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Simuliranje eksplozije pare v reaktorski votlini s splošnim programom za računsko dinamiko tekočin

Simulation of a Reactor Cavity Steam Explosion with a General Purpose Computational Fluid Dynamics Code

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Do eksplozije pare v reaktorski votlini lahko pride, če med hipotetično resno nezgodo v jedrski elektrarni popusti reaktorska posoda in se staljena sredica izlije v vodo, ki je v reaktorski votlini. Eksplozija pare je pojav medsebojnega delovanja goriva in hladiva pri katerem je časovna lestvica prenosa toplote s staljene sredice na vodo manjša od časovne lestvice za tlačno razbremenitev. To lahko povzroči tlačne udarne valove in kasneje, med raztezanjem pare, ki je pod visokim tlakom, nastanek izstrelkov, ki lahko poškodujejo okoliške objekte. Namen prispevka je predstaviti, kako je eksplozije pare mogoče obravnavati s splošnim programom za računsko dinamiko tekočin (RDT), podati vpogled v dogajanja med eksplozijo pare v reaktorski votlini tipičnega tlačnovodnega jedrskega reaktorja, in podati grobo oceno ogroženosti sten reaktorske votline in reaktorske posode ob eksploziji pare. Za dosego teh ciljev smo najprej razvili ustrezen namenski model eksplozije pare in nato opravili obsežno, primerno konzervativno parametrično analizo eksplozije pare v poplavljeni reaktorski votlini. Večfazni tok v reaktorski votlini med raztezanjem visokotlačne mešanice razpršene taline, kapljevite vode in vodne pare smo simulirali s programom CFX-5.7.1 za RDT, napetosti v stenah reaktorske votline pa s programom za simulacijo mehanike trdnin ABAQUS/Explicit.

(Ključne besede: reaktorji jedrski, nezgode reaktorjev, eksplozija pare, votlina reaktorska, računska dinamika tekočin)

A reactor cavity steam explosion might occur when, during a hypothetical severe reactor accident, the reactor vessel fails and the molten core pours into the water in the reactor cavity. A steam explosion is a fuel-coolant interaction process where the heat transfer from the melt to the water is so intense and rapid that the timescale for the heat transfer is shorter than the timescale for the pressure relief. This could lead to the formation of shock waves and the production of missiles at later times, during the expansion of the highly pressurized water vapour, which might endanger surrounding structures. The purpose of the paper is to demonstrate how steam explosions can be treated with a general purpose Computational Fluid Dynamics (CFD) code, to give an insight into the steam-explosion phenomenon in a typical Pressurized Water Reactor (PWR) cavity, and to provide a rough assessment of the vulnerabilities of cavity structures to steam explosions. To achieve this, a fit-for-purpose steam-explosion model was developed, followed by a comprehensive and reasonably conservative parametric steam-explosion study. The multiphase flow in the reactor cavity during the high-pressure pre-mixture expansion was simulated with the CFD code CFX-5.7.1 and the stresses in the reactor cavity walls were determined with the stress-analysis code ABAQUS/Explicit.

(Keywords: nuclear reactor accident, steam explosion, reactor cavity, computational fluid dynamics)

0 UVOD

Eno od najpomembnejših nerešenih vprašanj na področju taljenja sredice med hipotetično resno

0 INTRODUCTION

One of the most important remaining issues in core-melt progression during a hypothetical severe nezgodo v jedrski elektrarni je, kakšna je verjetnost nastanka eksplozije pare in kakšne so lahko njene posledice. Eksplozija pare se lahko razvije, ko pride staljena sredica v stik s hladilno vodo v reaktorski votlini. Eksplozija pare je pojav interakcije goriva in hladiva, pri katerem je časovna lestvica prenosa toplote s staljene sredice na vodo manjša od časovne lestvice tlačne razbremenitve ([1] do [3]). To lahko povzroči tlačne udarne valove in kasneje med raztezanjem pare, ki je pod visokim tlakom, nastanek izstrelkov, ki lahko poškodujejo okoliške objekte. Eksplozija pare je zapleten, močno nelinearen, večsestavinski in večfazen pojav, ki poteka na različnih krajevnih in časovnih lestvicah. Posledično je modeliranje eksplozij pare zelo zahtevno, negotovosti simuliranj resnih nezgod opravljenih z računalniškimi programi, ki temeljijo na modeliranju osnovnih pojavov eksplozije pare, pa so še vedno zelo velike. Zato je za oceno ogroženosti sten reaktorske votline in reaktorske posode med eksplozijo pare potreben parametričen postopek, ki zajame negotovosti razumevanja in modeliranja eksplozije pare. V ta namen smo razvili parametričen model eksplozije pare, ki ga je mogoče preprosto uporabiti in neposredno vključiti v splošne programe za računsko dinamiko tekočin (RDT).

Glavni namen opravljene študije je predstaviti, kako je eksplozije pare mogoče obravnavati s splošnim programom za RDT, podati fizikalno sliko dogajanj med eksplozijo pare v reaktorski votlini tipičnega tlačnovodnega jedrskega reaktorja in podati grobo oceno ogroženosti sten reaktorske votline in reaktorske posode ob eksploziji pare. Eksplozijo pare smo modelirali kot raztezajočo se visokotlačno mešanico staljene sredice, kapljevite vode in vodne pare, ki je v delno poplavljeni reaktorski votlini. Podoben, vendar manj zahteven postopek so uporabili tudi v študiji eksplozije pare, ki je predstavljena v [4]. Večfazni tok med raztezanjem visokotlačne mešanice smo simulirali s programom CFX-5.7.1 za RDT [12], napetosti v stenah reaktorske votline pa s programom za simulacijo mehanike trdnin ABAQUS/Explicit [13].

1 OPIS MODELA

1.1 Model eksplozije pare

Pri mešanju dveh kapljevin, pri katerih je temperatura ene kapljevine višja od temperature vrelišča druge, lahko pride do eksplozije pare. Potek

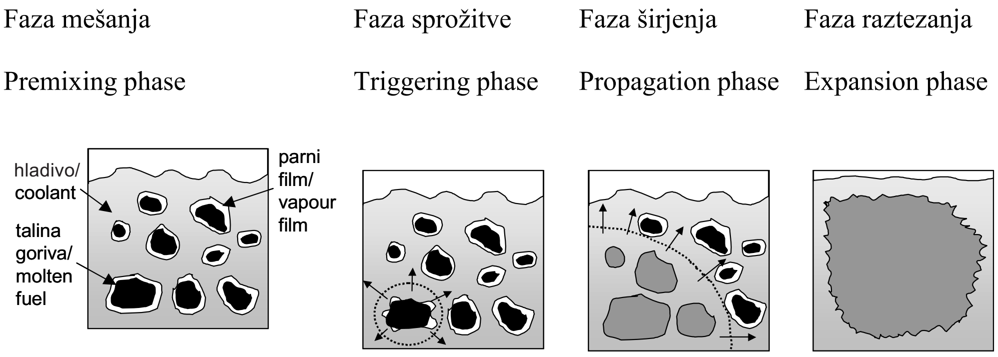
accident in a nuclear power plant is the likelihood and the consequences of a steam explosion, which might occur when the hot core melt comes into contact with the coolant water. A steam explosion is a fuel-coolant interaction process where the heat transfer from the melt to the water is so intense and rapid that the timescale for the heat transfer is shorter than the timescale for the pressure relief ([1] to [3]). This could lead to the formation of shock waves and the production of missiles at later times, during the expansion of the highly pressurized water vapour, which might endanger surrounding structures. A steam explosion is a complex, highly non-linear, coupled multi-component, multi-phase, multi-space-scale and multi-time-scale phenomenon. Consequently, the modelling of steam explosions is a difficult task and the uncertainties of reactor simulations performed with steam-explosion codes based on modelling fundamental steam explosion processes are still large. Therefore, for assessing the vulnerability of reactor-cavity structures to an ex-vessel steam explosion a parametric approach capturing the uncertainties in steam-explosion understanding and modelling is needed. For this purpose a comprehensive parametric steam-explosion model that can also be straightforwardly implemented in general purpose Computational Fluid Dynamics (CFD) codes was developed.

The main purpose of the performed study was to present how steam explosions can be treated with a general purpose CFD code, to give an insight into the steam-explosion phenomenon in a typical Pressurized Water Reactor (PWR) cavity, and to provide a rough assessment of the vulnerabilities of cavity structures to steam explosions. The steam explosion was modelled as an expanding high-pressure pre-mixture of dispersed molten fuel, liquid water and vapour in the partially flooded reactor cavity. A similar, but less sophisticated, approach was also used in the steam-explosion study presented in [4]. The multiphase flow during the high-pressure pre-mixture expansion was simulated with the CFD code CFX-5.7.1 [12] and the stresses in the cavity walls were determined with the stress analysis code ABAQUS/Explicit [13].

1 MODEL DESCRIPTION

1.1 Steam Explosion Model

Steam explosions are a subclass of what is called fuel-coolant interactions (FCI) in the safety studies of nuclear reactors. Based on the phenomena



Sl. 1. *Shema štirih zaporednih faz eksplozije pare*
Fig. 1. *Schematic presentation of the four consecutive phases of the steam explosion*

eksplozije pare lahko glede na dogajanja razdelimo v štiri zaporedne faze: faza mešanja, faza sprožitve, faza širjenja in faza raztezanja (sl. 1).

V **fazi mešanja** nastane območje, v katerem je staljena sredica grobo pomešana s hladilno vodo. Ker so delci taline obdani s plastjo pare, je prenos toplote s taline na vodo razmeroma majhen. V **fazi sprožitve** se eksplozija pare sproži. Sprožitveni dogodek je motnja, ki destabilizira plast pare okoli nekega delca taline, tako da pride do neposrednega stika med talino in vodo, ki privede do lokalnega povečanja prenosa toplote in povišanja tlaka ter fine fragmentacije delca. Med **fazo širjenja** pride do stopnjevanja eksplozije pare zaradi sklopitve potujočih tlačnih valov, fine fragmentacije delcev in prenosa toplote po sprožitvenem dogodku. Med **fazo raztezanja** se toplotna energija hladiva spreminja v mehansko energijo. Raztezanje visokotlačne mešanice razpršenega staljenega goriva, vode in vodne pare, ki povzroča odmikanje okoliških tekočin in tlačno obremenitev okoliških struktur, določa možen obseg škode, ki jo lahko povzroči eksplozija pare. Bolj izčrpen opis posameznih faz eksplozije pare je podan v [1] do [3].

Da bi lahko obravnavali eksplozijo pare s splošnim programom za RDT, smo razvili ustrezen parametrični model eksplozije pare. Za razliko od specializiranih programov za RDT za simulacijo eksplozij pare, pri katerih eksplozije pare modelirajo na mikroskali z osnovnimi povprečenimi ohranitvenimi enačbami večfaznega toka ([1], [2], [5] do [7]), v predstavljenem postopku eksplozijo pare modeliramo kot raztezajočo se visokotlačno mešanico razpršene taline goriva, kapljevite vode in vodne pare. Podoben postopek so uporabili tudi v študiji eksplozije pare, predstavljeni v [4], kjer so eksplozijo

occurring during a steam explosion it can be divided into four consecutive phases: the premixing phase, the triggering phase, the propagation phase and the expansion phase (Fig. 1).

In the **pre-mixing phase** a coarsely mixed region of molten corium and coolant water is formed. The melt and the water are separated by a vapour film, so the heat transfer between the melt and the water is relatively low. In the **triggering phase** the steam explosion is triggered. The triggering event is a disturbance that destabilizes the vapour film around a melt particle allowing liquid-liquid contact, which leads to locally enhanced heat transfer, pressurization and local fine fragmentation. During the **propagation phase** there is an escalation process resulting from the coupling between the pressure-wave propagation, the fine fragmentation, and the heat transfer after the triggering event. During the **expansion phase** the thermal energy of the coolant is converted into mechanical energy. The expansion of the high-pressure pre-mixture of dispersed molten fuel, water and vapour against the inertial constraints imposed by the surroundings determines the damage potential of the steam explosion. A more comprehensive description of the steam-explosion phases is presented in [1] to [3].

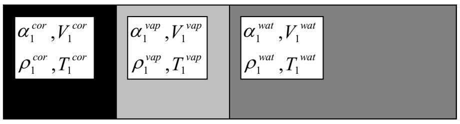
To be able to treat the steam explosion with a general purpose CFD code, an appropriate fit-for-purpose analytical model of the steam explosion was developed. In contrast to specialized steam-explosion CFD codes, where the steam explosion is modelled on a micro-scale using fundamental averaged multiphase flow conservation equations ([1], [2], [5] to [7]), in the presented approach the steam explosion is modelled reasonably simplified as an expanding high-pressure pre-mixture of dispersed molten fuel, liquid water and vapour. A similar approach was also used in the steam-explosion study presented in [4], where the steam pare obravnavali bolj preprosto kot raztezajoč visokotlačni parni mehur.

V splošnem predlagani model eksplozije pare temelji na Hicks-Menziesovem termodinamičnem postopku [1], vendar poleg tega upošteva tudi zamisel mikrointerakcijskega območja [8]. Zamisel mikrointerakcijskega območja praktično pomeni, da med eksplozijo pri termični interakciji med delci taline in hladivom ne sodeluje celotno hladivo, ampak le tisto, ki se nahaja v okolici delcev taline. Na sliki 2 je shematično prikazan model eksplozije pare. Staljena sredica je označena s črno barvo in nadpisom *cor*, vodna para s svetlo sivo barvo in nadpisom *vap* in kapljevita voda s temno sivo barvo in nadpisom *wat*. Predpostavili smo, da si vse faze delijo isto hitrostno polje in isti tlak, kar je smiselna poenostavitev. V prikazani nadzorni prostornini je vsaka faza opisana s prostorninskim deležem faze α, prostornino V, gostoto ρ in temperaturo T. Mikrointerakcijsko

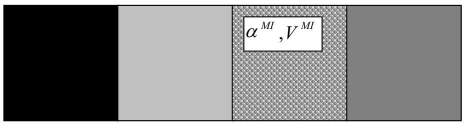
explosion was treated less sophisticatedly as an expanding high-pressure vapour bubble.

In general, the developed steam-explosion model is based on the Hicks-Menzies thermodynamic approach [1], taking into account the micro-interaction zone concept [8]. According to the micro-interaction zone concept not all the coolant thermally participates in the explosion, but only the coolant that is in the surrounding of the melt particles. In Figure 2 the steam-explosion model is schematically presented. The corium phase is denoted by the black colour and the superscript *cor*, the vapour phase by the light-grey colour and the superscript *vap,* and the liquid water phase with the dark-grey colour and the superscript *wat*. It was assumed that all the phases share the same velocity field and the same pressure, which is a reasonable simplification. In the presented control volume each phase is described with the phase volume fraction α, volume V, density ρ and temperature T.

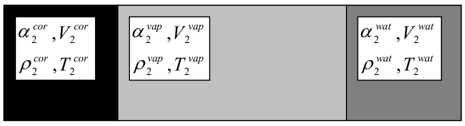
a) Faza mešanja (indeks 1) / Premixing phase (index 1)



b) Faza sprožitve in širjenja / Triggering and Propagation phase



c) Konec faze širjenja in začetek faze raztezanja (indeks 2) / End of Propagation phase and Start of Expansion phase (index 2)



d) Konec faze raztezanja (indeks 3) / End of Expansion phase (index 3)

Sl. 2. *Shema modela eksplozije pare (črna – staljena sredica, svetlo siva – para, temno siva – kapljevita voda, pikčasta siva – kapljevita voda v mikrointerakcijski coni)*

Fig. 2. *Schematic presentation of steam-explosion model (black – molten core, light grey - vapour, dark grey – liquid water, dotted grey – liquid water in micro-interaction zone)*

območje je označeno s pikčasto sivo barvo in indeksom *MI*.

V modelu smo predpostavili, da se ves prenos toplote med staljenim gorivom in hladivom dogodi v prvih treh fazah eksplozije pare in da se v fazi raztezanja proizvedena para, ki je pod visokim tlakom, razteza adiabatno. Opravljeno delo med predpostavljeno adiabatno fazo raztezanja $A_{2,3}$ lahko izračunamo iz enačbe:

The micro-interaction zone is denoted with the dotted grey colour and the index *MI*.

In the model it was assumed that all the heat transfer from the molten fuel to the coolant occurs during the first three steam-explosion phases, and that during the expansion phase the generated vapour, which is at high pressure, adiabatically expands. The work performed during the presumed adiabatic expansion phase $A_{2,3}$ can be calculated as:

$$A_{2\to3}=\int_{V_2^{vap}}^{V_3^{vap}} p\,dV=-\frac{p_2\left(V_2^{vap}\right)^{\kappa}}{\kappa-1}\frac{1}{V^{\kappa-1}}\Bigg|_{V_2^{vap}}^{V_3^{vap}}=\frac{p_2V_2^{vap}}{\kappa-1}\left(1-\left(\frac{p_3}{p_2}\right)^{\frac{\kappa-1}{\kappa}}\right) \quad (1),$$

kjer sta p_2 in p_3 tlaka na začetku in na koncu faze raztezanja, κ pa razmerje med specifično toploto pare pri stalnem tlaku in pri stalni prostornini. Pomemben parameter eksplozije pare je energijski izkoristek eksplozije pare, ki ga merijo tudi pri preizkusih eksplozije pare, in pomeni razmerje med opravljenim mehanskim delom med eksplozijo in začetno notranjo energijo staljene sredice [1]. V našem modelu pomeni energijski izkoristek eksplozije pare η osnovo za izračun vseh preostalih parametrov eksplozije pare. Ko izberemo razmere med fazo mešanja, lahko tlak na začetku faze raztezanja p_2 izračunamo iterativno z enačbo:

where p_2 and p_3 are the pressures at the start and the end of the expansion phase, and κ is the ratio of the vapour specific heats at constant pressure and at constant volume. An important parameter of the steam explosion is the steam-explosion energy-conversion ratio, which is also quantified in steam-explosion experiments and reflects how much internal energy of the melt is transformed into the mechanical energy of the explosion [1]. In our model the steam-explosion energy-conversion ratio, η, was used as the basis for the calculation of all the other steam-explosion parameters. After the conditions during the pre-mixing phase are chosen, the pressure at the start of the expansion phase, p_2, can be calculated by iteratively solving the equation:

$$p_2=\eta\frac{(\kappa-1)\,\rho_1^{cor}\alpha_1^{cor}c^{cor}\left(T_1^{cor}-T_1^{sat}\right)}{\alpha_2^{vap}\left(1-\left(\frac{p_3}{p_2}\right)^{\frac{\kappa-1}{\kappa}}\right)} \quad (2),$$

kjer so p_3 tlak v zadrževalnem hramu, c^{cor} specifična toplota sredice in T_1^{sat} temperatura nasičenja vode pri tlaku v zadrževalnem hramu. Prostorninski delež mikrointerakcijskega območja α^{MI}, ki določa prostorninski delež pare na začetku faze raztezanja $\alpha_2^{vap}=\alpha^{MI}+\alpha_1^{vap}$, smo izbrali tako, da je bil tlak p_2 na začetku faze raztezanja največji, pri čemer smo upoštevali fizikalno izvedljivost pojava. Zaradi predpostavke o adiabatnem raztezanju pare je mogoče gostoto mešanice med raztezanjem $\rho_{2\to3}^{mix}$ izračunati le kot funkcijo tlaka:

where p_3 is the containment pressure, c^{cor} is the core specific heat and T_1^{sat} is the water-saturation temperature at the containment pressure. The volume fraction of the micro-interaction zone α^{MI}, which determines the vapour volume fraction at the beginning of the expansion phase $\alpha_2^{vap}=\alpha^{MI}+\alpha_1^{vap}$, was chosen in such a manner that the pressure at the start of the expansion phase, p_2, was maximized, considering the physical feasibility of the process. Due to the assumption of the adiabatic vapour expansion, the density of the pre-mixture during the expansion process $\rho_{2\to3}^{mix}$ can be calculated solely as a function of pressure:

$$\rho_{2\to3}^{mix}(p)=\frac{\rho_2^{mix}}{\left(1-\alpha_2^{vap}\right)+\dfrac{\alpha_2^{vap}\rho_2^{vap}}{\rho_{2\to3}^{vap}(p)}}=\frac{\rho_2^{mix}}{1+\alpha_2^{vap}\left(\left(\dfrac{p_2}{p}\right)^{\frac{1}{\kappa}}-1\right)} \quad (3),$$

kjer sta ρ_2^{mix} gostota mešanice na začetku faze raztezanja in $\rho_{2\to3}^{vap}$ gostota pare med fazo raztezanja.

where ρ_2^{mix} is the pre-mixture density at the start of the expansion phase and $\rho_{2\to3}^{vap}$ is the vapour density during the expansion phase.

Z razvitim analitičnim modelom eksplozije pare določimo začetne pogoje na začetku faze raztezanja, samo fazo raztezanja pa je treba simulirati s programom za RDT ob upoštevanju enačbe stanja mešanice (en. 3). Pomanjkljivost predlaganega parametričnega modela eksplozije pare je, da je izračunan tlak mešanice p_2 na začetku faze raztezanja odvisen od izbranih razmer med fazo mešanja, saj je mogoče doseči enak energijski izkoristek eksplozije pare η z različnimi kombinacijami prostorninskega deleža pare v mešanici α_2^{vap} in tlaka mešanice p_2 (nižji α_2^{vap} povzroči višji p_2). Ker so razdiralne posledice eksplozije odvisne predvsem od tlačnega sunka (tj. integrala tlaka po času), ta lastnost modela ni resna pomanjkljivost za našo študijo. Namreč, pri nižjem α_2^{vap} je zaradi enačbe stanja mešanice (en. 3) tudi čas trajanja tlačnega impulza krajši, kar nadomesti vpliv povišanega največjega tlaka. Sicer pa je treba zaradi velikih negotovosti razumevanja in modeliranja eksplozij pare pri kateremkoli postopku postopati dovolj konservativno. Natančen opis razvitega modela eksplozije pare je podan v [9].

1.2 Model računske dinamike tekočin

Večfazni tok med četrto fazo eksplozije pare, tj. fazo raztezanja, smo simulirali s programom CFX-5.7.1. Večfazni tok sestavljajo tri faze: faza mešanice (mešanica razpršenega staljenega goriva, kapljevite vode in vodne pare), faza kapljevite vode in faza zraka. Da bi lahko opazovali tudi tlačne valove, smo vse tri tekočine obravnavali kot stisljive in jih modelirali s homogenim Eulerjevim modelom, ki predpostavlja, da si vse faze delijo skupno hitrostno in tlačno polje. Vpliv turbulence smo upoštevali z modelom turbulence k-ε. Energijske enačbe ni bilo treba reševati, saj smo prenos toplote med eksplozijo pare upoštevali že pri začetnih pogojih, ohlajanje pare v mešanici med raztezanjem pa smo upoštevali že z adiabatno enačbo stanja mešanice (en. 3). Enačbo stanja vode smo določili po standardnih preglednicah pare, zrak pa smo obravnavali kot idealen plin. Za preostale snovske lastnosti smo vzeli vrednosti, ki jih podaja program CFX-5.7.1.

Ker se izračuni RDT niso zbliževali na razmeroma redki numerični mreži, ki bi bila s fizikalnega vidika sicer ustrezna, in ker bi bili potrebni računski časi za izračun na trirazsežni (3D) zgoščeni

With the developed analytical steam-explosion model the initial conditions at the start of the expansion phase are determined, whereas the expansion phase itself has to be simulated with the CFD code, taking into account the derived equation of state for the pre-mixture (Eq. 3). The drawback of the proposed parametrical steam-explosion model is that the calculated pre-mixture high-pressure p_2 at the start of the expansion phase depends on the chosen pre-mixing conditions, since an identical steam-explosion energy conversion ratio η can be obtained with different combinations of the pre-mixture vapour fraction α_2^{vap} and pre-mixture pressure p_2 (lower α_2^{vap} results in a higher p_2). As the destructive consequences of an explosion depend mainly on the pressure impulse of the explosion (i.e., the integral of pressure over time), this characteristic of the model does not present a severe weakness for our study. Namely, according to the pre-mixture equation of state (Eq. 3), the duration of the pressure impulse is also shorter at lower α_2^{vap}, which compensates for the effect of the increased pressure peak. In any case, due to the large uncertainties in the understanding and modelling of steam explosions, a sufficient degree of conservatism has to be introduced in whichever approach is taken. A detailed description of the developed steam-explosion model is provided in [9].

1.2 Computational Fluid Dynamics Model

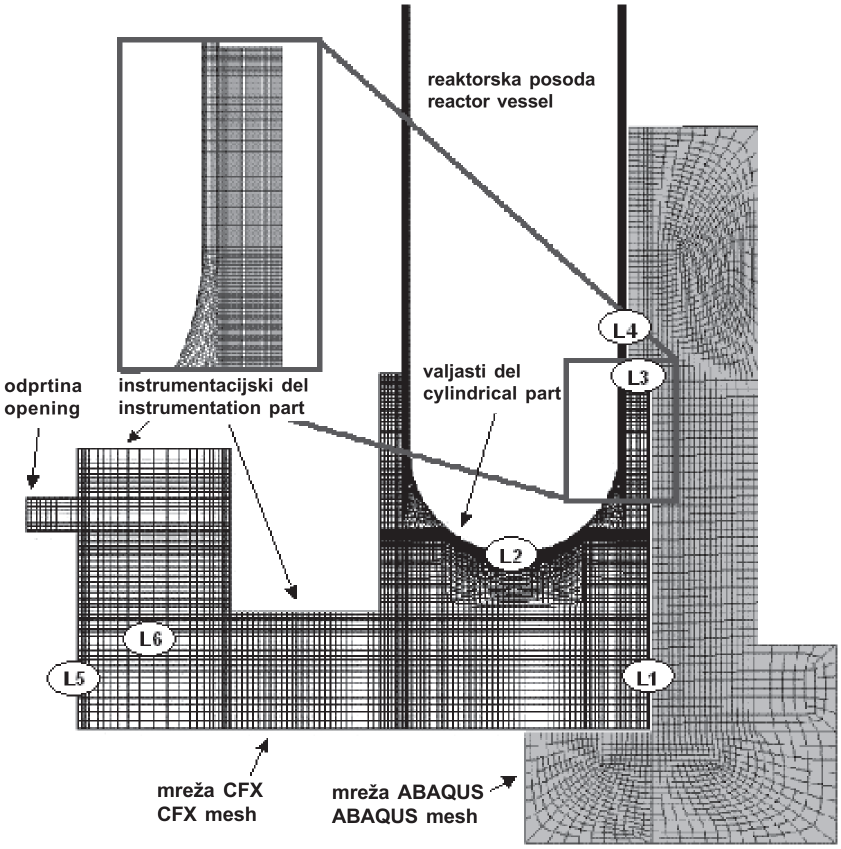
The multiphase flow during the steam-explosion expansion phase, consisting of three phases – the pre-mixture phase (mixture of dispersed molten fuel, liquid water and vapour), the liquid water phase and the air phase – was simulated using the CFX-5.7.1 code. To simulate the pressure waves, all three fluids were treated as compressible and were modelled by the homogeneous Eulerian model, which assumes that all the phases share a common velocity and pressure field. The effect of turbulence was taken into account with the k-ε turbulence model. The energy equation was not solved since the heat transfer during the steam explosion was taken into account already during the initial conditions, and the cooling of the vapour in the pre-mixture during the expansion process was taken into account already within the adiabatic pre-mixture equation of state (Eq. 3). The equation of state for water was determined using the standard water steam tables and air was treated as an ideal gas. For the other material properties the default values as provided by the CFX-5.7.1 code were used.

Since the CFD calculation did not converge on a relatively coarse numerical grid appropriate from the physical point of view, and since the required CPU times mreži bistveno predolgi, smo izračune opravili z dvorazsežnim (2D) geometrijskim modelom. Da bi zagotovili, da bodo rezultati simuliranj z 2D modelom kakovostno in kolikostno veljavni tudi za pravo 3D geometrijsko obliko reaktorske votline, je bilo treba izbrati ustrezno 2D geometrijsko obliko in ustrezne začetne ter robne pogoje. Zato smo uporabili dva različna 2D modela 3D geometrije reaktorske votline: **osno simetrični model**, ki je omejen na osno simetrične pojave v valjastem delu reaktorske votline neposredno pod reaktorsko posodo in okoli nje, ter **2D model reaktorske votline**, ki sicer obravnava celotno reaktorsko votlino, vendar ne upošteva 3D geometrijske oblike reaktorske votline in 3D narave pojavov. Geometrijska oblika in mreža 2D modela reaktorske votline sta prikazani na sliki 3. Natančen opis razvitega modela RDT je podan v [9].

Težave z zbliževanjem zaradi nezveznih začetnih pogojev smo odpravili tako, da smo vse

for the three-dimensional (3D) calculation on the refined grid would be exceedingly long, the calculations were performed using a two-dimensional (2D) geometry model. To ensure that the simulation results with the 2D model would also be qualitatively and quantitatively valid for the real 3D geometry of the reactor cavity, the 2D geometry and the initial conditions had to be appropriately selected. Therefore, the simulations were performed using two different 2D approximations for the 3D geometry of the reactor cavity: the **axially symmetric model**, which is limited to axially symmetric phenomena in the cylindrical part of the reactor cavity directly below the reactor vessel and around it; and the **2D cavity model**, which treats the whole reactor cavity but does not take into account the 3D geometry of the cavity and the 3D nature of the phenomena. The geometry and mesh of the 2D cavity model are presented in Figure 3. A detailed description of the CFD model is provided in [9].

To avoid convergence problems due to discontinuous initial conditions, all the discontinuous



Sl. 3. *Geometrijska oblika in mreža modela CFX računske dinamike tekočin za 2D model reaktorske votline in model mehanike trdnin ABAQUS za osno simetričen model stene reaktorske votline*
Fig. 3. *Geometry and mesh of CFX computational fluid dynamics 2D cavity model of reactor cavity and ABAQUS structural axially symmetric model of cavity wall*

nezvezne začetne pogoje ustrezno zgladili z zvezno odvedljivo posplošeno sigmoidno funkcijo:

initial conditions were appropriately smoothed with the continuously differentiable sigmoid-type function:

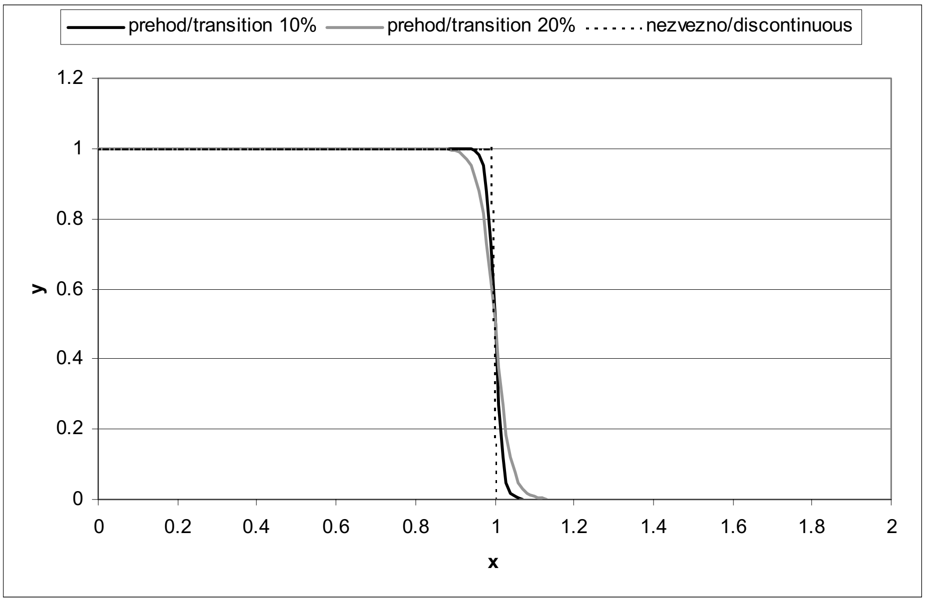
$$y(x) = 1 - \frac{1}{1 + e^{-10\frac{(x - x0)}{\Delta x}}} \qquad (4),$$

kjer je $x0$ točka, v kateri se funkciji $y(x)$ spremeni vrednost od 1 na 0 prek območja Δx. Na sliki 4 je predstavljen graf funkcije (en. 4) za $x0 = 1$ z $\Delta x/x0 = 0{,}1$ (črna krivulja) in $\Delta x/x0 = 0{,}2$ (siva krivulja) v primerjavi z nezvezno funkcijo (prekinjena črta).

Pri opravljenih izračunih smo vse nezvezne začetne pogoje smiselno zgladili prek območja 10% v navpični smeri in prek območja 20% v vodoravni smeri. Z zvezno odvedljivo funkcijo je bilo treba zgladiti predvsem začetno tlačno polje, saj se je, najverjetneje zaradi uporabljene interpolacijske sheme Rie-Chow v programu za RDT, tudi rešitev zglajenega začetnega problema, pri katerem pa je bila uporabljena nezvezno odvedljiva funkcija, razhajala po nekaj časovnih korakih. Interpolacijska shema Rhie-Chow se v programih za RDT uporablja za izračun tlaka na nepremaknjenih numeričnih mrežah in pri obravnavi velike večine splošnih tokov ne povzroča težav [10].

where $x0$ is the point where the function $y(x)$ changes its value from 1 to 0 over the range Δx. In Figure 4 the graph of the function (Eq. 4) is presented for $x0 = 1$ with $\Delta x/x0 = 0{,}1$ (black curve) and with $\Delta x/x0 = 0{,}2$ (grey curve) in comparison with the discontinuous function (dotted line).

In the performed simulations all the discontinuous initial conditions were reasonably smoothed over the range of 10% in the vertical direction and over the range of 20% in the horizontal direction. In particular, the initial pressure field had to be smoothed with a continuously differentiable function, since most probably due to the used Rhie-Chow pressure interpolation scheme in the CFD code, also the solution of a smoothed initial problem, but with a discontinuous differentiable function, diverged after just a few performed time steps. The Rhie-Chow interpolation scheme is used in CFD codes for the pressure calculation on collocated numerical grids and works relatively well for the vast majority of general flows [10].



Sl. 4. *Graf posplošene sigmoidne funkcije za 10% in 20% območje prehoda $\Delta x/x0$ v primerjavi z nezvezno funkcijo*

Fig. 4. *Graph of sigmoid-type function for 10% and 20% transition range $\Delta x/x0$ in comparison with discontinuous function*

1.3 Model mehanike trdnin

Glede na problem smo ocenili, da za ustrezno modeliranje sten reaktorske votline zadoščata dva modela: **osno simetrični model** valjastega dela reaktorske votline in **3D model** instrumentacijskega dela reaktorske votline. Modela ustrezno upoštevata dejstvo, da so stene reaktorske votline do določene višine obdane s temelji zadrževalnega hrama.

Vse stene, ki so v tipičnem tlačnovodnem jedrskem reaktorju izpostavljene mogočim vplivom eksplozije pare, so narejene iz armiranega betona. Predpostavili smo, da je najmanjša potrebna tlačna trdnost betona 30 MPa in da je najmanjša natezna trdnost betonskega jekla 400 MPa. V simulacijah smo gradiva modelirali zelo poenostavljeno, saj naš cilj ni bil natančno napovedovanje poteka deformacij zapletenega nehomogenega železobetona, ampak predvsem zaznavanje pomembnih poškodb. Zato smo predpostavili, da se železobeton tako pri tlačnih kakor nateznih napetostih odziva kot homogen in pretežno elastičen material. Ob predpostavki, da je v železobetonu 10 vol.% železa, smo za dejanske parametre našega homogenega modela izračunali naslednje vrednosti: gostota 2945 kg/m^3, Young-ov modul 45 GPa in Poissonovo razmerje 0,174. Predpostavili smo, da je meja plastičnosti 250 MPa in tako omogočili uporabo modelov poškodb, ki so na voljo v programu ABAQUS/Explicit. Predpostavili smo, da pride do poškodb, če hidrostatični tlak (natezni ali tlačni) preseže vrednost 50 MPa. Obremenitve sten vključujejo lastno težo in potek tlaka, ki smo ga dobili iz rezultatov simuliranj s programom CFX. Časovne in krajevne spremembe tlaka smo vključili v program ABAQUS/Explicit s FORTRAN podprogramom VDLOAD. Vrednosti med razpoložljivimi podatki smo določili z linearno interpolacijo po času in po kraju.

Na sliki 3 je prikazana mreža končnih elementov za osno simetričen model stene reaktorske votline. Natančen opis modela mehanike trdnin je podan v [9].

2 REZULTATI

2.1 Potek eksplozije pare

Da bi dobili fizikalno sliko dogajanja med eksplozijo pare v poplavljeni reaktorski votlini tipičnega tlačnovodnega jedrskega reaktorja in da bi okvirno ocenili tlačne obremenitve sten reaktorske

1.3 Structural Model

Based on the geometry of the problem, it is deemed sufficient to develop two models: an **axially symmetric model** of the cylindrical part of the reactor cavity and a **3D model** of the in-core instrumentation access. These models properly take into account the fact that the cavity walls are to a significant height embedded by the foundation of other containment structures.

All the walls potentially affected by the steam explosion in a typical PWR reactor cavity are made of heavily reinforced concrete. The minimum required compressive strength of the concrete was assumed to be 30 MPa, and the minimum required yield strength of the reinforcement steel was assumed to be 400 MPa. The material model used in the simulations is simplified to a significant extent and is aimed at the detection of significant damage rather than to give an accurate account on the deformation history of the complex and non-homogeneous reinforced concrete. A homogeneous and essentially elastic response was therefore assumed, both in tension and compression. The main “effective” parameters of the homogenous model, assuming about 10 vol.% of reinforcement steel, were as follows: a density of 2945 kg/m^3, a Young’s modulus of 45 GPa and a Poisson’s ratio of 0.174. The yield stress of 250 MPa was arbitrarily assumed to enable the use of approximate damage models, which are built in the ABAQUS/Explicit code. The damage was assumed to occur with hydrostatic pressure (tensile or compressive) exceeding 50 MPa. The loads include dead weight and pressure histories obtained from the CFX simulation results. The variations of pressures in time and space were included in the ABAQUS/Explicit code using the FORTRAN subroutine VDLOAD. Linear interpolation between the data points was used both in space and in time.

The finite-element model of the cavity walls for the axially symmetric model is presented in Figure 3. A detailed description of the structural model is provided in [9].

2 RESULTS

2.1 Steam-Explosion Scenario

A comprehensive reasonably conservative parametric analysis considering different steam-explosion scenarios was performed to get an insight into the steam-explosion phenomenon in a typical votline in reaktorske posode med eksplozijo pare, smo opravili obsežno, smiselno konservativno parametrično analizo različnih potekov eksplozije pare [9]. V tem prispevku predstavljamo le dva tipična primera eksplozije pare, ki se razlikujeta po kraju izliva taline (stranski izliv in osrednji izliv). Skupne predpostavke v obeh predstavljenih primerih so naslednje: tlak v zadrževalnem hramu: 1,5 bar; temperatura vode v reaktorski votlini: 343 K; raven vode v reaktorski votlini: 3 m; temperatura staljene sredice: 2800 K; velikost izliva taline: 0,25 m^2; primarni sistem je tlačno razbremenjen, prostorninski deleži v mešanici: staljena sredica 0,1; vodna para 0,1; kapljevita voda 0,8 in energijski izkoristek eksplozije pare 1 odstotek, kar privede do tlaka mešanice 400 bar. Pri preizkusih s prototipičnimi gradivi sredice (UO_2+ZrO_2, itn.) ([1] do [3]) so bili največji izkoristki eksplozij pare približno 0,5 odstotka in največje izmerjene vrednosti tlačnih konic približno 200 bar. Glede na te preizkuse, ki so bili opravljeni na pomanjšanih modelih reaktorskih razmer, so izbrane predpostavke konservativne.

Primer 1 predstavlja stranski izliv taline na koncu reaktorske votline, ki privede do nastanka mešanice debeline 0,5 m, **primer 2** pa predstavlja izliv taline v sredini reaktorske votline, ki privede do nastanka mešanice z radijem 0,8 m.

2.2 Rezultati simuliranj in razprava

Da bi dobili kakovostno in kolikostno sliko večfaznega toka med eksplozijo pare v reaktorski votlini, so na slikah 5 in 6 predstavljeni osnovni rezultati simulacij RDT četrte faze eksplozije pare, tj. faze raztezanja, za stranski izliv taline (primer 1) in za osrednji izliv taline (primer 2). Na slikah je prikazan časovni razvoj tlačnega polja in prostorninskega deleža mešanice ter vode. Za osrednji izliv taline je prikazano tudi hitrostno polje. Vidimo, da se fazne meje med mešanico, vodo in zrakom, ki so na začetku simulacije ostre, s časom razlezejo zaradi numerične difuzije, ki je značilna za diskretne numerične metode ([5] in [7]). Ta razpršitev medfaznih površin zaradi narave našega postopka obravnave eksplozije pare nima večjega vpliva na bistvene rezultate simuliranj in prav tako ne na sklepe opravljene študije.

Za simuliranje primera 1 (stranski izliv taline; slika 5) smo uporabili 2D model reaktorske votline, ki obravnava celotno reaktorsko votlino. Izhodišče eksplozije pare pri začetnem času (t =0 sekund) je

PWR cavity, to provide a rough estimation of the expected pressure loadings on the cavity structures during a steam explosion and to assess the vulnerabilities of cavity structures to steam explosions [9]. In this paper only two typical cases differing in the location of the melt pour (side pour and central pour) are presented in some detail. The common assumptions of the presented cases are as follows: containment pressure, 1.5 bar; cavity water temperature, 343 K; water level in cavity, 3 m; core temperature, 2800 K; melt pour size, 0.25 m^2; and a depressurised primary system. The pre-mixture volume fractions are as follows: core 0.1, vapour 0.1, liquid water 0.8, and steam explosion energy conversion ratio 1%, resulting in the pre-mixture pressure of 400 bar. During experiments with prototypic corium materials (UO_2+ZrO_2, etc.) ([1] to [3]) the maximum obtained steam-explosion energy conversion ratios are about 0.5%, and the maximum measured peak pressures are about 200 bar, so the assumptions are conservative regarding these small-scale experiments.

Case 1 presents a side-melt pour resulting in a pre-mixture of width 0.5 m at the cavity-end side, and **Case 2** presents a central-melt pour resulting in a pre-mixture with radius 0.8 m in the cavity centre.

2.2 Simulation Results and Discussion

To get a qualitative and quantitative picture of the multiphase flow during the steam explosion in the reactor cavity, in Figures 5 and 6 the basic results of the CFD simulation of the steam-explosion expansion phase for the side-melt pour (Case 1) and the central-melt pour (Case 2) are presented. In the figures the time development of the pressure field and the volume fractions of the mixture and water are shown. For the central melt pour the velocity field is also presented. It can be seen that the initially sharp interfaces between the mixture, the water and the air phases spread during the transient due to numerical diffusion, which is characteristic for discrete numerical methods ([5] and [7]). Due to the nature of our modelling approach this interface spreading has no significant influence on the main simulation results and on the conclusions of the performed study.

For the simulation of Case 1 (side-melt pour; Figure 5) the 2D cavity model, treating the entire reactor cavity in 2D, was used. The origin of the steam explosion at the initial time (t = 0 seconds) is indicated by the označeno s svetlo sivo pobarvanim visokotlačnim območjem in s svetlo sivo pobarvanim območjem mešanice na desni strani pod reaktorsko posodo. Zaradi visokega tlaka v mešanici, ki nastane zaradi burnega uparjanja, se začne mešanica raztezati in odrivati vodo in zrak iz reaktorske votline skozi ozek obročast kanal okoli reaktorske posode in skozi odprtino na levi strani reaktorske votline v instrumentacijskem delu. Med dvigovanjem ravni vode le ta trči v dno reaktorske posode (t = 0,013 s) in na tem območju povzroči lokalni porast tlaka, ki potiska reaktorsko posodo na stran in navzgor. Mešanica se razteza hitreje v navpični smeri proti zraku, saj je gostota zraka precej manjša od gostote vode. Po 0,044 s mešanica trči v zgornji del reaktorske votline (točka L3 na sliki 3), kjer se začne ozek obročast del reaktorske votline, in tam se tlak krajevno zviša. Medtem ko se tlak v reaktorski votlini naglo znižuje, se mešanica razteza še naprej in potiska vodo proti instrumentacijskem delu reaktorske votline. Po približno pol sekunde doseže raven vode odprtino v instrumentacijskem delu in voda začne odtekati v zadrževalni hram. Največje hitrosti tekočin presežejo 300 m/s in so dosežene na izhodu iz obročastega kanala po približno 0,05 s.

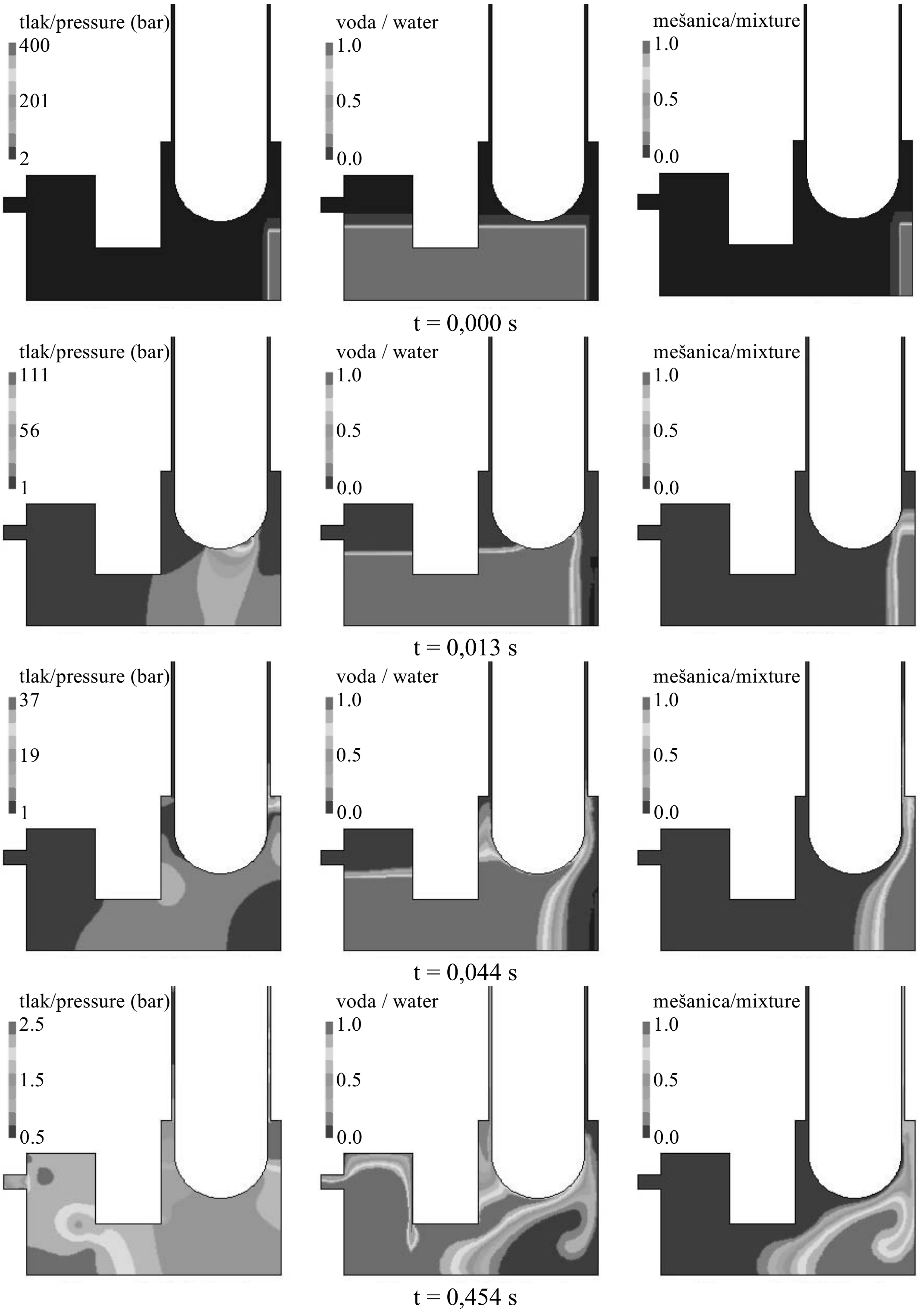
Primer 2 (osrednji izliv taline; sl. 6) smo simulirali z osno simetričnim modelom reaktorske votline, ki obravnava le valjasti del reaktorske votline. Področje, kjer pride do eksplozije pare, je označeno s svetlo sivo pobarvanim visokotlačnim območjem in s svetlo sivo pobarvanim območjem mešanice ob simetrijski osi pod reaktorsko posodo. Zaradi visokega tlaka v mešanici se začne mešanica, ki je v sredini reaktorske votline, raztezati in odrivati vodo in zrak skozi obročast kanal okoli reaktorske posode. Po 0,0125 s je mešanica praktično popolnoma obdana z vodo, saj se lahko voda odmika le navzgor (v stranskih stenah valjastega dela reaktorske votline nismo modelirali nobenih odprtin). Kasneje, ko so tlaki že nizki, steče voda nazaj v reaktorsko votlino in ustvari se velik vrtinec. Največje hitrosti tekočin presežejo 300 m/s in so dosežene na izhodu iz obročastega kanala po približno 0,05 s.

Na slikah 7 in 8 je prikazan potek tlaka v izbranih krajih, ki so pomembne z vidika ocene ogroženosti sten reaktorske votline in reaktorske posode. Te lokacije so označene na sliki 3 z L1 do L6. Pri 2D modelu reaktorske votline so tlačne krivulje podane za vse lokacije L1 do L6 (sl. 7), medtem ko lahko pri osno simetričnem modelu, zaradi omejene

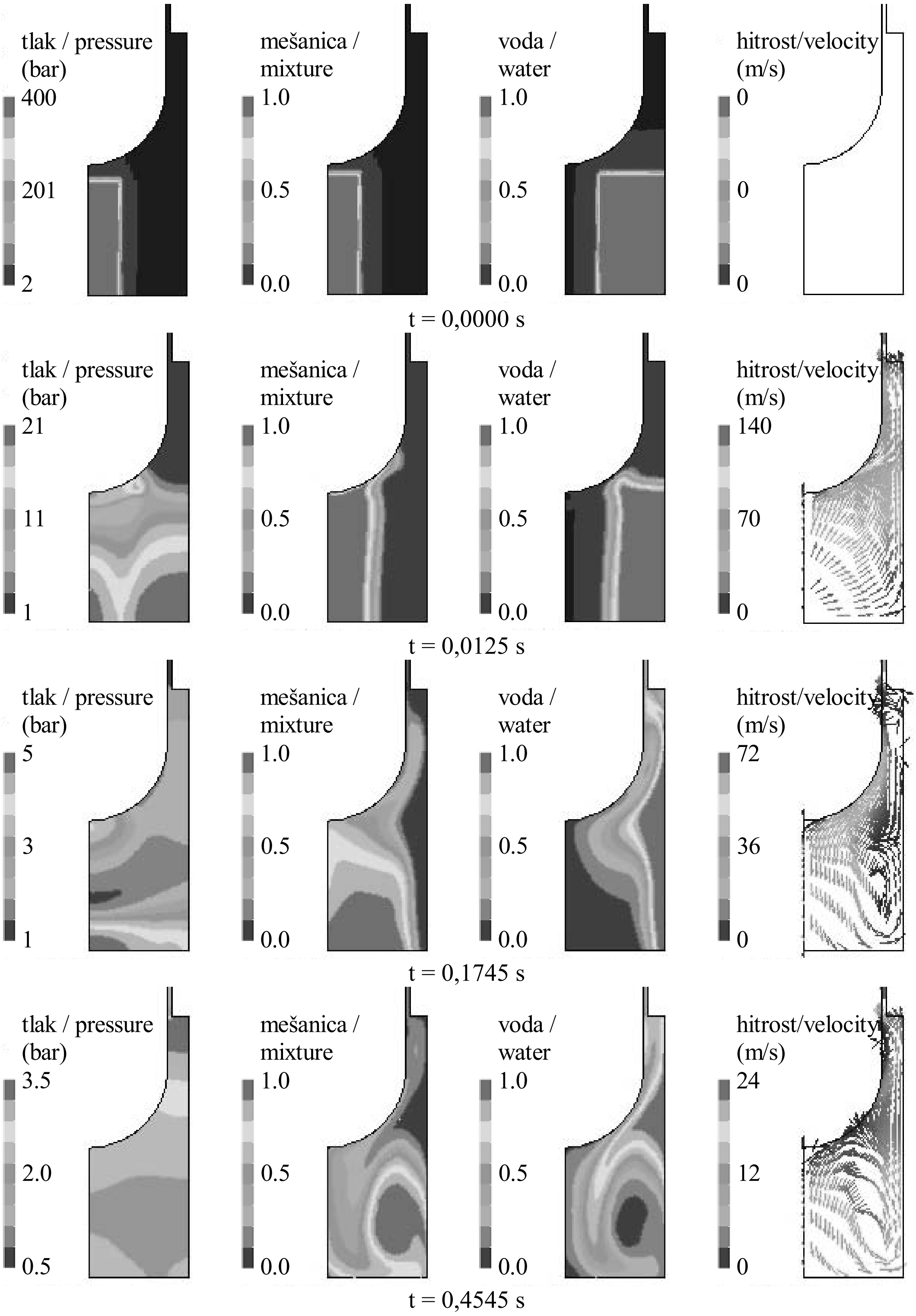
light-grey-coloured high-pressure region and by the light-grey coloured pre-mixture region embedded on the right-hand side below the reactor vessel. Due to the high pressure in the mixture, which is caused by the generated vapour, the mixture phase expands and pushes the water and air out of the cavity through the annulus around the reactor vessel and through the opening on the left-hand side in the instrumentation part of the cavity. As the water level rises, the water eventually hits the bottom of the reactor vessel (t = 0.013 s) causing a local pressure increase in this region, pressing the vessel sideways and upwards. The mixture phase expands faster towards the air since the density of air is much lower than the density of water. After 0.044 s the mixture phase hits the upper part of the cavity (point L3 in Figure 3), where the narrow annular part of the cavity begins, and the pressure there locally increases. As the pressure rapidly decreases with time, the mixture phase expands further and pushes the water towards the instrumentation part of the cavity. After about half a second the water level in the instrumentation part reaches the opening and is discharged into the containment. The maximum fluid velocities are above 300 m/s and are reached at the outlet of the annulus at about 0.05 s.

Case 2 (central-melt pour; Figure 6) was simulated using the axially symmetric cavity model, where only the cylindrical part of the reactor cavity is treated. The area indicating the origin of the steam explosion is shown with the light-grey-coloured high-pressure region and with the light-grey-coloured mixture region embedded below the centre of the reactor vessel. The high-pressure in the pre-mixing zone in the central part of the cavity causes an expansion of the mixture, which pushes the water and air through the annulus around the reactor vessel. After 0.0125 s the mixture is practically completely surrounded with water, as the water can be pushed only upwards (no openings in the side walls of the cylindrical part of the cavity are modelled). At later times, when the pressure is already low, the water flows back into the cavity and a big vortex is formed. The maximum fluid velocities are above 300 m/s and are reached at the outlet of the annulus at about 0.05 seconds.

In Figures 7 and 8 the pressure histories at selected locations, which are of importance for the assessment of the vulnerability of cavity structures, are presented. These locations are denoted in Figure 3 with L1 to L6. At the 2D cavity model the pressure curves are given for all the locations L1 to L6 (Figure 7), whereas for the axially symmetric model the



Sl. 5. *Tlak in prostorninski deleži faz v reaktorski votlini za stranski izliv (primer 1) pri različnih časih*
Fig. 5. *Pressure and volume fractions of phases in the reactor cavity for side-melt pour (Case 1) at different times*



Sl. 6. *Tlak, prostorninski deleži faz in hitrostno polje v valjastem delu reaktorske votline za osrednji izliv (primer 2) pri različnih časih*

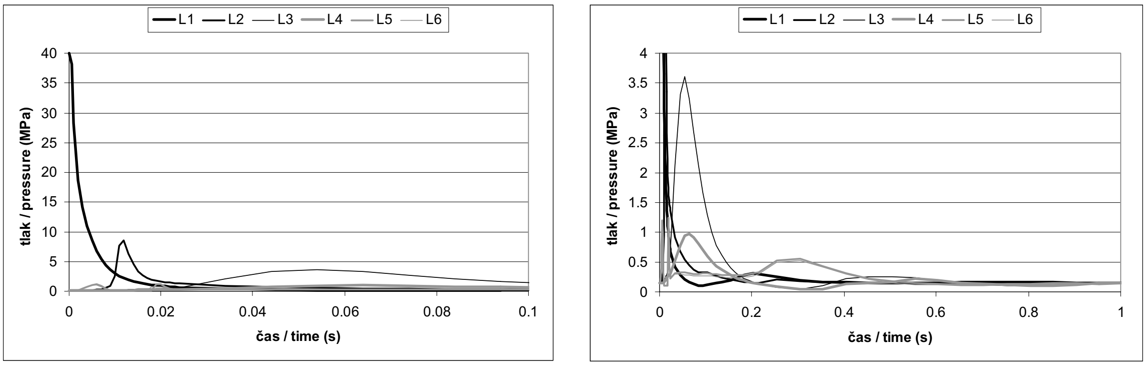
Fig. 6. *Pressure, volume fractions of fluid phases and velocity field in cylindrical part of reactor cavity for central-melt pour (Case 2) at different times*

geometrijske oblike, podamo tlačne krivulje le za kraje L1 do L4 (sl. 8). Vidimo, da je tlak najvišji v prvih milisekundah prehodnega pojava med tlačno razbremenitvijo visokotlačne mešanice, ko proti stenam potujejo tudi tlačni udarni valovi. Tlačne obremenitve sten reaktorske votline pri kasnejših časih, ki jih povzročijo trki tekočin z veliko hitrostjo, so mnogo manjše.

Analiza mehanike trdnin ABAQUS je pokazala, da se stene reaktorske votline ne bi poškodovale, če bi bila tlačna obremenitev sten manjša od 400 barov v valjastem delu reaktorske votline in manjša od 150 barov v instrumentacijskem delu reaktorske votline. S slike 7 in 8 je razvidno, da ti kriteriji poškodbe sten niso preseženi, tako da lahko sklepamo, da se stene reaktorske votline pri obravnavanih eksplozijah pare (primer 1 in primer 2) ne bi poškodovale. To ugotovitev smo potrdili tudi z dinamično analizo mehanike trdnin ABAQUS, pri

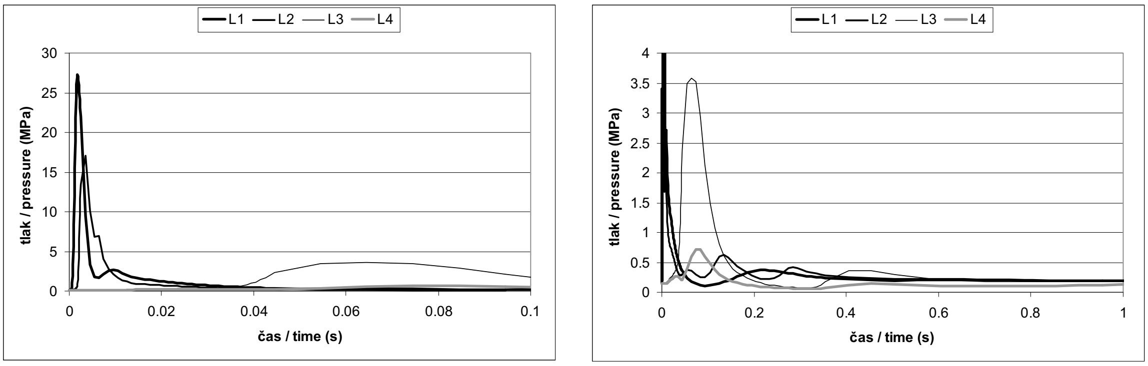
pressure curves can be given only for locations L1 to L4, due to the limited geometry (Figure 8). It can be seen that the pressure is the highest in the first milliseconds of the transient during the pre-mixture high-pressure relief, when the pressure shocks also propagate to the walls. The pressure loads on the cavity walls at later times, which are caused by the impact of the fluids with high velocity, are much lower.

The ABAQUS structural analysis showed that the cavity walls would not be damaged if the pressure loads on the walls in the cylindrical part of the cavity are lower than 400 bar, and in the in-core instrument part of the cavity, lower than 150 bar. From Figures 7 and 8 it can be established that these damage criteria are not exceeded, so one may conclude that the cavity walls during the considered steam-explosion scenarios (Case 1 and Case 2) would not be damaged. This conclusion was also confirmed with dynamic ABAQUS structural mechanical



Sl. 7. *Tlak v izbranih krajih kot funkcija časa (leva stran: začetni del simuliranja, desna stran: celotno simuliranje) za stranski izliv taline (primer 1)*

Fig. 7. *Pressure at selected locations as a function of time (left-hand side: initial part of simulation, right-hand side: full simulation) for side-melt pour (Case 1)*



Sl. 8. *Tlak v izbranih krajih kot funkcija časa (leva stran: začetni del simuliranja, desna stran: celotno simuliranje) za osrednji izliv taline (primer 2)*

Fig. 8. *Pressure at selected locations as a function of time (left-hand side: initial part of simulation, right-hand side: full simulation) for central melt pour (Case 2)*

kateri smo upoštevali časovne poteke tlaka, ki smo jih dobili s simuliranjem RDT. Podrobnosti so predstavljene v [9].

Na sliki 9 je prikazana navpična komponenta tlačne sile na reaktorsko posodo. Navpično komponento tlačne sile smo izračunali z integriranjem relativnega tlaka po površini reaktorske posode v navpični smeri. Sila, ki je potrebna za dvig reaktorske posode tipičnega dvozančnega tlačnovodnega jedrskega reaktorja, znaša približno 120 MN, kar smo konservativno izračunali iz mase reaktorske posode ob predpostavki, da se je vsa sredica že izlila iz reaktorske posode, in sile, potrebne za pretrganje hladnih in toplih vej. Na sliki 9 vidimo, da je največja tlačna sila v navpični smeri pri obeh obravnavanih primerih (primer 1: 50 MN, primer 2: 14 MN) bistveno manjša od konservativno ocenjene sile, potrebne za dvig reaktorske posode, tako da lahko sklepamo, da se pri obravnavanih eksplozijah pare reaktorska posoda ne bi dvignila. Ker bi bilo dno reaktorske posode pri resni nezgodi, ki bi pripeljala do izlitja taline iz reaktorske posode, zaradi visokih temperatur in porušitve oslabljeno, bi se dno reaktorske posode pri visokih tlakih verjetno deformiralo in tako bi bila največja tlačna sila na reaktorsko posodo v navpični smeri še manjša, kar je prikazano na sliki 9.

3 SKLEPI

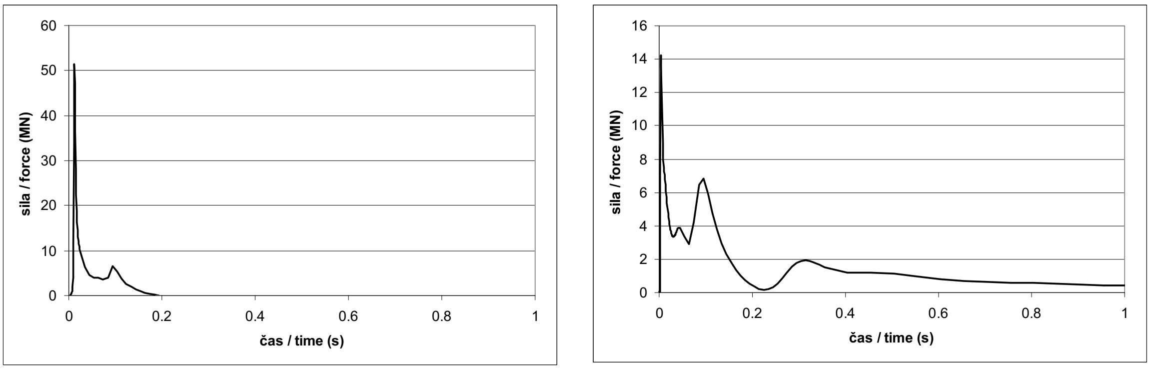
S splošnim programom za RDT smo opravili obsežno, smiselno konservativno parametrično analizo hipotetične eksplozije pare v poplavljeni reaktorski votlini tipičnega tlačnovodnega jedrskega reaktorja [9]. V tem prispevku smo predstavili le dva tipična primera

simulations, where the calculated pressure histories from the CFD simulations were applied. Further details are available in [9].

In Figure 9 the upward pressure force on the reactor vessel is presented. The upward pressure force was calculated as the integral of the relative pressure over the reactor vessel surface in the upward direction. For a typical two-loop PWR the reactor vessel's total restraining force is about 120 MN, calculated conservatively from the reactor-vessel mass (assuming that all the core has left the vessel) and the force needed to shear the cold and hot legs. In Figure 9 it can be seen that in both considered steam-explosion cases the maximum upward pressure force on the reactor vessel is much lower (Case 1: 50 MN, Case 2: 14 MN) than the conservatively estimated reactor vessel's total restraining force, so the reactor vessel would not be lifted in any of these steam explosions. Since during a severe accident resulting in an ex-vessel melt pour the reactor vessel's lower head would be weakened due to its heat up and failure, the reactor vessel's lower head would probably deform during high-pressure loads, and so the maximum upward pressure forces on the reactor vessel are expected to be even lower than presented in Figure 9.

3 CONCLUSIONS

A comprehensive analysis of a hypothetical ex-vessel steam explosion in a typical PWR reactor cavity was performed using a general purpose CFD code [9]. In this paper only two typical ex-vessel steam-explosion cases, differing in the location of



Sl. 9. *Tlačna sila na reaktorsko posodo v navpični smeri kot funkcija časa za primer 1 (leva stran) in primer 2 (desna stran)*

Fig. 9. *Upward pressure force on reactor vessel as a function of time for Case 1 (left-hand side) and Case 2 (right-hand side)*

eksplozije pare v reaktorski votlini, ki se razlikujeta po kraju izliva taline (stranski izliv in osrednji izliv).

Da smo lahko obravnavali eksplozijo pare s splošnim programom za RDT, smo najprej razvili ustrezen namenski model eksplozije pare. Izbrali smo smiselno konservativen potek izliva taline iz reaktorske posode, ki privede do nastanka obsežnega območja mešanice razpršene taline, vode in pare v reaktorski votlini. Predpostavili smo, da je energijski izkoristek eksplozije pare 1 % in izračunali pripadajoč začetni tlak mešanice 400 barov. Pri obeh obravnavanih primerih (stranski in osrednji izliv taline) smo večfazni tok med četrto fazo eksplozije pare, tj. fazo raztezanja, simulirali s programom CFX-5.7.1. Izračunane tlačne obremenitve sten reaktorske votline smo vzeli kot vhodni podatek za ABAQUS simulacijo napetosti v stenah reaktorske votline. Tlačne obremenitve sten reaktorske votline in reaktorske posode smo primerjali s kriteriji poškodb.

Rezultati opravljene analize RDT in analize mehanike trdnin so pokazali, da pri obeh obravnavanih primerih eksplozije pare kriteriji za poškodbe niso preseženi. To pomeni, da se pri eksploziji pare z energijskim izkoristkom 1 %, ki bi sledila predpostavljenemu konservativnemu poteku izliva taline iz reaktorske posode v poplavljeno reaktorsko votlino ob tlačno razbremenjenem primarnem sistemu, stene reaktorske votline v valjastem in instrumentacijskem delu reaktorske votline ne bi poškodovale in da se reaktorska posoda ne bi dvignila.

Celotna analiza eksplozije pare v poplavljeni reaktorski votlini, kjer so obravnavane tudi eksplozije pare z energijskim izkoristkom 10 %, je predstavljena v [9]. Nekaj rezultatov analiz potekev eksplozije pare z energijskim izkoristkom 10 % je predstavljenih tudi v [11].

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the melt pour (side pour and central pour), are presented in some detail.

To be able to perform the analysis with a general purpose CFD code a fit-for-purpose parametric steam-explosion model was developed. A reasonably conservative ex-vessel melt-pour scenario producing a large pre-mixture region was selected. It was assumed that the steam-explosion energy conversion ratio is 1%, resulting in a pre-mixture pressure of 400 bar. The multiphase flow during the steam-explosion expansion phase was simulated by the CFX-5.7.1 code for both considered cases, i.e., the side-melt pour and the central-melt pour. The calculated pressure loads on the cavity walls were taken as the input for the ABAQUS simulation of the stresses in the cavity walls. The pressure loads on the cavity walls and on the reactor vessel were compared with the established damage criteria.

The results of the performed CFD and structural analyses show that the damage criteria are not exceeded during either of the presented two steam-explosion cases. That means that during an ex-vessel steam explosion with an energy conversion ratio of 1%, following a reasonably conservative assumed ex-vessel melt pour at a depressurised primary system, the reactor cavity walls in the cylindrical and in-core instrumentation part of the reactor cavity would not be damaged and the reactor vessel would remain in place.

The complete ex-vessel steam-explosion analysis, where steam explosions with an energy conversion ratio of 10% are also treated, is presented in [9]. Some results of the analysis of the steam-explosion scenarios with an energy conversion ratio of 10% are given in [11].

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