network acquires these data as significant. Therefore, it can be realized that the neural network, as regards the influence on health, is more sensitive about the significance of impact than the mathematical model of the organization D, although the limiting values for each model as well as the neural network can be deemed as critical points due to the inexistence of recommendations of the standards or an exact analysis for their determination.

Taking into account a small training sample, the results that are obtained for the medium water and land showed a certain deviation in relation to the model of organization D.

4 CONCLUSION

A comparative analysis of the available mathematical models and the obtained results through the application of a neural network has determined that the chosen back-propagation neural network gave satisfactory results for a sufficiently large training sample for the medium air and people. In particular, a reduction in the results for two samples out of a total of 26 for medium people is negligible, considering that the evaluations of these impacts belong to the limited value of the mathematical model that certainly has to be a matter of dispute, and the model of the organization D itself in the part of the evaluation is certainly not perfect.

Satisfactory results for the mediums water and land were not obtained exactly because of the relatively small training sample, based on which the network was not able to produce the correct output.

The evident fact is that an evaluation like this, that itself has incorporated the specificities of available models from practice, has the highest character of objectivity and does not leave enough space for manipulations in the part of forming a register of significant impacts, and its efficiency and objectivity could be significantly improved through additional training of the neural network with innovated data.

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Ocena vpliva vhodnih parametrov v analizi toplotnega prehodnega pojava pod tlakom v reaktorski posodi Nuklearne elektrarne Krško v primeru majhne izlivne nezgode

The Estimated Influence of the Input Parameters in the analysis of the PTS in the Core of the PWR Krško NPP in the Case of the SB LOCA

Ivica Bašić[1] - Peter Crnjac[2]
([1]Nuklearna elektrarna Krško, Krško; [2]II. gimnazija Maribor, Maribor)

V prispevku smo se osredotočili na deterministično metodo izbire mejnih primerov ohladitve reaktorske posode Nuklearne elektrarne Krško pri posredovanju sistema za zasilno hlajenje sredice med malo izlivno nezgodo. Za osnovni izračun smo izbrali malo izlivno nezgodo z zlomom velikosti ustreznega premera 50,8 mm v hladni veji in termohidravlični računalniški program RELAP5/MOD3.3. V nadaljnji študiji smo s spreminjanjem parametrov sistema za zasilno hlajenje sredice za zlom na istem mestu simulirali še tri scenarije male izlivne nezgode. Namen študije je bil oceniti, koliko so mejni izbrani vhodni parametri nevarni za toplotni prehodni pojav pod tlakom v reaktorski tlačni posodi.

(Ključne besede: reaktorji jedrski, posode reaktorske, pojavi prehodni, nezgode izlivne male)

This paper focuses on the deterministic method of limiting cases of the Krško Nuclear Power Plant (NPP) reactor pressure-vessel cooling by mediating the emergency core-cooling system (ECCS) during a small-break loss-of-coolant accident (SB LOCA). The SB LOCA accident with the equivalent diameter break of 50.8 mm in the cold leg and the RELAP5/MOD3.3 computer code were selected for the basic calculation. In further study, by modifying the ECCS's parameters for the same break, three accidents of the SB LOCA were simulated. The purpose of our study was to estimate the potential risk of the extreme conservative input parameters for the pressurized thermal shock (PTS) in the reactor's pressure vessel.

(Keywords: nuclear reactors, pressure vessels, pressurized thermal chock, SB LOCA accident)

0 UVOD

Po nezgodi v jedrski elektrarni na Otoku treh milj so strokovnjaki s področja varnostnih analiz spoznali pomembnost male izlivne nezgode in poskušali z matematičnimi modeli, računalniškimi simulacijami in preizkusi na pomanjšanih modelih primarnih sistemov jedrskih elektrarn pojasniti pojave med nezgodo. Analize male izlivne nezgode morajo med drugim tudi dokazati zadostno zmogljivost sistema za zasilno hlajenje sredice, ki mora učinkovito ohladiti sredico in po izlivni nezgodi vzdrževati reaktor v varnem stanju hladne ugasnitve. V to področje posega tudi predstavljena študija, v kateri smo z deterministično varnostno analizo proučevali vpliv vhodnih parametrov sistema za varnostno vbrizgavanje na nastanek toplotnega prehodnega pojava pod tlakom v reaktorski posodi lahkovodnega reaktorja pri mali izlivni nezgodi.

1 MALA IZLIVNA NEZGODA V TLAČNOVODNI JEDRSKI ELEKTRARNI

Med mogočimi dogodki, ki lahko povzročijo poškodbo sredice, je tudi nezgoda z izgubo primarnega hladiva ali izlivna nezgoda. Izlivna nezgoda je definirana tako, da je puščanje tako veliko, da normalno polnjenje ne zadošča za vzdrževanje vsebine hladiva v primarnem sistemu. Za omilitev posledic izlivne nezgode se uporabljajo sistemi za zasilno hlajenje sredice. Projektirani so tako, da obvladajo celoten spekter izlivnih nezgod, od najmanjše (to je nezgoda, ki presega puščanje) do največje (zlom glavne obtočne cevi hladilnega sistema reaktorja). Več podsistemov je potrebnih za obvladovanje različnih vrst izlivnih nezgod in posameznih faz teh nezgod: visokotlačno varnostno vbrizgavanje, nizkotlačno varnostno vbrizgavanje in zbiralnik varnostnega vbrizgavanja. Pomen sistema za zasilno hlajenje sredice in njegovih podsistemov za območja nezgodnih scenarijev je podrobno obravnavan v literaturi ([1] do [3]).

Glede na velikost zloma in količino iztečenega hladiva, hitrost padanja primarnega tlaka in sproženje posameznih komponent sistema za zasilno hlajenje sredice delimo izlivne nezgode v tlačnovodni jedrski elektrarni na velike in male [4]. Po razvrstitvi Ameriškega združenja jedrskih strokovnjakov ANS (American Nuclear Society) so projektna stanja elektrarne razdeljena na štiri skupine v skladu s pričakovano pogostostjo dogodkov in njihovimi mogočimi radiološkimi posledicami za prebivalstvo [5]. Po tem standardu spada mala izlivna nezgoda v tretjo kategorijo mogočih nezgod z verjetnostjo nastopa 10^{-4} - 10^{-2}/reaktor-leto.

Scenariji male izlivne nezgode se od elektrarne do elektrarne lahko zelo razlikujejo glede na tip reaktorske posode ali uparjalnik in njune termohidravlične značilnosti. Pri mnogih tlačnovodnih elektrarnah navajajo pretočni prerez zloma 0,04645 m^2 (72 palcev^2), kar ustreza premeru cevnega priključka 240 mm (9,5 palca) kot zgornji meji za malo izlivno nezgodo. V to področje spadajo cevni priključki na tlačno mejo primarnega sistema, kakor so razbremenilni ventili na tlačniku, polnilna in praznilna linija, drenažne cevi ter različni instrumentacijski priključki. Skoraj v vseh hipotetičnih primerih se predpostavi zlom v hladni veji med reaktorsko posodo in reaktorsko črpalko, ker se to mesto zloma šteje kot najneugodnejše za omilitev posledic izlivne nezgode.

Dogodki med malo izlivno nezgodo običajno potekajo dovolj počasi, da lahko operaterji sledijo posameznim fazam [6] ter z dovolj zgodnjim in učinkovitim ukrepanjem preprečijo oz. zmanjšajo njene posledice. Posledice posameznih nezgodnih scenarijev pa so odvisne predvsem od projektnih osnov, razpoložljivosti opreme za njeno zmanjševanje in seveda od velikosti prereza izlivnega mesta. Kriteriji za oceno sprejemljivosti sistema za blažitev posledic male izlivne nezgode so za NEK (Nuklearna elektrarna Krško) vzeti po merilih Ameriškega upravnega organa za jedrsko varnost NRC (Nuclear Regulatory Commission), ki so zbrani v zakonu 10 CFR 50.46 [7].

2 TOPLOTNI PREHODNI POJAV POD TLAKOM

Sredica jedrskega reaktorja je močan vir nevtronov ter beta in gama sevanja, ki so mu izpostavljene komponente reaktorske sredice in reaktorska tlačna posoda. Najbolj ogroženi del tlačne posode je jekleni valjasti plašč posode okrog sredice, ki se mu po dolgotrajnem obsevanju poveča natezna trdnost, žal pa tudi njegova krhkost. Zvišanje primerjalne temperature prehoda iz krhkega v žilavi zlom zaradi nevtronske izpostavitve je znatno in lahko vpliva tudi na dovoljena temperaturno-tlačna stanja reaktorske posode, ki jih moramo upoštevati ob prehodnih pojavih [8].

V gradivu reaktorske tlačne posode so lahko neodkrite razpoke, ki so nastale med predelavo jekla ali izdelavo posode. Mogoča je tudi nezgoda, pri kateri bi sistem za zasilno hlajenje sredice vbrizgal hladno vodo pod visokim tlakom v normalno ogreto tlačno posodo. Dotok hladne vode sprva zniža temperaturo in tlak v primarnem sistemu, nato pa se tlak spet zviša, ker dotok zasilnega vbrizgavanja preseže prostorninsko krčenje hladila zaradi ohlajanja. Če jeklo tlačne posode ne bi bilo dovolj žilavo, bi lahko nastal varnostni problem, ki ga imenujemo toplotni prehodni pojav pod tlakom.

Za presojo nevarnosti toplotnega prehodnega pojava pod tlakom so torej odločilni prehodni pojavi in nezgode, ki povzročijo hitro ohlajanje primarnega sistema in reaktorske tlačne posode. Študija ameriškega upravnega organa za jedrsko varnost [9] je malo izlivno nezgodo označila kot glavni vzrok tveganja za pojav toplotnega prehodnega pojava pod tlakom, ker pride do zmanjšanja pretoka v primarnem sistemu pri razmeroma visokem tlaku. Ko pretok miruje, postane povratni kanal povsem odrezan od virov toplote (zaostala toplota, sekundarna stran uparjalnika). Zato se povratni kanal, ko vbrizgavamo kapljevino z visokotlačnim varnostnim sistemom, hladi veliko hitreje kakor bi se ob nominalnem pretoku.

Pri malih izlivnih nezgodah z razmeroma velikim zlomom (do prereza razbremenilnega ventila tlačnika) pogosto pride do mirovanja toka, vendar pa se tlak zniža razmeroma hitro, zato te nezgode niso zanimive z vidika toplotnega prehodnega pojava pod tlakom. Nasprotno pa lahko male izlivne nezgode pri manjših zlomih resno ogrozijo celovitost reaktorske posode, ker je tlačna razbremenitev počasna in so v steni posode napetosti zaradi tlaka še povečane s toplotnimi napetostmi ([10] in [11]). S tem so podani pogoji, ko je toplotni prehodni pojav pod tlakom mogoč: tlak je visok, reaktorska posoda pa se hitro ohlaja.

3 PROGRAMSKO ORODJE RELAP5/MOD3.3

Termohidravlične varnostne analize se praviloma izvajajo z računalniškimi programi. Postopki v jedrski elektrarni so tako zahtevni in zapleteni, da lahko z analitičnimi metodami samo grobo ocenimo obnašanje med prehodnimi pojavi. Osnova vsakega dinamičnega simuliranja obnašanja sistema, v katerem se pretaka voda in prenaša toplota, je matematični model toka tekočine. V predstavljeni študiji so bile raziskave in analize termohidrodinamičnih postopkov med malo izlivno nezgodo opravljene z računalniškim programom RELAP5/MOD3.3, ki je bil razvit za čimbolj resnične simulacije prehodnih pojavov v lahkovodnih jedrskih elektrarnah. Program vsebuje modele, ki so po dosedanjih dognanjih najboljši približek dogajanja v dvofaznem toku in je podrobneje obravnavan v [12] in [13].

Termohidrodinamični model v programu RELAP5/MOD3.3 je nehomogen in neravnovesen ter rešuje 6 parcialnih diferencialnih enačb za ohranitev mase, gibalne količine in specifične notranje energije za parno in kapljevinsko fazo. V programu so dodane še ohranitvene enačbe za morebitne neukapljive pline in trdne delce, raztopljene v hladivu, kot sklepne enačbe pa še povezave za prenos toplote med fazama, med hladivom in toplotnimi telesi in za medfazno trenje ter trenje ob steni. Skupaj z robnimi in začetnimi pogoji pomenijo te enačbe dosledno definiran matematični problem. Program vsebuje tudi enačbe točkovne reaktorske kinetike. Modeliranje nadzornih in krmilnih sistemov elektrarne, turbine, kondenzatorja ter sistemov napajalne vode uparjalnikov omogočajo vključene nadzorne spremenljivke in prožitvena logika.

4 OBLIKOVANJE BAZE PODATKOV IN VOZLIŠČENJE SISTEMA

Za preračun izlivnih nezgod in drugih prehodnih pojavov zahteva uporaba programa RELAP5 razčlenitev obravnavanega fizikalnega sistema na diskretna vozlišča, ki so med seboj povezana s spoji. Za vsako vozlišče je treba podati celotne geometrijske podatke ter poskrbeti za pravilna začetna stanja [14]. Z izbranimi toplotnimi telesi popišemo vire, ponore ter menjalnike toplote. Načeloma velja, da vsakemu vozlišču pripada eno toplotno telo in obratno, čeprav dostikrat zaradi oblike sistema to ni mogoče, še večkrat pa moramo zaradi omejenih računalniških zmogljivosti toplotna telesa modelirati bolj grobo kakor vozlišča [15].

Termohidravlični postopek je v vsakem vozlišču in spoju popisan z vsemi šestimi ohranitvenimi enačbami, temperaturno polje v toplotnem telesu pa določa enačba prevajanja toplote ob poljubnih robnih pogojih. Masna in energijska ohranitvena enačba se rešujeta po metodi končnih razlik za vsako vozlišče modeliranega sistema. Ohranitvena enačba za gibalno količino se prav tako rešuje po metodi končnih razlik, vendar med dvema spojema.

Za prehodna stanja kvalificiramo vozliščenje tako, da se merjeni podatki in robni pogoji čim bolje ujemajo z izračunanimi [16]. Vozliščenje je primerno, če lahko z njim simuliramo vse pomembne pojave in zajamemo značilnosti zgradbe elektrarne. Če vozliščenje ni primerno, ga je treba iterativno popravljati toliko časa, da izpolni merila sprejemljivosti, to je dobro ujemanje med izmerjenimi in izračunanimi rezultati [15].

5 PRERAČUNI MALE IZLIVNE NEZGODE

5.1 Vhodni model NEK

Analize male izlivne nezgode smo opravili z vhodnim modelom NEK, ki je prirejen za 2000 MW toplotne moči in nova zamenjana uparjalnika. Vhodni model je dokumentiran, preverjen, usposobljen za ustaljeno stanje in simulacijo vseh vrst nezgod ([14] in [16]). Osnovni geometrijski model je tudi neodvisno pregledan ([17] in [18]). Sistem je popisan z natančno geometrijsko obliko tokovnih poti v vseh glavnih komponentah, ki jih simuliramo: primarni hladilni sistem (modelirani sta obe primarni zanki: sredica, vroči, vmesni in hladni veji, sifon, reaktorski črpalki, tlačnik in uparjalnika) s sistemom za varnostno vbrizgavanje, na sekundarni strani pa so modelirane vse poti od uparjalnika prek glavnih parovodov do zbiralnika pare.

V model so vključeni vsi varovalni in varnostni sistemi reaktorja, ki lahko vplivajo na potek prehodnega pojava. Modelirani so tudi glavni krmilni sistemi, npr. krmiljenje moči reaktorja s krmilnimi palicami, krmiljenje ravni in tlaka v tlačniku, krmiljenje

Preglednica 1. *Značilnosti modela NEK za RELAP5/MOD3.3*

PARAMETER	ŠTEVILO
1. Število spojev	
- primarni krog	320*
- sekundarni krog	149
- skupno	469**
2. Število vozlišč	
- primarni krog	284
- sekundarni krog	213
- skupno	497
3. Število toplotnih teles	
- primarni krog	250
- sekundarni krog	126
- skupno	376**
4. Skupno število vozlišč v toplotnih telesih	2101
5. Število aktivnih toplotnih teles (reaktor)	12
6. Površine prenosa toplote (m^2)	
- sredica	3103,9
- U-cevi uparjalnika	7343,0
7. Število nadzornih spremenljivk	575
8. Število prožitev	
- spremenljivk	197
- logičnih	204
- skupno	401
11. Skupna prostornina primarnega kroga (m^3)	195,3

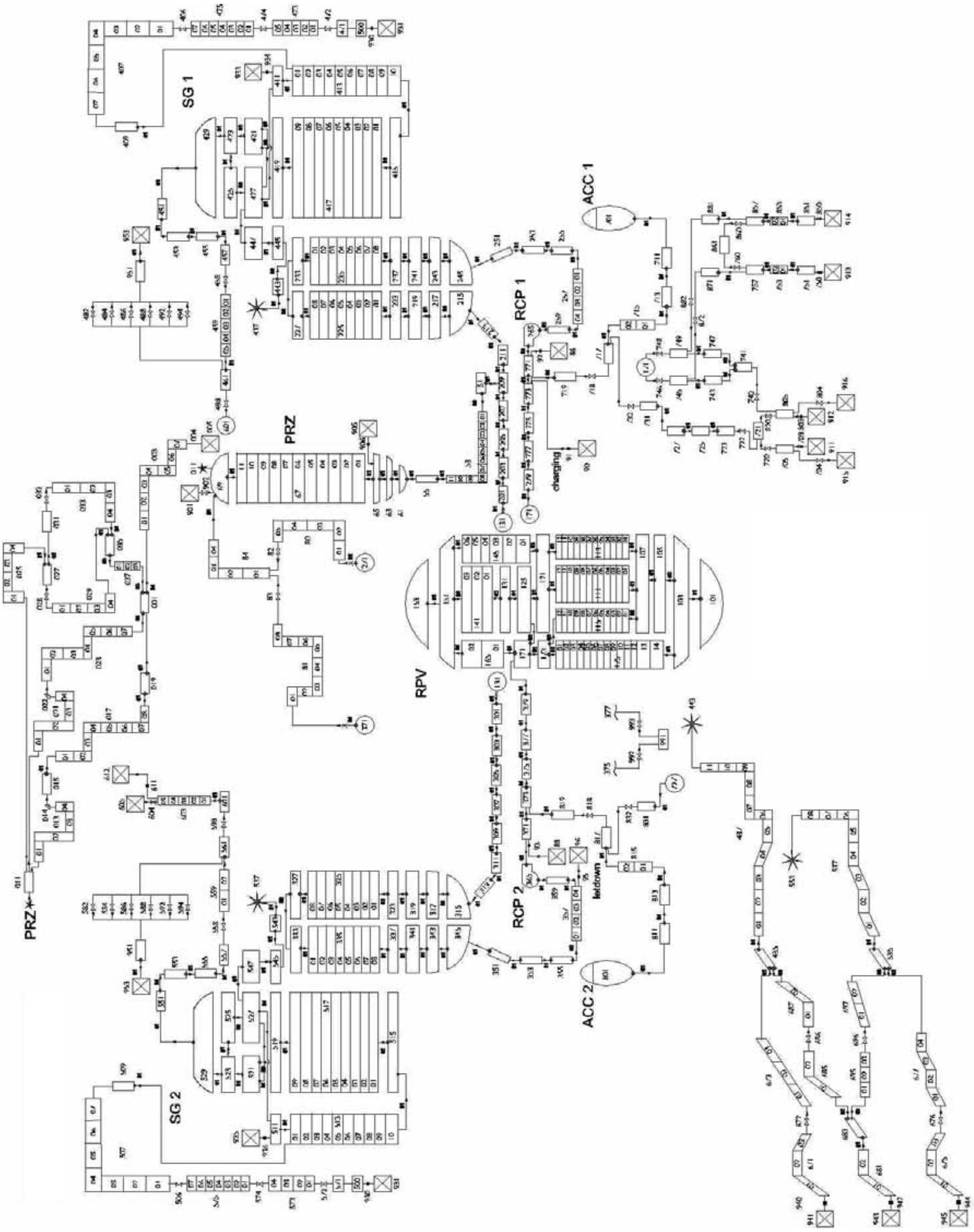
* skupaj z modelom sistema za zasilno hlajenje sredice
** skupaj z modelom zadrževalnega hrama

napajanja uparjalnikov, krmiljenje dušilnega obvoda pare itn. Večina pomožnih sistemov je zajeta le prek robnih pogojev. Standardni vhodni model NEK za program RELAP5/MOD3.3 za simulacijo male izlivne nezgode je sestavljen iz 497 vozlišč, povezanih s 469 spoji. Povečini so vozlišča dolga med 0,5 m in 2,5 m, z daljšimi so modelirani predvsem dolgi odseki, kot je npr. cev sistema za varnostno vbrizgavanje, prelivni vod, cevovod za prhe tlačnika, glavni parovod in cevovod sistemov glavne ter pomožne napajalne vode uparjalnikov. Strukture elektrarne so v stiku s primarnim in sekundarnim hladivom, zadrževalnim hramom in okolico preko 376 toplotnih teles. Merilna oprema, krmilni in varnostni sistemi so predstavljeni s 401 logičnim pogojem, tako imenovanimi prožitvami in 575 nadzornimi spremenljivkami. Osnovne značilnosti modela NEK za RELAP5/MOD3.3 so prikazane v preglednici 1. Nodalizacijska shema NEK za preračun male izlivne nezgode s programom RELAP5/MOD3.3 je prikazana na sliki 1.

5.2 Izbira scenarija

V računalniškem modelu NEK je bila mala izlivna nezgoda simulirana z zlomom velikosti 50,8 mm (2 palca) ustreznega premera v hladni veji na mestu med reaktorsko posodo in reaktorsko črpalko. Poleg velikosti zloma je treba pri scenariju določiti tudi število delujočih varnostnih sistemov in posege operaterjev. Pri naših izračunih smo povzeli vse potrebne avtomatske posege krmilja in varnostnih sistemov po obratovalnih navodilih za nezgodne dogodke NEK [20].

V predpostavljenem scenariju sta bili razpoložljivi obe progi sistema za varnostno



Sl 1. *Vozliščenje NEK za preračun male izlivne nezgode z RELAP5/MOD3.3*

vbrizgavanje in ohlajanje sredice; računali smo torej z nekonservativno predpostavko, da delujeta obe visokotlačni črpalki, oba akumulatorja in obe črpalki za nizkotlačno varnostno vbrizgavanje. Kot ponor toplote smo imeli na sekundarni strani na voljo sistem pomožne napajalne vode, ki je modeliran za vzdrževanje ravni uparjalnikov med 60 % in 70 %. Zaostalo toploto smo računali po standardu ANS-

79 [19], ki dejansko računa zaostalo toploto. V obravnavanem primeru je potek scenarija počasen, zato je poseg operaterjev en sam, in sicer ustavitev obeh reaktorskih črpalk, ko pade tlak pod 9,9 MPa, kakor to zahtevajo nezgodna obratovalna navodila.

Začetne razmere, predpostavke in glavne nastavitvene vrednosti varovalnega sistema ter krmilnih in varnostnih sistemov smo v analizi predvideli kakor se uporabljajo pri projektnih izračunih [21] in jih prikazujeta preglednica 2 in preglednica 3. Začetne vrednosti in nastavitve v RELAP5/MOD3.3 ustrezajo stanju elektrarne po posodobljenju uparjalnikov leta 2000 in jih določajo tehnične specifikacije NEK. Za vrednost pretoka hladiva skozi primarni sistem je vzeta majhna konservativna vrednost. Velja namreč ocena, da manjše razmerje pretoka skozi primarni sistem in pretoka visokotlačnega varnostnega vbrizgavanja v povratni kanal povzroči hitrejše ohlajanje gradiva reaktorske posode in nižjo temperaturo v povratnem kanalu. Moč reaktorja je 100 odstotna, prav tako tudi tlaki in nivoji ustrezajo vrednostim pri normalnem obratovanju pri 100 odstotni moči.

5.3 Izbira robnih pogojev analize

Po zamenjavi uparjalnikov in hkratnem povečanju moči je NEK začela postopoma delovati s polno močjo v okviru niza temperaturnih in tlačnih pogojev (delovno okno), medtem ko je smela prej elektrarna delovati s polno močjo le v eni točki tlak - temperatura. Varnostne analize za posodobljeno elektrarno morajo potrditi, da med prehodnimi pojavi in nezgodami ostanejo vsi pogoji znotraj meja in meril sprejemljivosti za delovno okno. V sedaj veljavnem, posodobljenem varnostnem poročilu NEK USAR (Updated Safety Analysis Report) [22], so zbrane informacije o zgradbi, predstavljene so projektne osnove in delovne omejitve ter analize struktur, sistemov in komponent ter analize obnašanja elektrarne med predpostavljenimi prehodnimi pojavi ali nezgodami.

V predstavljeni študiji smo se osredotočili na nekaj domnevnih kritičnih primerov med malo izlivno nezgodo, ki smo jih izbrali na podlagi delovnega okna in mejnih primerov, opisanih v varnostnem poročilu.

Preglednica 2. *Začetni pogoji modela za preračun male izlivne nezgode [16]*

PARAMETER	PODATKI PO MODELU BE*	RELAP5/MOD3.3
1. Tlak (MPa)		
tlačnik	15,51	15,51
uparjalnik	5,6	5,7
zbiralnika	5,27	5,27
2. Temperatura (K)		
hladna veja	560,3	560,3
vroča veja	597,8	597,7
napajalna voda uparjalnikov	494,3	494,3
zbiralnik vode za menjavo goriva	310,0	310,0
3. Masni pretok (kg/s)		
sredica	8499,5	8428,5
hladna veja	4450,0	4408,8
glavni parovod	512,0	510,6
zgornji obvod v povratnem kanalu	44,5	43,3
spodnji obvod	356,0	345,9
vodilo krmilnega svežnja	170,0	171,6
4. Raven kapljevine (%)		
tlačnik	62,3	62,3
uparjalnik (ozko mer. obm.)	60,0	60,0
5. Moč (MW)		
sredica	1994,0	1994,0
uparjalnik	941,0	938,8

* ravnovesni model elektrarne

Preglednica 3. *Začetne predpostavke za preračun male izlivne nezgode*

ZAČETNE PREDPOSTAVKE	
čas nastanka zloma	0 s
mesto zloma	hladna veja med črpalko in reaktorsko posodo
Razpoložljivost varnostnih sistemov	
visokotlačno varnostno vbrizgavanje	2/2
zbiralnika	2/2
nizkotlačno varnostno vbrizgavanje	2/2
pomožna napajalna voda uparjalnikov	2/2 (0/0)
glavni osamitveni ventil parovoda	avtomatsko
razbremenilni ventil tlačnika	avtomatsko
razbremenilni ventil uparjalnika	avtomatsko
ustavitev črpalke	ročno, 9,9 MPa
sproščanje zaostale toplote	ANS-79 U^{235} standard
porazdelitev moči	kosinusna, 17. krog, EOL
reaktorski varovalni sistem	dejanske zakasnitve
začepljenost	0 %

Varnostno poročilo in tehnične specifikacije NEK predpisujejo za vsa obratovalna stanja jedrske elektrarne dovoljena območja parametrov varnostnih sistemov, ki zagotavljajo njihovo varno posredovanje v primeru okvar ali nezgodnih stanj. Tako npr. tehnične specifikacije predpisujejo, da mora biti temperatura vode v zbiralniku vode za zamenjavo goriva, ki jo med izlivno nezgodo črpa visokotlačni sistem in vbrizgava v hladno vejo primarnega sistema, med 28 °C in 37 °C.

Pri danih začetnih predpostavkah in imenskih začetnih pogojih modela, ki jih določajo tehnične specifikacije NEK, smo najprej za izbrani scenarij z velikostjo ustreznega premera zloma 50,8 mm napravili osnovni preračun SBLO1. V nadaljnji študiji smo s spreminjanjem parametrov sistema za zasilno hlajenje sredice za zlom na istem mestu simulirali še dva scenarija male izlivne nezgode. Namen študije je bil oceniti najbolj kritične pogoje, ki se lahko pojavijo v povratnem kanalu reaktorske tlačne posode med varnostnim vbrizgavanjem pri simuliranih scenarijih. V drugem scenariju SBLO2 smo za preračune z RELAP5/MOD3.3 v tlačnih zbiralnikih sistema za zasilno hlajenje sredice izbrali najvišji dovoljeni tlak in najnižjo dovoljeno temperaturo. Sistem za visokotlačno varnostno vbrizgavanje je črpal iz zbiralnika vode za menjavo goriva vodo najnižje dovoljene temperature in jo z največjim dovoljenim pretokom vbrizgaval v hladno vejo. Kritični iztok skozi zlom smo popisali z največjim enofaznim oz. dvofaznim iztočnim koeficientom.

Velikost kritičnega iztoka je odvisna od koeficienta iztoka. Ker se tok spremeni iz enofaznega v dvofaznega, moramo upoštevati koeficient iztoka za obe fazi. Večji enofazni koeficient iztoka povzroči, da se skozi zlom izgublja več kapljevine, zato se sredica prej odkrije. Večji dvofazni koeficient iztoka pa ima dvojni vpliv: poleg večjega izgubljanja kapljevine se skozi zlom izgublja tudi več pare. Zaradi hitrejšega zniževanja primarnega tlaka sistem za zasilno hlajenje sredice dovaja več vode, zato se sredica bolj hladi.

Predvidevali smo, da utegne biti z vidika toplotnega prehodnega pojava pod tlakom zanimiv tudi scenarij SBLO3, v katerem smo največje dovoljene vrednosti vhodnih parametrov nadomestili z najmanjšimi in obratno. Rezultati simulacije SBLO2 in SBLO3 naj bi predvsem odgovorili na vprašanje, koliko so mejni izbrani vhodni parametri nevarni za nastanek toplotnega prehodnega pojava pod tlakom v reaktorski tlačni posodi. Robni pogoji za SBLO1, SBLO2 in SBLO3 so prikazani v preglednici 4, preostali začetni pogoji modela in predpostavke pa se v scenarijih niso spreminjali. Na voljo sta bili dve črpalki za visokotlačno varnostno vbrizgavanje in dva zbiralnika, vendar se je v vseh scenarijih sprožila le visokotlačna črpalka v veji št. 1, kjer je bil simuliran zlom. Kot ponor toplote je bila na voljo pomožna napajalna voda in dušenje pare v obeh uparjalnikih.

Preglednica 4. *Robni pogoji za analizo SBLO1, SBLO2 in SBLO3*

Robni pogoji		Imenski	Verjetnejši pojav topl. prehod. pojava	Negotovi pojav topl. prehod. pojava
Spremenljivka		**SBLO1**	**SBLO2**	**SBLO3**
tlak v zbiralniku		5,10 MPa	5,28 MPa	4,93 MPa
temperatura vode v zbiralniku		312 K	302 K	322 K
temperatura vode v zbir. za zamenjavo goriva		305 K	301 K	310 K
pretok sist. za visokotlač. vbrizg. (primerjalno)		1,0	1,05	0,95
iztočni koeficient	podhlajeni	0,89	1,11	0,66
	dvofazni	1,10	1,26	0,93

5.4 Analiza rezultatov

V nadaljevanju povzemamo analitično preverjanje strukturne celovitosti reaktorske tlačne posode. Zaporedje dogodkov za izbrane scenarije je opisano v preglednici 5.

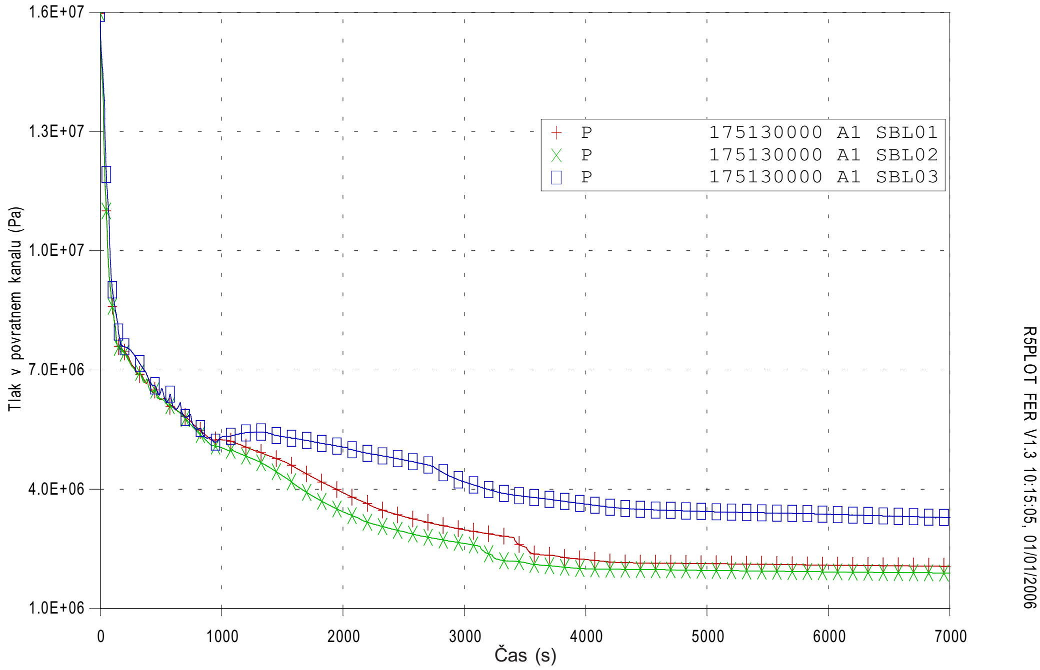
Pred začetkom prehodnega pojava je deloval reaktor s polno močjo. Ob času 0 s je bil simuliran v hladni veji št. 1 hipotetični zlom. Za boljši vpogled v simulirane prehodne pojave SBLO1, SBLO2 in SBLO3 so na slikah 2 do 5 predstavljeni nekateri pomembnejši sistemski parametri preračuna, čeprav RELAP5 omogoča opazovanje množice parametrov. Na sliki 2 je prikazan časovni potek tlaka v povratnem kanalu reaktorske tlačne posode za SBLO1, SBLO2 in SBLO3.

Začetno znižanje tlaka v primarnem sistemu z obratovalne vrednosti je zelo strmo. Pri vrednosti 12,9 MPa pride do hitre ustavitve reaktorja na nizek tlak v tlačniku. Hitra ustavitev reaktorja povzroči ustavitev turbine z zaprtjem njenih zapornih ventilov. Model NEK je zasnovan tako, da se zaradi ustavitve turbine zapre tudi dotok glavne napajalne vode. Ko se tlak zniža na 12,1 MPa, se sproži signal za varnostno vbrizgavanje. Signal za varnostno vbrizgavanje sproži varnostne sisteme. Najprej se sproži visokotlačno varnostno vbrizgavanje, ki ima vgrajeno 12 s zakasnitev in začne dovajati v primarni sistem hladno borirano vodo iz zbiralnika vode za zamenjavo goriva. Vse črpalke sistema za zasilno hlajenje sredice so povezane na sesalni strani z zbiralnikom vode za zamenjavo goriva kot začetni vir vode. Po njegovi izpraznitvi se z ročnim vodenjem zagotovi dotok vode iz zbiralnika zadrževalnega hrama.

Naslednja bi se sprožila pomožna napajalna voda, ki pa se sproži še na signal osamitve glavne napajalne vode. Ker se prej sproži signal za osamitev

Preglednica 5. *Zaporedje dogodkov za osnovni preračun SBLO1, SBLO2 in SBLO3*

Dogodek	Scenarij	SBLO1	SBLO2	SBLO3
odprtje zloma v hladni veji		0 s	0 s	0 s
ustavitev reaktorja/turbine		23 s	23 s	33 s
osamitev glavne napajalne vode		24 s	24 s	34 s
sprožitev signala za varnostno vbrizgavanje		35 s	35 s	47 s
tlačnik prazen		38 s	38 s	50 s
ustavitev reaktorske črpalke		127 s	127 s	145 s
izenačitev primarnega in sekundarnega tlaka		1100 s	980 s	1400 s
vbrizgavanje zbiralnikov		1180 s	1090 s	2090 s
nastanek/umaknitev parnega mehurja v glavi reaktorske posode		193 s / 3900 s	200 s / 3626 s	223 s / 3450 s
konec preračuna		7000 s	7000 s	7000 s



Sl. 2. *Časovni potek tlaka v povratnem kanalu reaktorske posode*

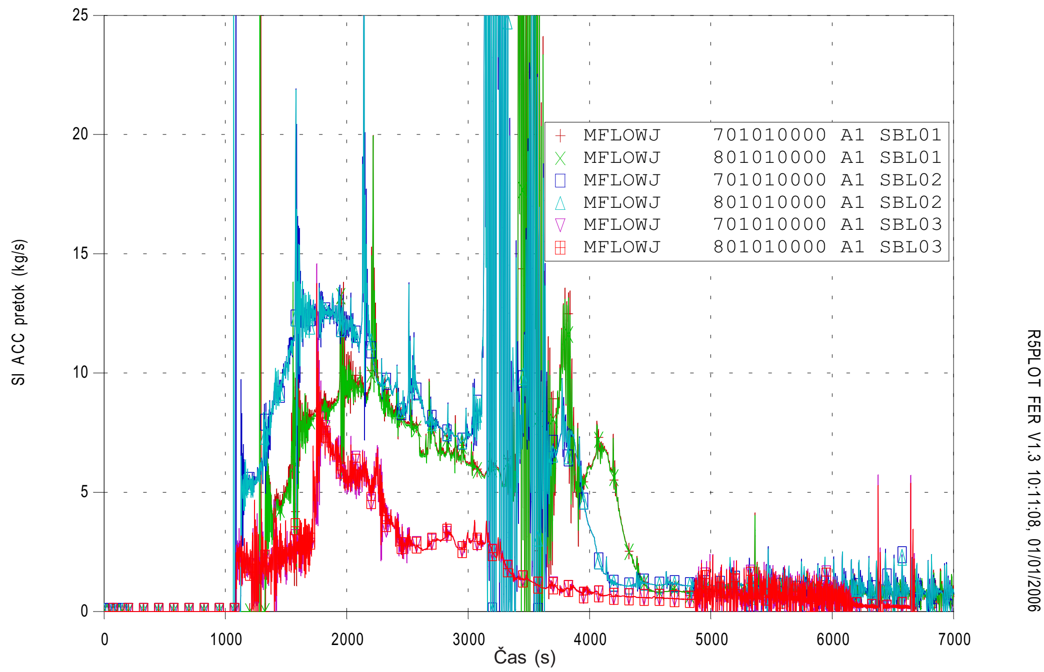
glavne napajalne vode kakor pa signal za varnostno vbrizgavanje, se črpalke za pomožno napajalno vodo vklopijo na signal za osamitev glavne napajalne vode z vgrajeno zakasnitvijo 20 s po prejemu signala. Namen pomožne napajalne vode je med drugim tudi ohranjati uparjalnike kot ponor toplote, ki iz primarnega sistema odstranijo nakopičeno in zaostalo toploto. Uparjalnika morata biti razpoložljiva vse dotlej, dokler vse zaostale toplote ne odvajamo samo skozi poškodovano mesto.

Pretok hladiva skozi zlom je omejen s kritičnim iztokom, zato je s tem omejeno tudi odvajanje toplote. Toplota, ki se ne more odvesti skozi zlom, se odvede na sekundarno stran uparjalnika. Tlak v primarnem sistemu je krmiljen s temperaturo vode na sekundarni strani uparjalnika. Pogoj za ohlajanje reaktorskega hladiva je, da je tlak na sekundarni strani manjši od tlaka v primarnem sistemu, ker je v pogojih med malo izlivno nezgodo tlačna razlika merilo za temperaturno razliko.

Ob nadaljnjem zniževanju tlaka pri 9,9 MPa operater ročno ustavi reaktorsko črpalko v skladu z nezgodnimi obratovalnimi navodili. Ko dosežemo pogoje nasičenja v najbolj vročem delu primarnega hladila, začne v pokrovu reaktorske posode rasti parni mehur, ki v naslednji fazi igra vlogo tlačnika in uravnava tlak v primarnem sistemu. Zaradi zmanjševanja pretoka v primarnem sistemu je odvod toplote na sekundarno stran postopoma zmanjšan. Ko se parni mehur v pokrovu reaktorske posode zveča toliko, da doseže priključek vroče veje, je s tem začasno ustavljen naravni obtok primarnega hladiva. V primarnem krogu ostane kapljevina le v spodnjem delu reaktorske posode in v najnižjem delu hladne veje med črpalko in uparjalnikom. To vodno zaporo imenujemo tesnilo zanke.

Nastajanju in praznjenju tesnila zanke dvofazne mešanice v sifonu hladne veje je v literaturi posvečene precej pozornosti ([23] do [25]), saj razvoj tega pojava pri mali izlivni nezgodi bistveno vpliva na potek dogodkov v sredici, še posebej na čas, ko je sredica odkrita. Dokler se tesnilo zanke ne odzrači, je mesto zloma poplavljeno in para ne more doseči zloma, s tem pa se ne more znižati tlak primarnega sistema, ampak je enak tistemu na sekundarni strani. Do tedaj izteka iz primarnega sistema veliko podhlajene kapljevine in sredica se začne odkrivati ter segrevati. Vezna posoda, ki jo sestavljajo sifon hladne veje, povratni kanal in reaktorska posoda, se prazni skozi zlom, dokler para ne prebije tesnila zanke. Voda, ki se je do tedaj zadrževala v povratnem kanalu, poplavi sredico in ustavi njeno morebitno pregrevanje. Raven v reaktorski posodi se ustali malo više, kakor je dno sifona v hladni veji.

Ko se zlom odkrije, se poveča odvod zaostale toplote skozi zlom in tlak v primarnem sistemu se zniža, dokler se pri nastavitvenih vrednostih za



Sl. 3. *Pretok vbrizgavanja zbiralnikov v hladni veji primarnega sistema*

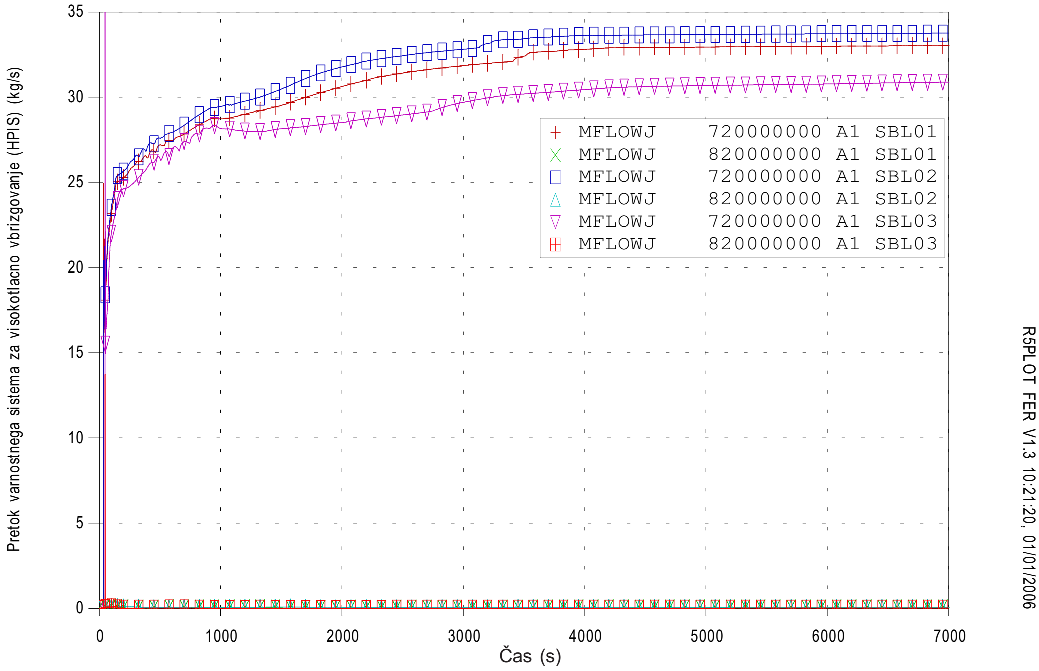
posamezne scenarije iz preglednice 4 zaradi višinske razlike ne izlije v primarni sistem velika količina hladne borirane vode iz pasivnih zbiralnikov. Slika 3 prikazuje pretok vbrizgavanja zbiralnikov v obeh vejah za scenarije SBLO1, SBLO2 in SBLO3. S slike je razbrati, da se v skladu z robnimi pogoji v preglednici 4 najprej sprožita zbiralnika v scenariju SBLO2 in najkasneje pri SBLO3. Kakor je razvidno s slike 3 se nobeden od zbiralnikov v preizkusu ni popolnoma izpraznil. Tlak v zbiralniku namreč nadzorujejo z dotokom dušika, ki pa ne sme zaiti v primarni sistem. Ker je dušik neukapljiv v razmerah, v katerih obratuje jedrska elektrarna, bi se lahko nabiral v nekaterih delih sistema in oviral ali popolnoma zaustavil naravni obtok primarnega hladiva.

Vbrizgavanje zbiralnikov še dodatno pospeši znižanje tlaka. Po vključitvi zbiralnikov prihaja v povratnem kanalu reaktorske posode do izrazito neravnovesnega termohidrodinamičnega fizikalnega pojava, saj se večja količina hladne vode iz zbiralnikov na razmeroma majhnem prostoru meša z nasičeno kapljevino iz hladne veje, vsebina pa odteka v povratni kanal in delno skozi zlom [15]. V tej fazi preizkusa lahko spremljamo izrazita nihanja dvofaznega kritičnega pretoka skozi zlom, te pričajo o burnih tridirazsežnih pojavih v zgornjem delu povratnega kanala reaktorske posode in pričakovati je bilo, da jih RELAP5/MOD3.3 ne bo mogel zadovoljivo poustvarjati.

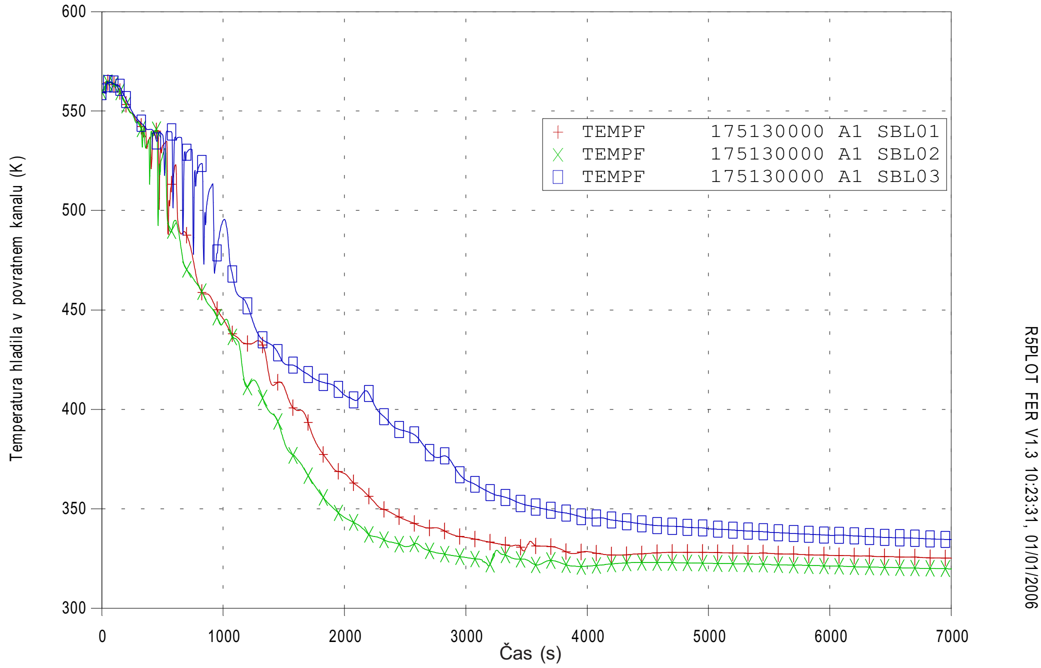
Omeniti velja še pomen zbiralnika, ki vbrizgava hladivo v hladno vejo št. 2. Izbrizgana hladna voda iz tega zbiralnika sicer ne more uiti neposredno proti zlomu in se zato vsebina tega zbiralnika popolnoma prelije v primarni sistem. Pomembno pa je, koliko vode odteče v sredico in koliko se je nateče v sifon hladne veje. Tako lahko tlak v primarnem sistemu za kratek čas zviša in vbrizgavanje zbiralnikov se upočasni ali za kratek čas ustavi.

Ker pa je nadaljnji potek preizkusa močno odvisen od tega, koliko hladne vode je iz zbiralnika odteklo naravnost v zlom in koliko po povratnem kanalu v sredico, je treba poudariti, da je pravilno modeliranje te faze nezgode odločujočega pomena. Od tega je namreč odvisna količina hladiva, ki po prenehanju vbrizgavanja iz zbiralnikov ostane v primarnem sistemu. Le tako je mogoče kasneje pravilno napovedati čas in sam mehanizem odkrivanja in pregrevanja reaktorske sredice.

V zadnji fazi lahko opazujemo sorazmerno umirjen prehodni pojav ob postopnem zmanjševanju masnega pretoka skozi zlom. Ko se masni pretok skozi zlom izenači z masnim pretokom, ki ga dobavlja črpalka za visokotlačno varnostno vbrizgavanje, se ustvari ravnovesje mase v primarnem hladilnem krogu in elektrarna se še naprej počasi ohlaja. Slika 4 prikazuje količino mase, ki smo jo vbrizgali v primarni sistem s črpalko za visokotlačno varnostno vbrizgavanje.



Sl. 4. P*retok sistema za visokotlačno vbrizgavanje v hladno vejo*



Sl. 5. *Časovni potek ohlajanja hladiva v spodnjem delu povratnega kanala*

Krivulja + pomeni časovni potek za SBLO1, □ za SBLO2 in ∇ za SBLO3. Prav tako je s slike razvidno, da se visokotlačna črpalka v veji št. 2 v nobenem scenariju ni sprožila.

Po približno 4000 s se vzpostavi toplotno ravnovesje, saj zlom in sistem za varnostno vbrizgavanje odvajata vso zaostalo toploto. Stanje je stabilno, saj je sredica pokrita, tlak je stabilen in uparjalnika nista potrebna za hlajenje. Voda iz sistema za visokotlačno varnostno vbrizgavanje zadošča za hlajenje sredice, zato je po 7000 s računanje končano. Ob odvajanju zaostale toplote skozi zlom dosežemo parametre elektrarne, pri katerih lahko začneta črpalki sistema za nizkotlačno varnostno vbrizgavanje dovajati v primarni sistem velike količine hladne vode. S tem se zopet vzpostavi povratni obtok in zagotovi dolgoročno hlajenje sredice.

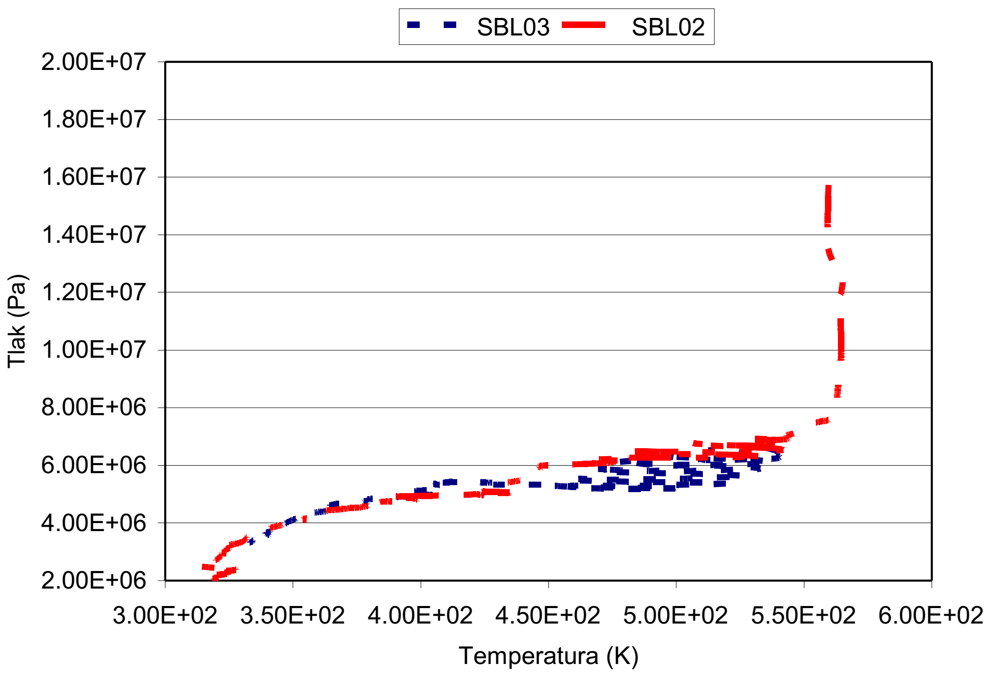
Ker potrebuje mehanika loma za svoje preračune poleg tlaka v primarnem sistemu še temperaturni potek v povratnem kanalu, si oglejmo še najpomembnejše temperaturne poteke, ki smo jih ob danih robnih pogojih preračunali za posamezne scenarije s programom RELAP5/MOD3.3.

Slika 5 prikazuje časovne poteke temperature hladiva v spodnjem delu povratnega kanala za SBLO1 (označeno s +), SBLO2 (označeno z X) in SBLO3 (označeno s □). Primerjajmo časovne poteke temperature v povratnem kanalu reaktorske posode za izbrane scenarije s tlačnimi (sl. 2). Zadošča primerjava za 3000 s simuliranih scenarijev male izlivne nezgode, ker dejansko ocenjujemo, da obstaja v tem času največja verjetnost za pojav morebitnega toplotnega prehodnega pojava pod tlakom. Očitno je, da so časovne spremembe temperature, ki so bistvene za nastanek toplotnega prehodnega pojava pod tlakom, večje v primeru SBLO2, saj je v tem primeru odvod dT/dt skoraj povsod bolj negativen kakor pri SBLO3.

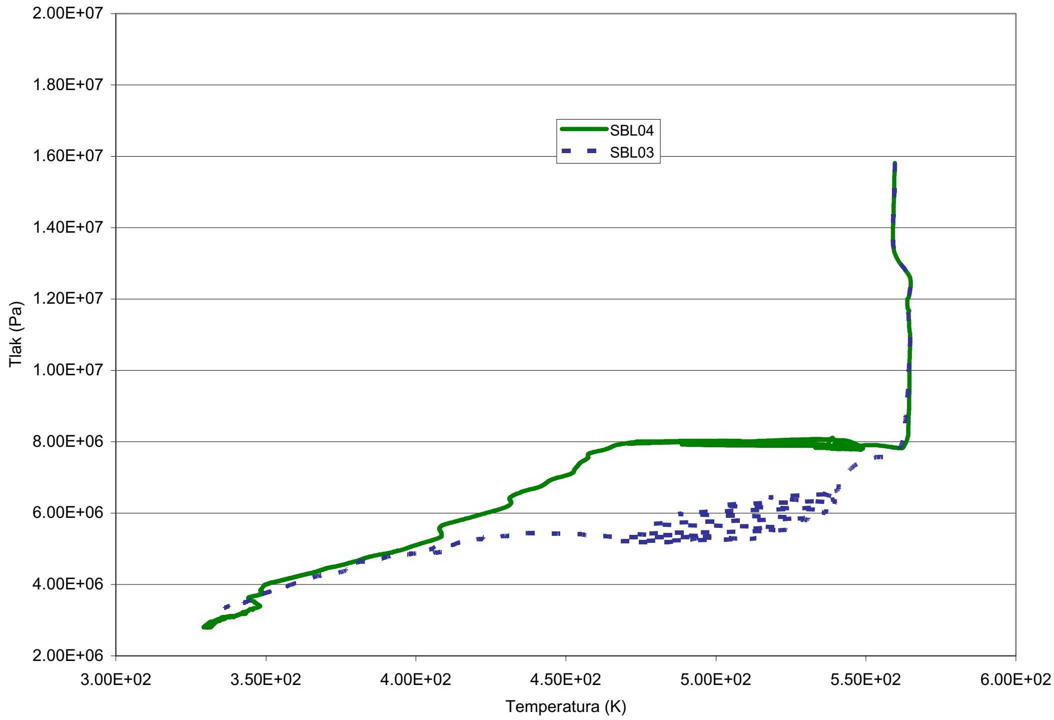
5.5 Uporaba preračunov za reaktorsko tlačno posodo

Namen študije je bil oceniti najbolj kritične pogoje, ki se lahko pojavijo v povratnem kanalu reaktorske tlačne posode med varnostnim vbrizgavanjem pri simuliranih scenarijih male izlivne nezgode. S časovnimi poteki tlaka (sl. 2) in temperature (sl. 5) izrazimo tlak v povratnem kanalu kot funkcijo temperature (okoli 4000 podatkov za scenarij dolg 7000 s), kar prikazuje slika 6.

S slike je razvidno, da je SBLO2 hujši primer kakor SBLO3, saj lahko ocenimo, da se v najbolj kritični točki scenarija SBLO2 za nastanek toplotnega prehodnega pojava pod tlakom ohladi voda v povratnem kanalu reaktorske tlačne posode za 92 K pri tlaku 6,16 MPa, medtem ko se pojavi v scenariju SBLO3 najbolj kritični trenutek pri nižjem tlaku 5,4 MPa, ko se voda ohladi le za 90 K. Slika tudi prikazuje, da je v področju tlakov med 6,5 MPa in 5,5 MPa temperatura vode v povratnem kanalu reaktorske posode povsod nižja v scenariju SBLO2. Druge izrazite temperaturne oscilacije pri SBLO2 in SBLO3, ki se pojavijo pri danih tlačnih vrednostih zaradi odvajanja pare skozi razbremenilne ventile uparjalnika, ne pomenijo mogoče nevarnosti za pojav toplotnega prehodnega pojava pod tlakom.



Sl. 6. *Tlak v povratnem kanalu v odvisnosti od temperature pri SBLO2 in SBLO3*



Sl. 7. *Odvisnost tlaka od temperature v povratnem kanalu pri SBLO3 in SBLO4*

Rezultati simulacije so jasno odgovorili na vprašanje, da so izbrani mejni vhodni parametri scenarija SBLO2 nevarnejši za toplotni prehodni pojav pod tlakom kakor izbira parametrov pri SBLO3. Mnoge študije so pokazale, kako pomembna blažitvena naprava je v primeru majhne izlivne nezgode sistem pomožne napajalne vode, ki zagotavlja ponor toplote iz uparjalnikov [4]. Zato smo pričakovali zanimive sklepe tudi pri spremenjenem scenariju SBLO4, v katerem smo predpostavili, da pomožna napajalna voda ni razpoložljiva. To pomeni, da smo izgubili ponor toplote na sekundarni strani in da se zaostala toplota lahko odvaja le skozi zlom, medtem ko so začetni pogoji modela in predpostavke ostale prav takšne kakor pri SBLO3. Odvisnost tlaka od temperature v povratnem kanalu reaktorske posode za izbrana scenarija prikazuje slika 7.

S slike je razvidno, da se v najbolj kritični točki scenarija SBLO4 za pojav toplotnega prehodnega pojava pod tlakom ohladi voda v povratnem kanalu reaktorske tlačne posode za 95 K pri bistveno višjem tlaku 8 MPa, ker ni prišlo do polnjenja uparjalnika in odvajanja toplote skozi razbremenilne ventile sekundarnega kroga. Tako lahko sklenemo, da je ta primer morda še nevarnejši za pojav toplotnega prehodnega pojava pod tlakom v gradivu reaktorske posode kakor SBLO2, pri katerem so bili robni pogoji izbrani kot verjetnejši za pojav toplotnega prehodnega pojava pod tlakom, vendar je deloval sistem pomožnega napajanja uparjalnikov.

6 SKLEP

Rezultati študije kažejo uspešnost izračuna termohidravličnega računalniškega programa RELAP5/MOD3.3 na področju izbora mejnih prehodnih pojavov in scenarijev (vključno z odzivom celotne elektrarne in njenih varnostnih ter pomožnih sistemov), potrebnih za mehanske in trdnostne analize toplotnega prehodnega pojava pod tlakom v tlačnovodnih jedrskih elektrarnah, predvsem pri ocenjevanju negotovosti vhodnih parametrov (p in T kot funkciji časa ali izbira najbolj kritičnih vrednosti odvodov dT/dt ter dT/dp). Pomembnost uporabe sistemskega orodja RELAP5/MOD3.3 se je pokazala predvsem pri vzpostavitvi zanesljivih temperaturnih in tlačnih robnih pogojev v izbranem kritičnem delu (področje reaktorske posode, ki je izpostavljeno nevtronskemu fluksu in zvari posameznih delov) pri analizi zapletenega modela primarnega kroga in medsebojnega vpliva niza pomožnih sistemov (krmiljenje tlaka v tlačniku, vbrizgavanje varnostnih zbiralnikov ali sistema za visokotlačno vbrizgavanje, delovanje sistema pomožne napajalne vode uparjalnikov ipd). Poudariti pa moramo, da bi bilo potrebno za podrobnejšo analizo spreminjati še dodatne parametre za ocenjevanje temperaturnega gradienta skozi gradivo reaktorske posode, kakor je npr. koeficient toplotne prestopnosti med vodo in gradivom ter gradivom in izolacijo oz. okolico.

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Ocena natančnosti satelitske navigacije pri upravljanju naravnih virov

An Accuracy Assessment of Satellite Navigation in Natural-Resource Management

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Prispevek obravnava možnosti uporabe navigacijske tehnologije satelitskega določanja lege (SDL - GPS) pri upravljanju z naravnimi viri. Nastal je na podlagi rezultatov SDL prikazov zemljišč na približno 30 krajih v Baranji (vzhodna Hrvaška). Sprejemniki SDL so bili uporabljeni predvsem za določanje lege izbranih zemljišč. Dinamičnega kartiranja zemljišč nismo spremljali. Raziskave smo se lotili z namenom, da bi dogradili svoje znanje o delu s podatki SDL, o vključevanju sistema SDL v sistem zemeljskega informacijskega sistema ter preizkusili delovanje bolj natančnega sistema diferencialnega satelitskega določanja lege (DSDL). Raziskali smo razlike med podatki, pridobljenimi s tremi metodami določanja lege v prostoru: a) georeferenčnoim zračnim fotografiranjem (AERO), b) standardnim signalom SDL, in c) popravljenim signalom DSDL. Glede na referenčno vrednost smo ugotovili sistematično odstopanje in polmer napake (rezultati DSDL). Ugotavljanje razlik med metodama SDL in AERO ni dalo statistično pomembnih razlik. Glede na rezultate raziskave moramo povzeti, da lahko metodo SDL uspešno uporabimo pri kartiranju zemljišč ter tudi sicer pri prepoznavanju drugih naravnih virov. Določanje lege z nekorigiranim signalom SDL omogoča enako dobro ali celo večjo natančnost določitve lege, kakršno dobimo z zračnimi fotografijami v povprečnem merilu 1:20.000. Uporaba satelitskega določanja lege je odvisna od potreb posameznih uporabniških skupin, pri čemer so posebno pomembni vidiki natančnosti, polmera 95% verjetnosti, zanesljivosti rezultatov in izvedljivosti.

(Ključne besede: navigacija satelitska, satelitsko določanje lege, kmetijstvo usmerjeno, upravljanje z gozdovi, ocena natančnosti)

This article deals with the possibilities of applying GPS navigation technology to the management of natural resources. It is based on the results of GPS soil mapping at about 30 locations in Baranja (eastern Croatia). The GPS receivers were used primarily for the positioning of the soil-sampling sites. Dynamic mapping was not monitored. The practical purpose of the research was to learn more about working with GPS data, integrating GPS into geographic information system (GIS), and testing the possibilities of the more precise Differential GPS (DGPS). The differences between the data obtained using three methods of point positioning in space were tested: a) geo-referenced aerial photographs (AERO), b) a standard GPS signal, and c) a corrected DGPS signal. A systematic deviation and an error radius were established with respect to the reference value (the DGPS results). Testing the difference between the GPS and AERO did not show any statistically significant difference between these two methods. According to the results of the research, GPS positioning can be successfully applied to soil mapping and to natural-resource inventories in general. Positioning with an uncorrected GPS signal provides equal or better positioning accuracy than that obtained from aerial photographs at an approximate scale of 1:20,000. The use of satellite positioning depends on the needs of a given user group, where aspects relating to precision, a 95% probability radius, the reliability of results and the feasibility are of particular importance.

(Keywords: satellite navigation, GPS, precision agriculture, forest management, accuracy assessment)

0 UVOD

Navigacijski sistemi SDL postajajo vse bolj popularni, saj so lahko v pomoč pri zelo različnih

0 INTRODUCTION

GPS (Global Positioning System) navigational systems are becoming increasingly dejavnostih. Sisteme, kakor na primer Trimble's AVL (avtomatsko lociranje vozila), pogosto uporabljajo policija, zdravstveno reševalna služba, druge reševalne službe, gasilske čete, pa tudi mnogi drugi strokovnjaki, ki želijo zanesljivo in hitro doseči kraj nesreče. Zaradi načina sledenja reševalnim vozilom s SDL, ki so ga uvedli v Chicagu, je reševalna služba v tem mestu postala veliko bolj učinkovita in zanesljiva. Dve taksi družbi v Avstraliji sledita svojim taksistom s tehnologijo SDL in sta zaradi novega načina dela že povečali svoj dobiček. Neka ribolovna družba na Novi Zelandiji uporablja SDL pri usmerjanju ladij, ki se tako na svoje začetne lokacije lahko vrnejo brez zamudnega izgubljanja smeri. V Skandinaviji pa so razvili alarmni sistem, ki omogoča hitro in učinkovito zdravstveno pomoč pri nesrečah v gozdovih [1]. Na Hrvaškem se SDL uporablja za sledenje medvedov, volkov in risov, da bi zagotavljali nadzor nad premiki velikih zveri [2]. Da bi čim bolj zmanjšali število poškodb, ki jih povzroči gozdarska mehanizacija, se SDL uporablja tudi za prepoznavo površin s težko zemljo, ki tlači gozdni ekosistem.

Zamisel o uporabi satelitskega določanja lege, ki bi nadomestilo sedanji radijski ali radarski sistem, se je pojavila v sedemdesetih letih prejšnjega stoletja. V začetku so te sisteme določanja lege razvijali predvsem za vojaške namene in je bila njihova raba lokalno omejena. Predhodniki modernega sistema SDL so »Omega«, kasneje pa tudi "Loran-C" in "Transit". Čeprav so ga razvijali predvsem v vojaške namene, je SDL od leta 1978 rabljen tudi v civilne namene. Ob koncu leta 1983 je predsednik Reagan odobril uporabo tako-imenovanega »standardnega določanja lege« (Standard Positioning Service – SPS) z naključnim odstopanjem 100 metrov za civilne potrebe. Od zgodnjih devetdesetih let prejšnjega stoletja se je trg SDL večal z izjemno hitrostjo, ki v mnogih pogledih spominja na razmah uporabe interneta.

0.1 Satelitski navigacijski sistemi

SDL temelji na delovanju 24 satelitov, ki jih upravlja *obrambno ministrstvo ZDA*. Ti sateliti krožijo okoli Zemlje na povprečni višini 20.200 km in s povprečnim obhodnim časom 12 h. Na ta način so, s katerekoli točke na 95% Zemljine površine, izmed desetih satelitov najmanj štirje sateliti »vidni« 24 ur dnevno. Merjenje lege sprejemnika v trirazsežnem sistemu temelji na izračunu vektorja razdalje – med satelitom in sprejemnikom. Tu ima najpomembnejšo vlogo osnovni del satelita –

popular with many people taking part in a variety of activities. Systems such as Trimble's AVL (Automatic Vehicle Location), for example, are widely used by the police, emergency medical services, search-and-rescue services, fire brigades, but also by many others who want to reach the scene of an accident both reliably and quickly. The GPS emergency-vehicle tracking system introduced in Chicago has made the 911 service more efficient and reliable. Two taxi companies in Australia now track their taxi drivers with GPS and are already increasing their profits. A New Zealand fishing company uses GPS to facilitate the return of its ships to the same locations without unnecessary straying off course. A GPS alert system has been developed in Scandinavia to provide rapid and efficient medical aid to the casualties of forestry accidents [1]. Croatia uses a GPS system to track the movement of bears, wolves and lynxes for the purpose of large-game management [2]. To minimize the damage due to forestry mechanization, a GPS is used to map the areas of heavy soil trampling in forest ecosystems.

The idea of using a satellite positioning system as opposed to existing radio and radar systems was born in the 1970s. In the beginning, these positioning systems were developed primarily for military purposes and were of local character. The predecessors of the modern GPS are "Omega", and more recently "Loran-C" and "Transit". Although developed primarily for the military, GPS began to be used for civilian purposes in 1978. In late 1983, president Reagan authorized the use of the so-called Standard Positioning Service (SPS) with an uncertainty of about 100 m for civilian use. Since the early 1990s, the GPS market has been growing at an exponential rate, similar in many ways to the expanding use of the internet.

0.1 Satellite Navigation Systems

GPS is based on 24 satellites maintained by the *US Department of Defense*. These satellites orbit the earth at a mean altitude of about 20,200 km, with a mean orbit time of 12 h. In this way at least four (of ten) satellites are "visible" 24 hours a day from any position on 95% of the Earth's surface. Measuring the position of the receiver in the 3D system is based on the measurement of a distance vector – from the satellite to the receiver. Here, the most important role is played by the fundamental part of the satellite – the atomic clock – which measures atomska ura – ki meri čas v milijoninkah sekunde (čas, ki je potreben, da elektromagnetni val naredi pot od satelita do Zemlje znaša približno 0,07 sekunde). Ker poznamo ta čas, lahko vektor poti (d) izrazimo na dva načina:

the time in millionths of seconds (the time needed for the electromagnetic wave to cover the distance from the satellite to the earth is of the order of 0.07 seconds). With a knowledge of this time, this vector (d) of the route can be expressed in two ways:

$$d = \sqrt{(X_s - X_p)^2 + (Y_s - Y_p)^2 + (Z_s - Z_p)^2} = c \cdot (t - \Delta t) \quad (1),$$

kjer so:
X_s, Y_s, Z_s prostorske koordinate satelita in X_p, Y_p, Z_p prostorske koordinate sprejemnika,
c je hitrost elektromagnetnih valov,
t je čas potreben, da elektromagnetni val naredi pot od satelita do sprejemnika
Δt je napaka ure v sprejemniku.

Za določitev neznank v enačbi (*Xp, Yp, Zp,* Δt) so potrebne najmanj štiri neodvisne enačbe istega tipa. In prav zato je SDL organiziran tako, da so ob kateremkoli času iz katerekoli točke na Zemlji vidni vsaj štirje sateliti.

Vsak satelit oddaja tri vrste binarnih kodiranih sporočil (takoimenovana psevdonaključna sporočila):
a) C/A označuje grobo oceno
b) P označuje natančnost
c) Y označuje stanje

Kodni sporočili C/A in P sta pri vsakem satelitu drugačni, tretja koda, Y, pa je signal, ki prenaša podatke o legi satelita v danem trenutku. Te tri kode se prenašajo na dveh mikrovalovnih frekvencah: na pasu L1 (1575,42 MHz) in na L2 (1227,60 MHz). Pas L2 prenaša podatke o natančnosti (P), kar omogoči natančnost določitve lege na vsaj 22 m. Ta signal je trenutno dosegljiv le pooblaščenim uporabnikom (vojska in nekatere gospodarske družbe) [3].

where:
X_s, Y_s, Z_s are the spatial satellite coordinates, and X_p, Y_p, Z_p are the spatial receiver coordinates,
c is the speed of the electromagnetic waves,
t is the time needed for the electromagnetic wave to travel from the satellite to the receiver
Δt is the clock error in the receiver.

To determine the unknowns in the equation (*Xp, Yp, Zp,* Δt), a minimum of four independent equations of this form are needed. It is for this reason that GPS is organized so that at least four satellites are visible at all times from any position on earth.

Each satellite in fact broadcasts three types of binary codes (the so-called Pseudo Random Codes):
a) C/A or Coarse Acquisition
b) P or Precision
c) Y or Status Information

The C/A and P codes are specific to each satellite, while the third, Y, signal carries the data relating to a satellite's position at any given moment. These three code types are broadcast on two microwave frequencies: the L1 band (1575.42 MHz) and the L2 band (1227.60 MHz). The L2 band carries the data of the precise code (P), which enables a positioning accuracy of at least 22 m. This signal is currently available only to authorized users (the military and some companies) [3].

0.2 Tržne usmeritve

Mednarodni trg popolnoma obvladujejo ameriške naprave SDL. Zato je razumljivo, da je v literaturi drugih narodov satelitska navigacija pogosto imenovana kar SDL. Podobno kakor digitalna informacijska oprema je tudi SDL v zadnjih letih postalo pomemben del vsakodnevnega življenja. Uporabniki in izvedbe tehnologije SDL so prikazani v preglednici 1.

Največji trg za uporabe SDL nedvomno predstavljajo kopenska navigacija (tovornjaki, traktorji in osebna vozila) in potrošne dobrine. Kopenska navigacija, sprejemniki mobilnih telefonov, osebni računalniki, rekreativne in druge podobne dejavnosti trenutno zavzemajo približno 60% trga z napravami za SDL. Sickle [5] predvideva, da bo v prihodnosti vsako

0.2 Commercial trends

The international market is completely dominated by the American GPS. It is understandable, therefore, that in foreign literature satellite navigation is often referred to as GPS. In recent years GPS has increasingly become a part of everyday life, in a similar way to digital information equipment. The basic user groups and applications are presented in Table 1.

Clearly, the largest market for GPS applications is land-based navigation (trucks, tractors and personal vehicles) and consumer goods. Currently, land-based navigation, mobile-phone receivers, PCs, recreation and others account for about 60% of the GPS market. According to Sickle [5], there will come a time when every vehicle, whether

Preglednica 1. *Glavna področja uporabe SDL, razpon stroškov sprejemnika in ocena velikosti celotnega trga [4]*
Table 1. *Main groups of GPS applications, range of receiver costs and estimation of total market size [4]*

Področja uporabe Group of applications	Razpon stroškov sprejemnika v USD Range of receiver costs in $	Skupno število modelov / gospod.družb (pribl.) Total models /companies (app.)	Celotna velikost trga v milijonih USD (1994) Total market size in millions of $ (1994)
kopenska navigacija land-based navigation	299 do/to 82.000	200 / 35	180
geodezija land surveying	355 do/to 82.100	102 / 34	145
aeronavtična navigacija aeronautical navigation	355 do/to 60.000	144 / 30	62
navtična navigacija nautical navigation	299 do/to 60.000	166 / 43	100
neposredno trženje consumer direct market	-	-	-

vozilo – osebno, javno, policijsko ali transportno – uporabljalo satelitski navigacijski sistem.

Ocena števila prodanih sprejemnikov SDL v Evropi dosega stotine tisočev prodanih enot, na Hrvaškem pa je to število še vedno neznatno.

0.3 Napake SDL in njihovi viri

Nekatere mogoče vire napak SDL lahko razdelimo v dve skupini:

a) Sistemske napake: na primer napake atomske ure, atmosferske zakasnitve (zamuda signala, ki jo

civilian or public, police or transport, will be using a satellite navigation system.

The number of GPS receivers sold in Europe is estimated at hundreds of thousands; however, in Croatia this number is still insignificant.

0.3 GPS errors and their sources

Some possible sources of GPS errors can be divided into two groups:

a) System errors: for example, satellite-clock errors, atmospheric delay (delayed signal caused by

Preglednica 2. *Tipi SDL*
Table 2. *Types of GPS positioning*

Tip določanja lege Type of positioning	Približna vodoravna natančnost (polmer 95% verjetnosti) Approximate horizontal accuracy (95% probability radius)		Približna cena (USD) Approximate price ($)
	idealna* ideal*	povprečna mean	
SDL – standardni sistem, (enkratna določitev položaja) SPS – standard system, (single fix)	50 m	100 m	100 do/to1000
SDL – standardni sistem, (povprečenje) SPS – standard system, (averaging)	30 m	50 m	100 do/to1000
DSDL – diferencialni sistem (<30 km) DGPS – differential system (<30 km)	1,3 m	< 5 m	1000 do/to5000
NDL – natančen sistem PPS – precise system	22 m	-	-
kombiniran sistem SDL-GLONASS (nediferenciabilen) Combined GPS-GLONASS (non-differentiated)	15 m		> 2000
zelo natančen sistem highly precise system	< 0,001 m		> 5000

* - na natančnost ne vplivajo sistemske napake, vplivajo le naključne napake, ki so majhne.
* - accuracy not affected by any system error but only by random errors, which are minimal.

povzročijo vplivi ozračja), izbiralna dostopnost (ID) in drugo.

b) Naključne napake: napake sprejemnikove ure, uporabniške napake in drugo.

Preglednica 3 vsebuje prikaz strukture napak SDL.

Očitno je največji delež napak povezan s sistemskimi napakami signala SDL. Ker se število napak SDL bistveno ne poveča v polmeru 30 km, lahko povečamo natančnost standardnega signala na en meter (v kombinaciji z izračunom povprečja), če poznamo natančni čas izračuna določene napake. Z uporabo krmilnega sprejemnika, ki z veliko natančnostjo meri koordinate na mestih, kjer so le-te poznane, je mogoče izračunati napako SDL za vsak merilni korak (ID, atmosferska zakasnitev). Ta metoda se imenuje diferencialno SDL (DSDL) in je trenutno najpogosteje uporabljena metoda določanja položaja v komercialnih uporabah. DSDL praviloma potrebuje najmanj dva sprejemnika. Poznamo dva glavna tipa metode DSDL:

a) DSDL v realnem času ali trenutna odprava napak (dva sprejemnika uporabljamo za odpravo napake – GSP in sprejemnik radijskih ali satelitskih signalov),

b) DSDL v času po obdelavi podatkov ali poznejša odprava napak.

atmospheric influences), selective availability (SA) and others.

b) Random errors: receiver-clock errors, errors caused by user handling and others.

A summary of the GPS error structure is presented in Table 3.

Clearly, the largest portion of all errors relates to system errors in the GPS signal. As the amount of GPS errors does not change substantially within a 30-km radius, knowing the exact time when a certain error has been calculated makes it possible to improve the standard signal to about a 1-m accuracy (in combination with averaging). Using a control receiver that measures the coordinates, where they are known, with a much higher precision, it is possible to calculate a GPS error for every measuring interval (SA, atmospheric delay). This method is called Differential GPS (DGPS) and is currently the most frequently used positioning method in commercial applications. As a rule, DGPS requires at least two receivers. There are two main types of DGPS:

a) Real-time DGPS or momentary error elimination (two receivers are used to eliminate an error – GPS and a receiver of radio or satellite signals),

b) Post-processing DGPS or subsequent error elimination.

Preglednica 3. *Viri napak SDL in njihove vrednosti. Standardne in popravljene (diferencialne) vrednosti*
Table 3. *GPS error sources and their values. Standard and corrected (differential) values*

Vir Source	Tipična vrednost satelita (m) Typical value per satellite (m)	
	Standardna Standard	Diferencialna Differential
atomska ura satellite clock	1,5	0
orbitalne napake orbital errors	2,5	0
ionosfera ionosphere	5,0	0,4
troposfera troposphere	0,5	0,2
šum (sprejemnik) noise (receiver)	0,3	0,3
‘večpotnost’ ‘multipath’	0,6	0,6
ID/SA	30	0
Idealna natančnost Ideal accuracy	Standardna Standard	Diferencialna Differential
vodoravna horizontal	50	1,3
navpična vertical	78	2,0
trirazsežna 3D	93	2,8

Najnaprednejši sistem, ki ga trenutno poznamo, oddaja popravni signal sprejemniku SDL po radijskih valovih. V razvitem svetu takšne sisteme razvijajo na državni ravni, obstojajo pa tudi številne mednarodne družbe, ki ponujajo tovrstne storitve (na primer, Omnistar prek satelita daje DSDL popravni signal na globalni ravni, torej pokriva tudi celotno območje Hrvaške). Po nakupu sprejemnika SDL in potrebnega dodatnega sprejemnika uporabnik ugotovi radijsko frekvenco lokalnega DSDL, na katero se mora mesečno ali letno prijaviti.

1 METODOLOGIJA

Da bi ugotovili možnosti navigacijskih uporab SDL na področju upravljanja z naravnimi viri, smo na približno 30 krajih v Baranji (vzhodna Hrvaška) izvedli raziskavo. Uporabljali smo sistem GARMIN, ki vključuje dva sprejemnika SDL – SDL 100 SRVY II. Glede na ceno (1.500 USD), sprejemnika sodita v srednji razred sprejemnikov SDL. Posamezni sprejemnik tehta približno 300 g, njegov zagonski čas je približno 2 minuti. Ugotavljali smo razlike med tremi metodami določanja lege v prostoru:

1. georeferenčnim zračnim fotografiranjem (AERO) v povprečnem merilu 1:20.000
2. standardnim signalom SDL
3. signalom DSDL – merilno povprečje 180 (interval = 1 s)

Prvi SDL je bil postavljen na kraj s poprej določenimi geodetskimi koordinatami (z merilno natančnostjo približno 0,5 m). To lokacijo smo poimenovali BAZA ali osnovna lokacija. Drugi sprejemnik SDL smo uporabljali za meritve na terenu (TEREN). Po opravljenem delu na terenu, smo podatke iz osnovnega in iz terenskega sprejemnika prenesli v računalnik in jih obdelali. Ker smo koordinate SDL vnesli v sistem geografskih koordinat (z elipsoidom WGS84), so bili izvirni podatki spremenjeni v lokalni Gauss-Kruegerjev sistem (Besslov elipsoid). Spremembo smo izvedli po metodi sedmih parametrov (Trimblovi parametri za področje celotne Hrvaške) [6].

Glede na specifikacije lahko rečemo, da popravljeni signal SDL (DSDL) doseže natančnost 1-5 m pri statičnih meritvah oziroma pri kartiranju zemljišča (povprečna vrednost, dobljena na osnovi več ko 180 posameznih odčitkov). Pri dinamičnih meritvah se natančnost zmanjša na 3 do 10 m. Na tej stopnji raziskave nismo izvedli dinamičnega kartiranja

Today, the most advanced system involves broadcasting a correction signal to a GPS receiver via radio waves. In the developed world, such systems are being developed at the state level, but there are also a number of international companies that provide such services (for example, Omnistar offers a DGPS correction signal via a satellite at the global level, covering the whole territory of Croatia as well). After determining the radio frequency of the local DGPS, when purchasing an additional receiver with the GPS receiver, the user must also subscribe (monthly or annually) to the frequency.

1 METHODOLOGY

In order to investigate the possibilities of GPS navigation applications in natural-resource management mapping, research was conducted at about 30 locations in Baranja (eastern Croatia). The GARMIN system of two GPS receivers – GPS 100 SRVY II – was used in the investigation. These receivers belong to the medium class of GPS receivers in terms of price ($1,500). The receiver weighs about 300g, and its initiation time is about 2 minutes. The differences between three methods of spatial point positioning were tested:

1. Geo-referenced aerial photographs (AERO) at an approximate scale 1:20,000
2. Standard GPS signal
3. DGPS signal – 180 measurement average (interval = 1 s)

One GPS receiver was positioned at a location of previously determined surveying coordinates (measurement accuracy about 0.5 m). This location was called BASE or the base location. The second receiver was used for the field measurement (FIELD). After completing the fieldwork, data from the BASE and the FIELD receivers were transferred to a PC and processed. Since the GPS coordinates were read in the geographic coordinate system (with WGS84 ellipsoid), the original data were converted into the local Gauss-Krueger system (Bessel's ellipsoid). The conversion was accomplished according to the 7-parameter method (Trimble's parameters for the whole of Croatia) [6].

According to the specifications, the corrected GPS signal (DGPS) achieves an accuracy of 1–5 m during a static measurement or for location mapping (average value of over 180 individual readings). For dynamic measurements the accuracy decreases to 3–10 m. At this stage of the research, dynamic mapping (lines) was not ob-

(črt). Sprejemnika SDL smo uporabili predvsem za določanje leg vzorčnih zemljišč. Te podatke smo kasneje obdelali s sistemom GIS, da bi preverili našo glavno raziskovalno domnevo: nujnost uporabe orodja GIS pri kartiranju in modeliranju prostorskih parametrov zemljišča. Praktični namen raziskave pa je bil pridobitev znanja in izkušenj pri delu s podatki SDL, njihovo vključevanje v sistem GIS in preverjanje možnosti, ki jo ponuja bolj natančna metoda DSDL.

2 REZULTATI

Rezultate naše raziskave moramo razdeliti v dve skupini: na tiste, ki smo jih pridobili z izkušnjami, in tiste, ki smo jih pridobili z obdelavo statističnih podatkov.

Izkušnje z uporabo metode SDL zadevajo ravnanje z napravo, porabo časa in praktične pomanjkljivosti metode:

Ravnanje: Za uporabo sprejemnika Garmin ne potrebujemo posebnega znanja, vendar pa lahko neizkušenost pri njegovi uporabi povzroči resne napake in nepravilne razlage.

Poraba časa: Zagonski čas naprave je 2 do 4 minute. Dodatni čas (približno 1,5 ure) je potreben za prenos podatkov (do 3 MB za vsak snemalni dan) na osebni računalnik.

Pomanjkljivosti: Pričakovano natančnost smo dosegli le na prostem. V primeru gostih krošenj (na primer v sto let starem hrastovem gozdu) signal postane šibek, vrednosti lahko odstopajo za 200 m, in meritve pogosto postanejo neizvedljive. Za štiri kraje nismo mogli obdelati podatkov, ker le-ti niso ustrezali zahtevam. Poglavitna pomanjkljivost pa zadeva odpravo napak SDL. Med postopkom DSDL bi moral biti merilni čas daljši kot je sicer določeno (3 minute za vsak kraj), ker je bilo v povprečju le 60% podatkov (psevdorazdalje) primernih za obdelavo. Glavni problem je torej nezadostno pokritje krajev.

Podatke smo statistično obdelali s statističnim paketom Minitab12 (1998, Minitab Inc.). Primerjali smo podatke, pridobljene s tremi metodami določanja lege. Rezultate DSDL smo uporabili kot referenčne vrednosti. Vse navedene vrednosti se nanašajo na vodoravno določanje lege, z drugimi besedami, upoštevali smo le koordinati XY. Izračunano sistematično odstopanje metode SDL od referenčnih vrednosti DSDL (povprečje za 25 krajev) je bilo 13,0 m, in 16,1 m od metode AERO. Da bi pridobili dejanski vrednosti odstopanja – 16,0 m za SDL in 19,1 m za AERO – bi moralo biti to odstopanje kombinirano z ocenjeno srednjo vrednostjo napake DSDL, ki znaša

served. The GPS receivers were primarily used to position soil-sampling sites. These data will later be processed with GIS in order to test the main research hypotheses: the mapping and modeling of spatial soil parameters using GIS tools. The practical purpose of the research was to learn more about working with GPS data, how to integrate GIS, and to test the possibilities of the more precise DGPS.

2 RESULTS

The results of this research can be divided into two groups: those gained from experience and those gained from statistical data processing.

The experience with the use of GPS relates to handling, time consumption and practical drawbacks:

Handling: The Garmin receiver does not require any special knowledge, yet inexperience may cause large errors and incorrect interpretations.

Time consumption: The initialization time lasts from 2 to 4 minutes. Additional time (about 1½ hours) is spent transferring the data (up to 3 MB for one day of recording) to a PC.

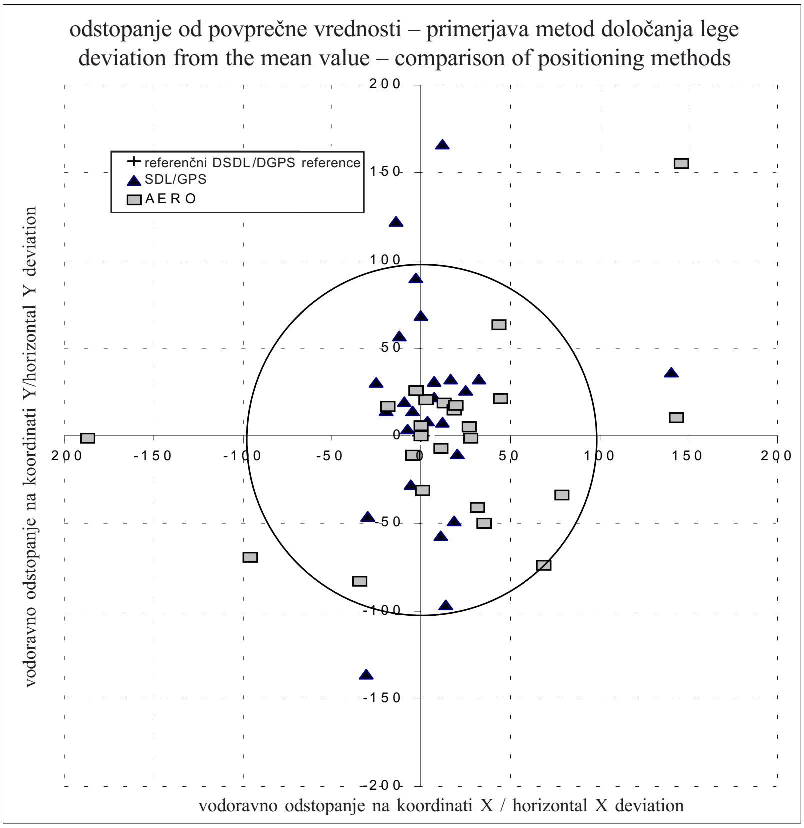
Drawbacks: The expected accuracy is only achieved in the open. In the case of dense tree cover (for example, a 100-year-old oak forest) the signal is weak, the values may deviate by 200 m, and a measurement is often impossible. During data processing four locations were rejected because they did not satisfy the requirements for a calculation. The main drawback involves the elimination of GPS errors. In the DGPS procedure, the measuring time must be longer than planned (3 minutes per location), because only 60% of the data (pseudo-ranges) were on average suitable for processing. The main problem was insufficient coverage.

The data were statistically processed with the Minitab12 statistical package (1998, Minitab Inc.). The data from three positioning methods were compared. The DGPS results were used as the reference values. All the mentioned values relate to horizontal positioning; in other words, only the XY coordinates were taken into account. The calculated systematic deviation of the GPS method from reference DGPS values (average for 25 locations) was 13.0 m, and 16.1 m for the AERO method. To obtain the true deviation value – 16.0 m for GPS and 19.1 m for AERO – this deviation should be combined with the estimated mean DGPS error

Preglednica 4. *Indikatorji primerjave med tremi metodami določanja lege*
Table 4. *Indicators of the comparison of three positioning types*

Statistični parameter N = 180 ali 3 min Statistical parameter N = 180 or 3 min	povprečje mean (m)	povprečno odstopanje mean deviation s_x (m)	minimum (m)	maksimum maximum (m)	porazdelitev distribution
DSDL*/DGPS*	25	2	0	10	logaritemsko normalna log-normal
odstopanje SDL-DSDL deviation GPS-DGPS	59,6	48,3	9	167	logaritemsko normalna log-normal
odstopanje AERO-DSDL deviation AERO-DGPS	64,2	57,9	6	213	logaritemsko normalna log-normal

* - domnevno odstopanje od dejanske vrednosti
* - assumed deviation from true value



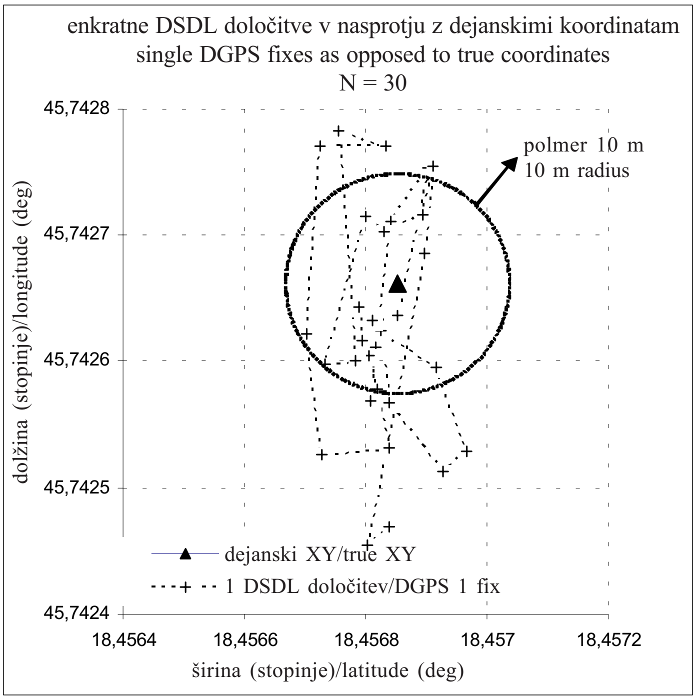
Sl. 1. *Primerjava treh metod določanja lege. Rezultati metode DSDL so uporabljeni kot referenčne vrednosti (domnevna napaka je < 5 m). Diagram prikazuje odstopanja osnovne SDL meritve, pa tudi meritve izven polmera 95% verjetnosti.*
Fig. 1. *Comparison of three methods of field positioning. The results of the DGPS method are used as the reference value (assumed error is < 5 m). The deviation of the raw GPS, as well as the outliers of the 95% probability radius, can be seen.*

približno 3 m. Polmer napake SDL, ki znaša 16 m in smo ga pridobili s povprečenjem, se nanaša na neodvisne vzorce, tj. na vzorce, pridobljene v različnih časovnih korakih, daljših od ene ure. Glede na podobno raziskavo [7], v kateri je uporabljena metoda nepopravljenega signala SDL, ki izraža povprečje nepretrganega merjenja (brez daljših časovnih korakov), je mogoče povečati natančnost na približno 25 m (povprečje 600 vrednosti – sekunde). Vrednost te sistematične namerne napake je večinoma določena s selektivno dostopnostjo. Hkrati pa polmer, znotraj katerega smo izvedli večino meritev, oziroma polmer 95% verjetnosti, znaša približno 100 m v primeru enkratnega prebiranja pri metodi SDL. Povprečenje (za 300 vrednosti) ga zmanjša na približno 70 m [8] (slika 1), medtem ko pri metodi DSDL polmer znaša med 10 m v primeru enkratnega odčitavanja DSDL do 6 m (povprečje 180 vrednosti) (slika 2).

S primerjanjem metod SDL in AERO nismo odkrili statistično pomembnih razlik (t-test dveh vzorcev, $P_{0,05} = 0{,}77$).

of about 3 m. The GPS error radius of 16 m, derived from averaging, relates to independent samples, i.e., to samples taken at different time intervals longer than 1h. According to similar research [7], using a method of uncorrected GPS signal averaging with continuous measuring (without longer time intervals), it is possible to improve the accuracy to about 25 m (average of 600 values – seconds). The value of this systematic intentional error is mostly dictated by selective availability (SA). On the other hand, the radius within which the majority of the measurements were made, or the 95% probability radius, is about 100 m for a single reading for the GPS method. Averaging (300 values) decreases it to about 70 m [8](Figure 1), while for DGPS it ranges from 10 m for a single DGPS reading to 6 m (average of 180 values) (Figure 2).

Testing the difference between the GPS and the AERO methods revealed no statistically significant differences between these two methods (t-test for two samples, $P_{0.05} = 0.77$).



Sl. 2. *Odstopanja enkratnih določitev DSDL od povprečne/dejanske vrednosti; krog označuje polmer 95 % verjetnosti.*

Fig. 2. *Fluctuation of single DGPS fixes from the averaged/true value; the circle indicates the 95% probability radius.*

3 RAZPRAVA

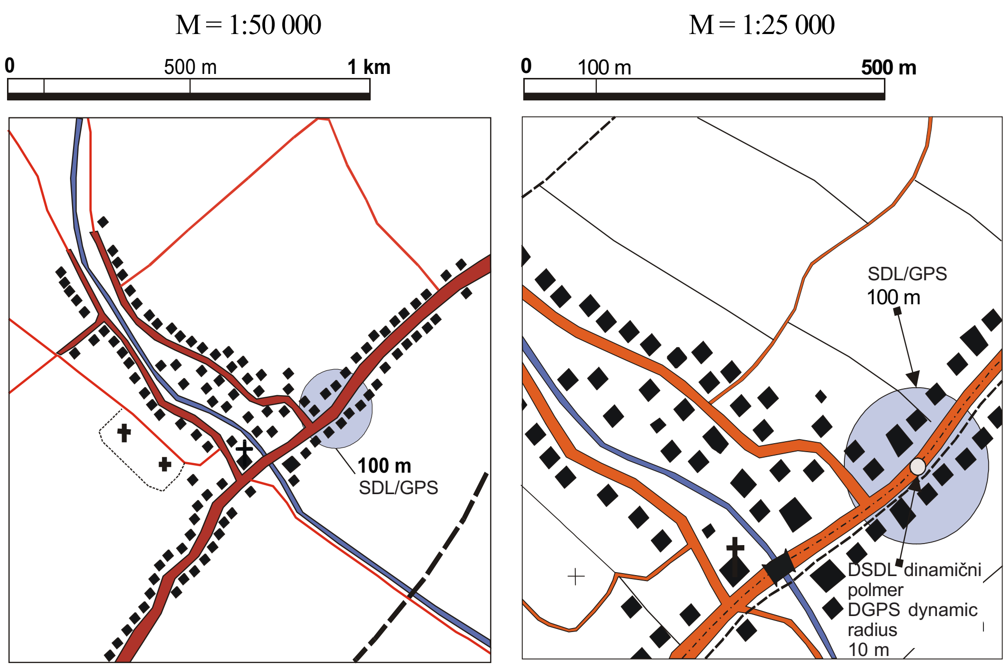
3.1 Inteligentni transportni sistem in upravljanje

V uvodu smo omenili le nekaj primerov vsakodnevne rabe satelitske navigacije v tržne civilne namene. Od namestitve navigacijskega sistema SDL v vozila v zgodnjih devetdesetih letih prejšnjega stoletja, je njegova tržna raba postala zelo raznolika. Sisteme avtomatske navigacije in načrtovano upravljanje prometa v prihodnosti običajno imenujemo *pametni transportni sistemi* [9]. Razvoj in uporaba teh sistemov v upravljanju sta, na primer, že pripeljala do oblikovanja nove ekonomske smeri, imenovane *znanstveno usmerjeno upravljanje*. Izraz *znanstveno usmerjeno kmetijstvo/znanstveno usmerjeno poljedelstvo* se je uveljavil na področju kmetijstva, medtem ko se v gozdarstvu tovrstne uporabe razvijajo počasneje zaradi slabšega sprejema satelitskega signala v gozdovih. Uporabniki SDL v gozdnatih in hribovitih predelih bi morali, ob uporabi že omenjenih komponent, imeti dostop tudi do zunanje antene in zunanjega vira napajanja, kar pa bi znatno povečalo

3 DISCUSSION

3.1 Intelligent transportation systems in management

The introduction mentions only a few of the commercial civilian uses of satellite navigation in everyday life. Since the installation of the GPS navigation system in vehicles in the early 1990s, its commercial uses have diversified. Systems with automated navigation, and the envisaged traffic management of the future, are commonly known as *Intelligent Transportation Systems* [9]. The development and application of these systems in management, for example, has led to the establishment of a new branch of the economy called *Precision management*. The term *Precision agriculture/Precision farming* has become established in the field of agriculture, whereas in forestry the applications are developing at a slower rate due to poorer signal reception in forests. GPS users in forested and hilly areas should, along with the already mentioned components, have at their disposal an external antenna and an external source of power, which considerably increases the size of



Sl. 3. *Razlika v določitvi lege glede na različna merila – 1:25000 in 1:50000. Medtem ko za manjša merila zadostuje celo nepopravljen signal SDL, pa mora biti za večja merila navigacijska napaka manjša od 5 m. Kroga označujeta specifični polmer 95% zanesljivosti.*

Fig. 3. *Difference in positioning related to map scale – 1:25000 and 1:50000. While even an uncorrected GPS signal is enough for smaller scales, larger management scales demand a navigation error smaller than 5 m. The circles indicate a specific 95% confidence radius.*

obseg začetne investicije. Trenutna standardna vrednost napake SDL, ki znaša približno 100 m v vodoravni smeri in približno 150 m v navpični smeri, ne zadovolji številnih potencialnih uporabnikov na področju upravljanja (slika 3).

Uporaba DSDL v kmetijstvu je pokazala, da lahko, na primer, ob enakem ali celo boljšem pridelku dosežemo znaten prihranek pri pognojevanju (pogosto celo 30%). Hkrati lahko v polni meri upoštevamo ekološka načela, kot na primer varstvo kakovosti vode. Temeljni cilj znanstveno usmerjenega kmetijstva je podrobna določitev ekoloških in proizvodnih dejavnikov, kakor so lastnosti zemlje, podnebne razmere, raba gnojil, pridelek idr., znotraj danega območja. Gnojenje, na primer, vključuje štiri korake:

- analiziramo in lociramo primere pomanjkanja hranljivih snovi (elementov) v določenem območju,
- podatke obdelamo s programom GIS in izdelamo karto pomanjkanja hranljivih snovi,
- karto pomanjkanja hranljivih snovi uporabimo za izračun celotnih potreb po gnojilih,
- na podlagi karte razdelimo gnojila, pri čemer uporabljamo avtomatiziran sistem (DSDL).

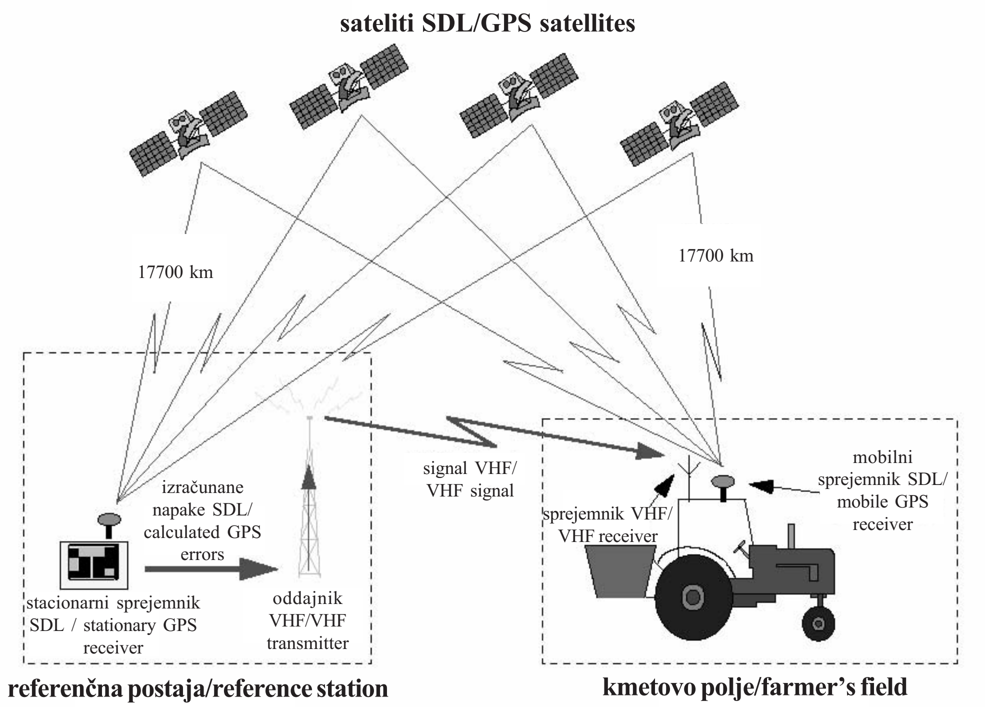
Čeprav so raziskave pokazale, da sprejemno-prikazovalni sistemi DSDL še vedno zahtevajo izdatno naložbo [10], pa upadanje cen opreme informacijske tehnologije kaže na to, da bodo ti

the initial investments. The current standard value of GPS error of about 100 m in the horizontal direction, and about 150 m in the vertical direction does not satisfy numerous potential uses in management (Figure 3).

DGPS application in agriculture has proved that, for example, considerable savings can be made with fertilizers (often as much as 30%) at equal or even better crop yields. At the same time, ecological principles, such as water-quality protection, are fully observed. The basic goal of precision agriculture is to map in detail the ecological and production factors within a given field, such as soil attributes, climatic conditions, fertilizer input, yield and others. For example, fertilizing involves three steps:

- nutrient (elements) deficiency in the field is sampled and geo-referenced,
- data are processed within the GIS program and a nutrient-deficiency map is generated,
- the nutrient-deficiency map is used to calculate the total fertilizer requirement,
- based on the map, fertilizers are distributed using the automated and oriented (DGPS) system.

Although investigations have shown that DGPS display receiver systems still require a large investment [10], a falling trend in the prices of information-technology equipment indicates that



Sl. 4. *Shematičen prikaz storitve DSDL na področju znanstveno usmerjenega kmetijstva (povzeto iz vira [9])*
Fig. 4. *Schematic overview of DGPS service for application in precision agriculture (taken from [9])*

sistemi kmalu postali običajna in široko uporabljana orodja (podobno kakor računalniki). Takšne sisteme že izdatno uporabljajo v Nemčiji, Avstriji, Veliki Britaniji in nekaterih drugih evropskih državah.

4 SKLEPI

Rezultati raziskave kažejo, da lahko metodo SDL uspešno uporabljamo pri kartiranju zemljišč in pri prepoznavanju drugih naravnih virov. Določanje lege z nepopravljenim signalom SDL omogoči enako dobro ali celo boljšo natančnost določitve lege, kakor jo dobimo z zračnimi fotografijami v povprečnem merilu 1:20.000. Uporaba satelitskega določanja lege je odvisna od potreb posameznih uporabniških skupin. Da bi lahko objektivno ocenili funkcionalnost postopka SDL za določene potrebe, moramo upoštevati naslednje elemente:

- Gre za enkratno meritev ali za povprečenje?
- Kakšna je sistemska napaka za dani čas meritve?
- Kolikšna je natančnost oziroma napaka povprečne vrednosti rezultata?
- Kakšen je polmer 95-odstotne verjetnosti za izbrano metodo določanja lege?
- Kolikšna je zanesljivost rezultatov v primeru uporabe metode DSDL, in kako to zanesljivost merimo?
- Katera metoda je najbolj donosna za določeno uporabo?

Vrednost povprečne napake DSDL (enkratna določitev) je, na primer, sprejemljiva za kartiranje v delovnem merilu 1:25.000 (to merilo je primerno za

they will soon become a common and widely available tool (like computers). Such systems already have large-scale uses in Germany, Austria, the UK and other European countries.

4 CONCLUSIONS

The results of this research indicate that GPS positioning can successfully be applied to soil mapping and to natural resource inventories in general. Positioning with an uncorrected GPS signal provides equal or better positioning possibilities than aerial photographs with an approximate scale of 1:20,000. The use of satellite positioning depends on the needs of a given user group. In order to make an objective assessment of GPS functionality for a defined need, the following elements should be considered:

- Is it a single measurement or is it averaging?
- What is the system error for the given measurement time?
- What is the precision or the mean error of the averaged result?
- What is the 95% probability radius for the selected positioning method?
- If the DGPS method is used, what is the result reliability and how is it tested?
- Which method is the most profitable for the application?

The value of the mean DGPS error (single fix) is sufficient for a working scale of 1:25,000, for example (scale suitable for detailed management

Preglednica 5. *Delovno merilo in ustrezen sistem določanja lege. Največja natančnost določitve lege = 0,2 mm na zemljevidu.*
Table 5. *Working scale and adjacent position system. Maximum location accuracy = 0.2 mm on map.*

Delovno merilo Working scale	**Kartografski detajl Mapping Detail**	**Primerna metoda določanja lege Suitable positioning method**	**Razpon uporabnosti Application range**
1:5000	1 m	natančne kombinirane metode highly accurate combined methods	geodezija, gradbeništvo surveying, civil engineering
1:25000 - 1:50000	5 m - 10 m	DSDL (enkratna določitev) DGPS (single fix)	navigacija vozil na področju upravljanja (traktorji, reševalne službe, policija, gasilske čete); navigacija ladij in letal; izdelava organizacijskih načrtov in drugo vehicle navigation in management (tractors, emergency service, police, fire fighter service); ship and airplane navigation; construction of management plans and others
<1:100000	> 20 m	SDL (enkratna določitev) GPS (single fix)	navigacija vozil za osebne namene, osebna navigacija vehicle navigation for personal use, personal navigation

podrobne organizacijske načrte). Preglednica 5 prikazuje glavne uporabniške skupine SDL glede na natančnost metode in ceno naprave.

Treba je poudariti, da nakup sistema DSDL še ne zagotavlja uspeha projekta. Nepogrešljiv del opreme je njen osnovni del, digitalni zemljevid (ali GIS) v ustreznem merilu in z vsebino, ki se spreminja glede na tip sistema. Z drugimi besedami, v delo je treba vključiti tudi tehnologijo GIS.

plans). Table 5 lists the main GPS application groups in terms of accuracy/price.

It should be pointed out that the purchase of a DGPS system does not guarantee the success of the application. An indispensable part of the equipment is the base, i.e., a digital map (or GIS) with a suitable scale and content, depending on the type. In other words, the use of GIS technology should be integrated.

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Osebne vesti - Personal Events

Doktorati, magisteriji in diplome - Doctor's, Master's and Diploma Degrees

DOKTORATI

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svojo doktorsko disertacijo:

dne *25. maja 2006*: **mag. Jurij Prezelj**, z naslovom: "Zmanjšanje vpliva akustične povratne zanke v sistemih za aktivno dušenje hrupa".

S tem je navedeni kandidat dosegel akademsko stopnjo doktorja znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svoje magistrsko delo:

dne *26. maja 2006*: **Matej Bašelj**, z naslovom: "Medsebojni vplivi aktivnih nukleacijskih mest pri nasičenem mehurčkastem vrenju na tanki grelni foliji".

S tem je navedeni kandidat dosegel akademsko stopnjo magistra znanosti.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

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Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne *25. maja 2006*: Zdravko BRATUŠA, Mitja KRANC, Blaž ŠAMEC.

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Strojniški vestnik - Journal of Mechanical Engineering 52(2006)6, 433-434
Navodila avtorjem - Instructions for Authors

Navodila avtorjem - Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Za članke iz tujine (v primeru, da so vsi avtorji tujci) morajo prevod v slovenščino priskrbeti avtorji. Prevajanje lahko proti plačilu organizira uredništvo. Če je članek ocenjen kot znanstveni, je lahko objavljen tudi samo v angleščini s slovenskim povzetkom, ki ga pripravi uredništvo.

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

For papers from abroad (in case that none of authors is Slovene) authors should provide Slovenian translation. Translation could be organised by editorial, but the authors have to pay for it. If the paper is reviewed as scientific, it can be published only in English language with Slovenian abstract, that is prepared by the editorial board.

VSEBINA ČLANKA

Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

THE FORMAT OF THE PAPER

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a mini version of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

OBLIKA ČLANKA

Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

Ne uporabljajte urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

THE LAYOUT OF THE TEXT

Texts should be written in Microsoft Word format. Paper must be submitted in electronic version.

Do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v **slovenskem jeziku**, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v ločljivosti, primerni za tisk, v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Diagrami in risbe morajo biti pripravljeni v vektorskem formatu.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove in naslove elektronske pošte.

SPREJEM ČLANKOV IN AVTORSKE PRAVICE

Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Author information

The information about the authors should be enclosed with the paper: names, complete postal and e-mail addresses.

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