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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.

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

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

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

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

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, **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, **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:

$$p_0 = \rho TR \sum (Y_i / M_i) \tag{5}$$

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:

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

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:

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

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:

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

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.

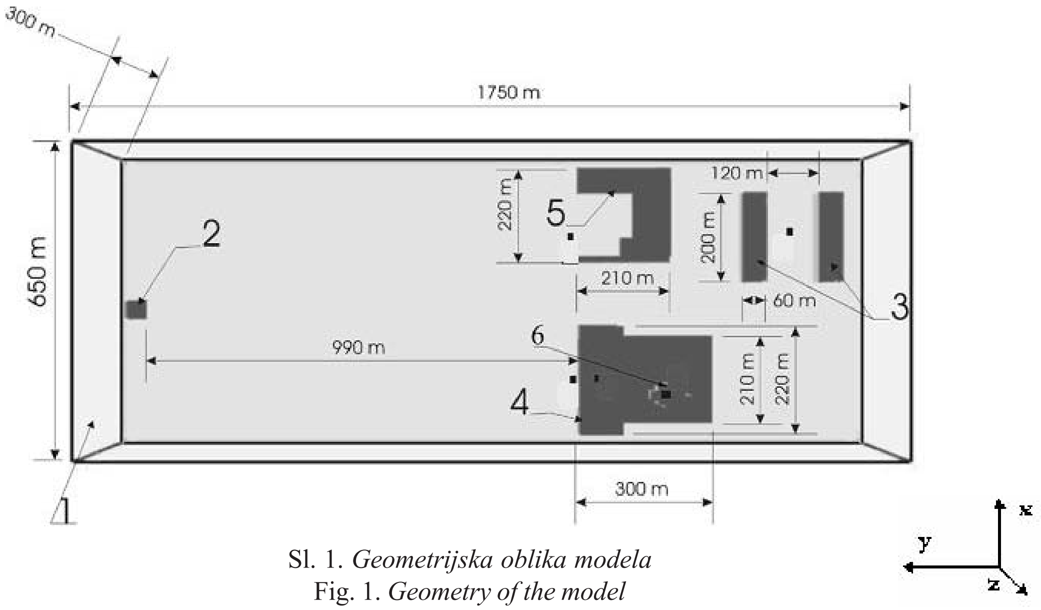
Uporabljena je neenakomerna kartezična mreža z 170 × 180 × 50 računskimi točkami v smereh x, y in z. Simulacija je zahtevala približno 70 ur računskega časa na osebnem računalniku 2,5 MHz.

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.

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.

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 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

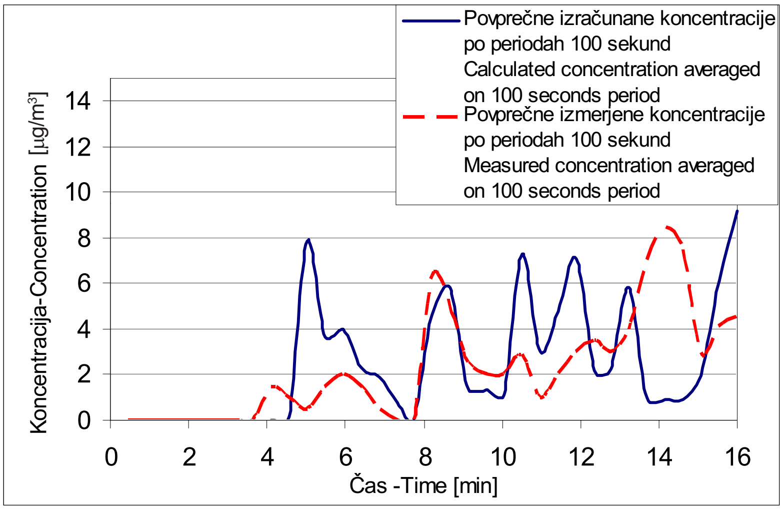
The validation of the model is made using the experimental data obtained from the ‘’Alaskan Clean Seas’’ experiment, conducted in the Prudhoe Bay in Alaska in September, 1994. In the Test 2, 12.2 m^3 of crude oil was ignited in a pool of 8 × 8 meters. The smoke-concentration measurement sensors were 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:

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

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 °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

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

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°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 μg/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 μg/m^3 do 250 μg/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

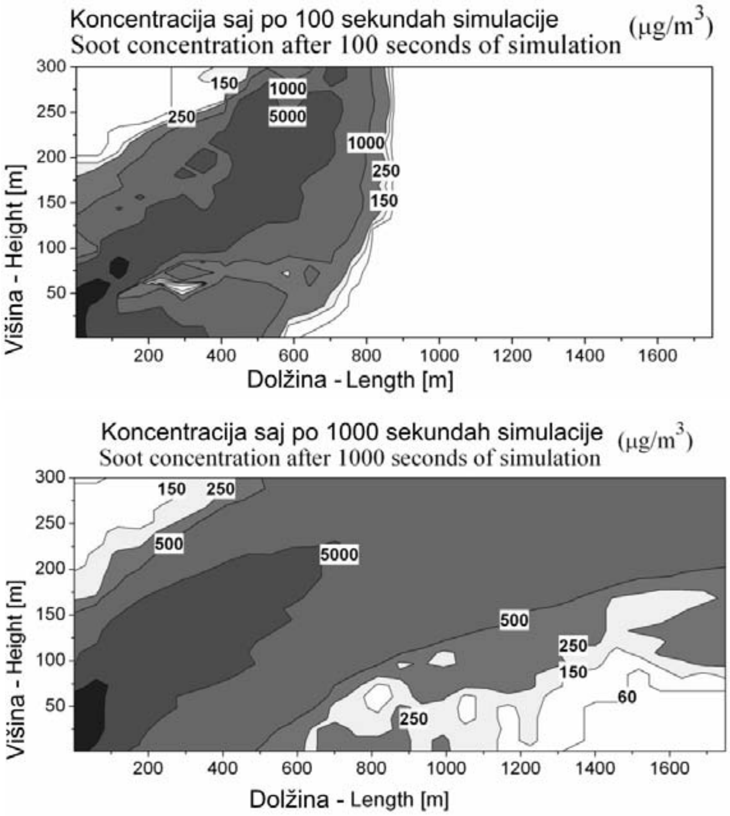
respiration is more difficult, but health is not threatened.

- concentrations of soot above 1000 μg/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 μg/m^3 to 250 μg/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.

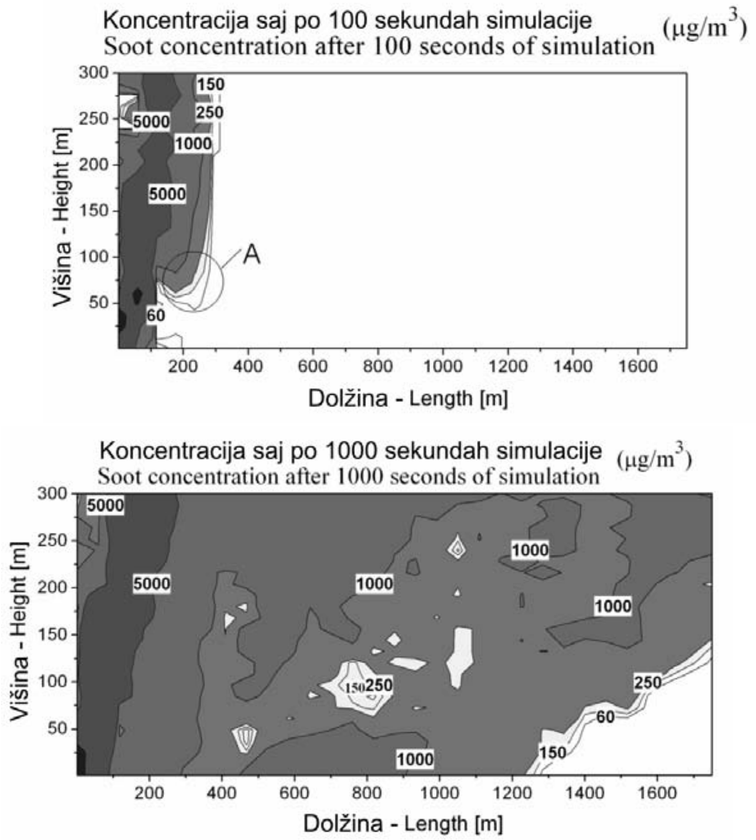
3.1 Izguba podatkov zaradi odprtih robnih pogojev

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.

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

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.

4 SKLEP

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

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.

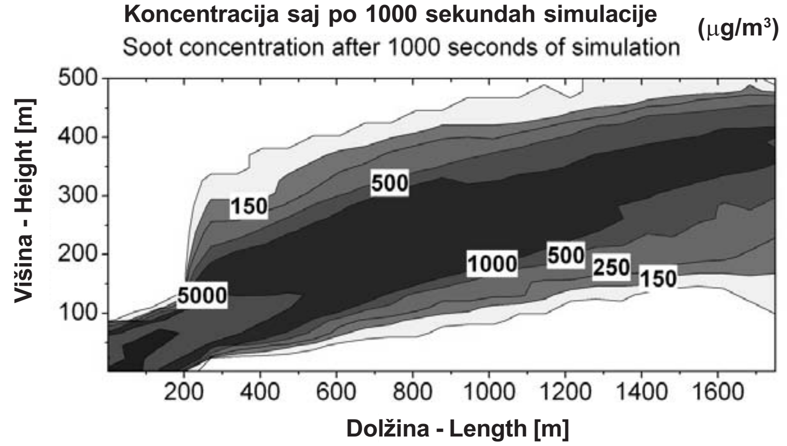
3.2 Consideration of Probabilistic Safety Assessment for external fire event

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 CONCLUSION

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

6 LITERATURA
6 REFERENCES

[1] Baum H.R., McGrattan K.B., Rehm R.G. (1996) Large eddy simulation of smoke movement in three dimension, *International Interflam Conference*, Cambridge, England.

[2] Fletcher C.A.J. (1991) Computational techniques of fluid dynamics, Volume 2, Second edition, *Springer-Verlag*, Berlin, Heidelberg.

[3] Drysdale D. (1998) An introduction to fire dynamics, *Wiley*, New York.

[4] McGrattan K.B., Walton W.D., Putorti A.D., Twilley W.H., McElroy J., Evans D.D. (1995) Smoke plume trajectory from *In Situ* burning of crude oil in Alaska: Field experiments, U.S. Department of Commerce, Ronald H. Brown, Secretary, *National Institute of Standards and Technology*.

[5] McGrattan K.B., Floyd J., Forney G., Baum H. (2001) Development of combustion and radiation models for large scale fire simulation, *Third Technical Symposium on Computer Applications in Fire Protection Engineering*, Baltimore.

[6] McGrattan K.B. (2003) NIST, Fire dynamics simulator-technical reference guide, *U.S. Department of Commerce*.

[7] Nuclear power plant (1998) NE Krško PSA Project Summary Report, *NEK*, pp. 94-103.

[8] Nuclear power plant (1999) PSA of NPP Krško-Internal Fire Analysis, *NEK*, pp. 12/4-12/5.

[9] Vidmar P. (2003) Fire spread model at traffic accident around nuclear power plant, Magistrska naloga, Fakulteta za matematiko in fiziko, Ljubljana.

[10] DiNenno P.J. (1995) SFPE handbook of fire protection engineerinng, Second edition, *Society of Fire Protection Engineering*, USA.

[11] Grosshandler W. (1993) RadCal: A narrow band model for radiation calculations in a combustion environment. NIST technical note (TN 1402), *National Institute of Standards and Technology*, Gaithersburg, Maryland.

[12] Vidmar P., Petelin S. (2003) Analiza požara pri prometni nezgodi, *Strojniški vestnik* 49(2003)5, str. 1-13.

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