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Simuliranje odgovora zadrževalnega hrama jedrske elektrarne med veliko izlivno nezgodo

Simulation of Nuclear Power Plant Containment Response During a Large-Break Loss-of-Coolant Accident

Ivo Kljenak - Borut Mavko

S termohidravličnim računalniškim programom CONTAIN so bili simulirani pojavi v zadrževalnem hramu jedrske elektrarne med veliko izlivno nezgodo v dvozančnem tlačnovodnem reaktorju. Analizirani so bili tlačni in temperaturni odzivi ter porazdelitve hladiva in energije.

(Ključne besede: elektrarne jedrske, zadrževalni hram, nezgode izlivne, simuliranje)

Containment phenomena during a large-break loss-of-coolant accident in a two-loop pressurized-water reactor nuclear power plant were simulated with the CONTAIN thermal-hydraulic computer code. Pressure and temperature responses as well as coolant and energy distributions were analyzed.

(Keywords: nuclear power plant, containment, loss-of-coolant accident, simulations)

0 UVOD

Simuliranja nezgod v jedrskih elektrarnah s termohidravličnimi računalniškimi programi, ki omogočajo analizo različnih vidikov projektnih in resnih nezgod, lahko močno prispevajo k varnosti postrojenj. Čeprav vsebujejo rezultati določeno nezanesljivost, tovrstna simuliranja prispevajo tudi k boljšemu razumevanju medsebojnega vpliva fizikalnih pojavov, do katerih prihaja med nezgodami.

Računalniški program CONTAIN ([1] in [2]) je bil razvit v Sandia državnih laboratorijih (ZDA) s podporo Zvezne jedrske upravne komisije ZDA. CONTAIN omogoča celovito analizo pojavov v zadrževalnem hramu jedrske elektrarne. Eden izmed osnovnih načrtovanih ciljev CONTAIN-a je upravičeno napovedovanje prehodne funkcije zadrževalnega hrama (fizikalnih, kemičnih in radioloških pogojev) med resnimi in projektnimi nezgodami. Program CONTAIN med drugim vsebuje modele za termodinamiko vodne pare in zraka, pretoke med predelki, kondenzacijo in uparjanje na konstrukcijah in aerosolih, transport, aglomeriranje in usedanje aerosolov ter zgorevanje plinov. Prav tako vsebuje modele za pojave v reaktorski votlini, kakor sta interakcija med staljeno sredico in betonom ter uparjanje hladiva v bazenu. Prevod toplote v konstrukcijah, razpadanje in transport razcepkov, zaostala toplota zaradi radioaktivnih procesov ter

0 INTRODUCTION

Simulations of accidents in nuclear power plants (NPPs) with thermal-hydraulic computer codes, which were developed to analyze various aspects of design-basis and severe accidents, may significantly contribute to the safety of installations. Although results carry a certain amount of uncertainty, such simulations can contribute to a better understanding of the interaction between the physical phenomena which occur during accidents.

The CONTAIN computer code ([1] and [2]) was developed by Sandia National Laboratories, USA, with US Nuclear Regulatory Commission sponsorship. CONTAIN provides an integrated analysis of containment phenomena in NPPs. One of the major design objectives of CONTAIN is to provide reasonable predictions of the containment transient response (physical, chemical and radiological conditions) during the course of severe and design-basis accidents. The CONTAIN code includes atmospheric models for steam and air thermodynamics, intercompartment flows, condensation and evaporation on structures and aerosols, aerosol transport, agglomeration and deposition, and gas combustion. It also includes models for reactor cavity phenomena such as the interaction between concrete and the molten core as well as coolant-pool boiling. Heat conduction in structures, fission-product decay and transport, termohidravlični in dekontaminacijski učinki varnostnih sistemov so prav tako modelirani.

Pri projektnem dogodku izlivne nezgode se snov (hladivo) in energija sproščata skozi zlom cevi iz reaktorskega hladilnega sistema v zadrževalni hram. Sproščanje poteka med izlivno fazo, ponovnim polnjenjem, poplavljanje sredice in popoplavno fazo. V tej raziskavi je bil program CONTAIN (verzija 1.2) uporabljen za simuliranje odziva zadrževalnega hrama med veliko izlivno nezgodo v hladni veji dvozančnega tlačnovodnega reaktorja vrste Westinghouse. Določeni so bili tlačni in temperaturni odziv ter porazdelitev kapljevitega in parnega hladiva med prvimi 3000 s prehodnega pojava. Prav tako so analizirane energijske bilance.

1 VHODNI MODEL ZADRŽEVALNEGA HRAMA JEDRSKE ELEKTRARNE

1.1 Celice zadrževalnega hrama

CONTAIN je ničrazsežni program, ki obravnava sistem zadrževalnega hrama kot mrežo medsebojno povezanih prostorov ali “celic”. V vsaki celici so navzoče tekočine mirujoče in homogene. Vsaka celica lahko pomeni resnični notranji predelek ali skupino predelkov. V nekaterih primerih je primerno razdeliti predelek na več celic zaradi modeliranja pojavov, kakor so naravna konvekcija ali razslojevanje plinov. Celice so medsebojno povezane s pretokom snovi ali prevodom toplote preko vmesnih konstrukcij. CONTAIN je zasnovan za obravnavanje razmeroma majhnega števila celic.

radioactive-decay heating, and thermal-hydraulic and fission product decontamination effects of engineered safety features are also modeled.

In a design-basis event of a loss-of-coolant accident (LOCA), mass (coolant) and energy are released from the reactor coolant system (RCS) through the pipe break to the containment. These releases continue over blowdown, refill, reflood, and post-reflood phases. In this paper, the code CONTAIN (version 1.2) was used to simulate the containment response during a cold-leg large-break (LB) LOCA in a two-loop Westinghouse-type pressurized water reactor (PWR). Pressure and temperature responses, as well as coolant liquid and vapor distributions during the first 3000 s of the transient were calculated. Energy balances were also analyzed.

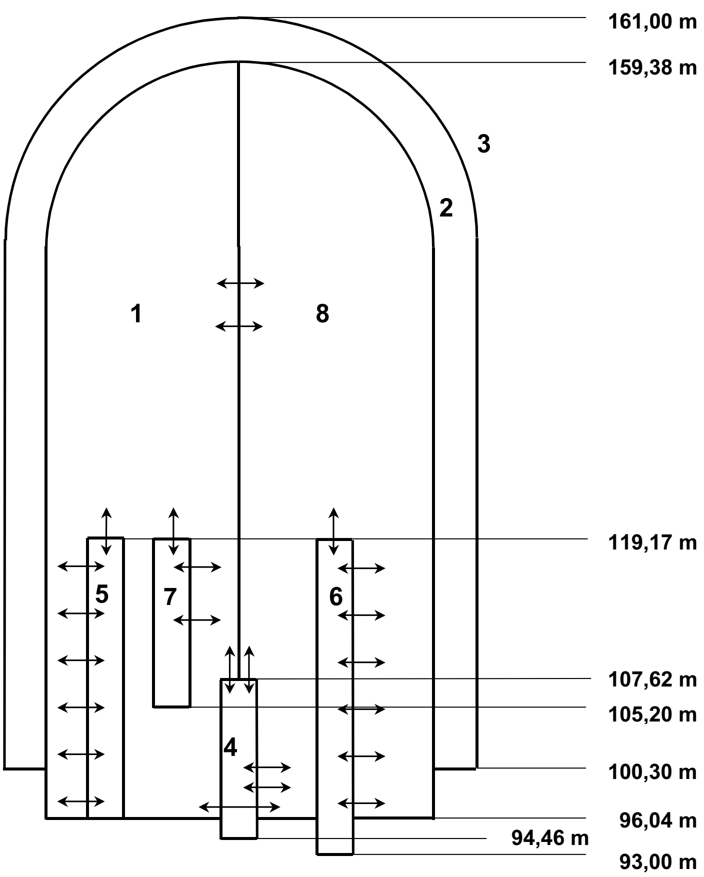
1 INPUT MODEL OF NUCLEAR POWER PLANT CONTAINMENT

1.1 Containment cells

CONTAIN is a lumped-parameter code, which treats a containment system as a network of interconnected control volumes or “cells”. In each cell, fluids are stagnant and homogeneous. The cells represent an actual internal containment compartment or group of compartments. In some cases, a compartment may be partitioned into several cells to model phenomena such as natural convection or gas stratification. The cells communicate with each other by means of the mass flow of material or heat conduction through intermediate heat-transfer structures. CONTAIN is designed to use a relatively small number of cells.

Preglednica 1. *Prostornine in višine celic*
Table 1. *Cell volumes and heights*

Št. No.	Celica Cell	Prostornina Volume m^3	Višina Height m
1	glavni predelek - prva celica main compartment - first cell	19347	63,3
2	medprostor annulus	11122	60,7
3	okolica environment	10^{10}	1000
4	reaktorska votlina reactor cavity	112	13,2
5	predelek severnega uparjalnika north steam generator compartment	1135	23,1
6	predelek južnega uparjalnika south steam generator compartment	1243	26,2
7	predelek tlačnika pressurizer compartment	349	14,0
8	glavni predelek - druga celica main compartment - second cell	19347	63,3



Sl. 1. *Shematični prikaz celic in tokovnih poti modela zadrževalnega hrama (višine se nanašajo samo na celice)*
Fig. 1. *Schematic of containment model cells and flow paths (elevations refer to cells only)*

V tem prispevku je bil uporabljen model zadrževalnega hrama, ki temelji na [3]. Razvoj modela se je začel že v prejšnjih delih ([4] in [5]). Zadrževalni hram je razdeljen takole (slika 1, preglednica 1):

- glavni predelek hrama, ki vključuje kupolo (2 celici),
- kolobarjasti medprostor med jekleno stavbo in zaščitno betonsko stavbo (1 celica),
- reaktorska votlina (1 celica),
- predelka severnega in južnega uparjalnika (1 celica za vsak predelek),
- predelek tlačnika (1 celica).

Okolica je bila prav tako upoštevana kot dodatna celica za modeliranje "izgube" toplote iz zadrževalnega hrama.

Opisana geometrijska razdelitev, čeprav dokaj preprosta, je zadostna za namene sedanje analize. Kakor vidimo iz primera vhodnega modela za jedrsko elektrarno Surry (ZDA) [2], so pri uporabi programa CONTAIN velike razlike med prostorninami posameznih celic običajne.

1.2 Tokovne poti med celicami zadrževalnega hrama

Obravnava tokov med celicami je značilna za ničrazsežni program. Pretok med celicami poteka prek povezav, imenovanih "tokovne poti", ki določajo

In this paper, a containment model based on the model described in [3] was used. The development of the model was started in the course of earlier work ([4] and [5]). The containment is subdivided as follows (fig. 1, table 1):

- containment main compartment, including the dome region (2 cells),
- annulus between containment steel vessel and containment concrete-shield building (1 cell),
- reactor cavity (1 cell),
- north and south steam-generator compartments (1 cell for each compartment),
- pressurizer compartment (1 cell).

The environment was also taken into account as an additional cell to model heat "loss" from the containment.

The presented geometrical configuration, although relatively simple, is sufficient for the purposes of the present analysis. As can be seen from the example input model for the Surry nuclear power plant, USA [2], large differences between the volumes of different cells are common when using the CONTAIN code.

1.2 Flow paths between containment cells

The treatment of intercell flow is typical of a control-volume code. Flow is assumed to occur between cells through junctions, called "flow paths", izmenjavo snovi in energije med celicami. Tokovne poti ne opravljajo naloge zadrževanja mase: snov, ki se pretaka po tokovni poti, se hipoma prenese v ciljno celico.

Izračun masnega toka skozi tokovno pot temelji na enačbi:

that determine the exchange of mass and energy between the cells. The flow paths are not repositories: the material flowing into a flow path is placed immediately in the downstream cell.

The calculation of the mass flow rate through a flow path is based on the following equation:

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

kjer pomenijo: W - masni tok, t - čas, ΔP- tlačno razliko med povezanima celicama, C_{FC} - koeficient izgub, ρ - gostoto tekočine, A - prerez tokovne poti in L - vztrajnostno dolžino tokovne poti.

Tokovne poti v vhodnem modelu so shematično prikazane na sliki 1. Njihove karakteristike so podane v preglednici 2. Vrednost koeficienta izgub C_{FC} je pri vseh tokovnih poteh enaka 1,0 (glej obravnavo v [6]).

where W is the mass flow rate, t is the time, ΔP is the pressure difference between connected cells, C_{FC} is the flow-loss coefficient, ρ is the fluid density, A is the flow-path cross-sectional area and L is the flow-path inertial length.

Flow paths in the input model are shown schematically in fig. 1. Their characteristics are tabulated in table 2. The flow-loss coefficient C_{FC} is equal to 1.0 for all flow paths (see discussion in [6]).

1.3 Toplotne konstrukcije v celicah hrama

Ponori toplote v zadrževalnem hramu lahko prek procesov prenosa toplote in snovi zbirajo precejšnji delež toplotne energije, dovedene v zadrževalni hram med nezgodo, in tako omejujejo obremenitve hrama (tlak in temperaturo ozračja). V CONTAIN-u obstajata dve vrsti ponorov: toplotne

1.3 Heat structures in containment cells

Through heat and mass transfer processes, containment heat sinks can absorb a considerable fraction of the thermal energy introduced into the containment during an accident and thus provide a mitigating effect with respect to the containment loads (atmosphere pressure and temperature). In CON-

Preglednica 2. *Tokovne poti med celicami*
Table 2. *Flow paths between cells*

Št. No.	Od celice From cell	do celice to cell	A m^2	A/L m
1	4	1	0,31	0,0415
2	8	4	0,31	0,0415
3	4	8	1,75	0,270
4	4	8	0,25	0,026
5	1	8	100	1,0
6	8	1	100	1,0
7	1	8	2,0	1,0
8	7	1	1,70	1,266
9	7	1	9,0	6,667
10	1	7	9,0	3,333
11	5	1	6,17	0,068
12	5	1	0,91	0,023
13	5	1	2,36	0,061
14	5	1	0,91	0,021
15	5	1	2,35	0,078
16	5	1	2,25	0,061
17	5	1	14,66	0,800
18	6	8	5,64	0,060
19	6	8	0,91	0,023
20	6	8	2,42	0,066
21	6	8	0,91	0,022
22	6	8	2,35	0,078
23	6	8	2,12	0,066
24	6	8	15,27	0,800

konstrukcije ter plasti spodnjih delov celic (v primeru obravnavanega simuliranja so to bazeni kapljevine in betonska tla). Zaradi njihove pomembnosti je modelirana vrsta procesov prenosa toplote in snovi, to so: naravni in prisilni konvektivni prenos toplote, prenos toplote in snovi pri kondenzaciji, prenos toplote pri uparjanju in prevod toplote.

Pri izračunu konvektivnega prenosa toplote z ozračja celic na toplotne konstrukcije je bilo Nusseltovo število določeno iz naslednje povezave:

TAIN, these sinks are of two main types: heat structures and lower cell layers (liquid pools and concrete floors in the present simulation). Because of their importance, a variety of heat and mass transfer processes are modeled, such as natural and forced convection heat transfer, condensation mass and heat transfer, boiling heat transfer and heat conduction.

When calculating convective heat transfer from the cell atmosphere to heat structures, the Nusselt number was determined from the following correlation:

$$Nu = 0{,}037\, Re^{0{,}8}\, Pr^{0{,}33} \qquad (2),$$

kjer so: *Nu* - Nusseltovo število, *Re* - Reynoldsovo število in *Pr* - Prandtlovo število. Reynoldsovo število je v programu CONTAIN določeno iz ustreznih povprečij hitrosti tokov v tokovnih poteh, priključenih na obravnavano celico.

V vhodnem modelu so bile upoštevane naslednje toplotne konstrukcije [3]: valj in kupola jeklene stavbe hrama, valj in kupola zunanje betonske zaščitne stavbe hrama, žerjav, cevovodi, električna in različna oprema, sistemi za gretje, prezračevanje in klimatizacijo, platforme, podloge, kanal za menjavo goriva in notranji beton.

Čeprav lahko resnične toplotne konstrukcije zavzamejo dokaj zapletene oblike, se v programu CONTAIN modelirajo kot krogle, valji ali ravne plošče, ki so lahko navpično ali vodoravno usmerjeni. Poleg tega elementi iz zgoraj naštetih kategorij niso bili modelirani posamično, temveč so bili zbrani v “reprezentativne” konstrukcije. Zaradi poenostavitev namreč, ki so opazne pri modeliranju tokov in termodinamičnih procesov v ozračju hrama, podrobno modeliranje toplotnih konstrukcij ne bi nujno izboljšalo zanesljivosti rezultatov simuliranja.

Toplotne konstrukcije so bile porazdeljene med vsemi celicami modela zadrževalnega hrama. Karakteristike toplotnih konstrukcij (material, geometrijska oblika, debelina) temeljijo na podatkih iz [3].

1.4 Varnostni sistemi

CONTAIN omogoča tudi modeliranje varnostnih sistemov zadrževalnega hrama: ventilatorskih hladilnikov in prh. Štirje ventilatorski hladilniki in dva sistema prh so bili vključeni v vhodni model (v celicah 1 in 8). V obravnavanem scenariju smo predpisali, da se prhe zadrževalnega hrama sprožijo, ko tlak v hramu doseže 2,06 bar, medtem ko ventilatorski hladilniki delujejo od nastanka zloma.

Pri modeliranju prenosa toplote in snovi med kapljicami iz prh in ozračjem celic je bila uporabljena naslednja povezava za Nusseltovo število:

where *Nu* is the Nusselt number, *Re* is the Reynolds number and *Pr* is the Prandtl number. In the CONTAIN code, the Reynolds number is calculated from appropriate averages of flow velocities in the flow paths connected to the considered cell.

The following heat structures were taken into account in the input model [3]: containment vessel cylinder and dome, shield building cylinder and dome, polar crane, piping, electrical and miscellaneous equipment, HVAC (heating, ventilation and air-conditioning) systems, platforms, embedments, refueling canal and interior concrete.

Although actual heat structures may assume complex shapes, they are modeled in CONTAIN as either spheres, cylinders or slabs, which may assume either vertical or horizontal orientation. In addition, elements from the above-listed categories were not modeled individually, but were grouped into “representative” structures. Due to the inherent simplifications used in the modeling of flows and atmosphere thermodynamics, a detailed modeling of heat structures would not necessarily improve the reliability of the simulation results.

Heat structures were distributed among all the cells of the containment model. The characteristics of heat structures (material, geometry, thickness) are based on data from [3].

1.4 Engineered safety features

CONTAIN also allows the modeling of containment engineered safety features: fan coolers and containment sprays. Four fan coolers and two spray systems were included in the input model (in cells 1 and 8). In the present simulation, it was prescribed that containment sprays are initiated when the containment pressure reaches 2.06 bar, whereas fan coolers are assumed to be active from the time when the break occurred.

When modeling heat and mass transfer between spray droplets and cell atmosphere, the following correlation was used for the Nusselt number:

$$Nu = 2{,}0 + 0{,}60\, Re^{1/2}\, Pr^{1/3} \qquad (3),$$

medtem ko je bilo Sherwoodovo število določeno iz naslednje povezave:

whereas the Sherwood number was calculated from the following correlation:

$$Sh = 2{,}0 + 0{,}60\ Re^{1/2}\ Sc^{1/3} \qquad (4),$$

kjer sta *Sh* Sherwoodovo število in *Sc* Schmidtovo število.

where *Sh* is the Sherwood number and *Sc* is the Schmidt number.

2 ZAČETNI IN ROBNI POGOJI

2.1 Začetni pogoji

Predpisani začetni tlak v zadrževalnem hramu je bil enak 1,10 bar. Začetna izbrana temperatura atmosfere hrama in toplotnih struktur je bila 322 K, razen pri reaktorski posodi, uparjalnikih in tlačniku, pri katerih je bila začetna temperatura površine enaka 342 K. Zlom se začne pri t = 10 s.

2.2 Robni pogoji - vir hladiva iz reaktorskega hladilnega sistema

Velika izlivna nezgoda (prvih 1000 s) je bila simulirana ločeno od simuliranja s CONTAIN-om s termohidravličnim računalniškim programom RELAP5/MOD2 [7]. Pri tej nezgodi pride do dvostranskega zloma na hladni veji med reaktorsko posodo in črpalko reaktorskega hladiva. Velikost zloma je enaka 40% celotnega prereza hladne veje. Razpoložljivi so dva sistema za visokotlačno in en sistem za nizkotlačno varnostno vbrizgavanje ter dva zbiralnika.

Masna toka in specifični entalpiji hladiva (vode) z obeh strani zloma so bili vključeni kot viri v vhodni model za CONTAIN (v celico 6). Nedavno so bili razviti programi, ki omogočajo sklapljanje simuliranih procesov v reaktorskem hladilnem sistemu in v zadrževalnem hramu ([8] in [9]). Pri sedanjem delu, vpliv tlaka zadrževalnega hrama na tok skozi zlom iz reaktorskega hladilnega sistema ni bil upoštevan.

Pri veliki izlivni nezgodi se med popoplavno fazo v reaktorskem hladilnem sistemu vzpostavi masno ravnovesje med tokom skozi zlom in vbrizgavanjem sistema za zasilno hlajenje sredice [10]. Za oba vira hladiva (z obeh strani zloma) je bil masni tok skozi zlom med *t* = 1000 s in *t* = 3000 s izbran enak povprečni vrednosti med *t* = 500 s in *t* = 1000 s. Energijsko ravnovesje v reaktorskem hladilnem sistemu se vzpostavi med vbrizgavanjem hladne kapljevine iz sistema za zasilno hlajenje sredice, dovajanjem toplote iz sredice in odvajanjem tople tekočine skozi zlom. Ker je kapljevina iz sistema za zasilno hlajenje podhlajena in so hitrosti v hladni veji majhne, lahko predpostavimo, da para iz sredice kondenzira v hladni veji ter skozi zlom odteka kapljevina [10].

Rezultati simuliranja s programom RELAP5/MOD2 kažejo, da se tlak v primarnem

2 INITIAL AND BOUNDARY CONDITIONS

2.1 Initial conditions

The initial pressure in the containment was prescribed to be 1.10 bar. The initial temperature of the containment atmosphere and heat structures was set equal to 322 K, except for the reactor pressure vessel, steam generators and pressurizer, whose initial surface temperature was set equal to 342 K. The break occurs at time t = 10 s.

2.2 Boundary conditions – coolant source from reactor coolant system

A LB LOCA (first 1000 s) was simulated separately from the CONTAIN simulation with the RELAP5/MOD2 thermal-hydraulic computer code [7]. A double-ended cold-leg guillotine break occurs between the reactor vessel and the reactor coolant pump. The break size is equal to 40% of the full cold-leg cross-section. Two high-pressure safety injection systems, one low-pressure safety injection system and two accumulators are available.

Coolant (water) break mass flow rates and specific enthalpies from both ends of the break were included as sources in the CONTAIN input model (in cell 6). Recently, codes which enable coupling of simulated processes in the RCS and containment have been developed ([8] and [9]). In the present paper, the influence of containment backpressure on break flow from the RCS was not taken into account.

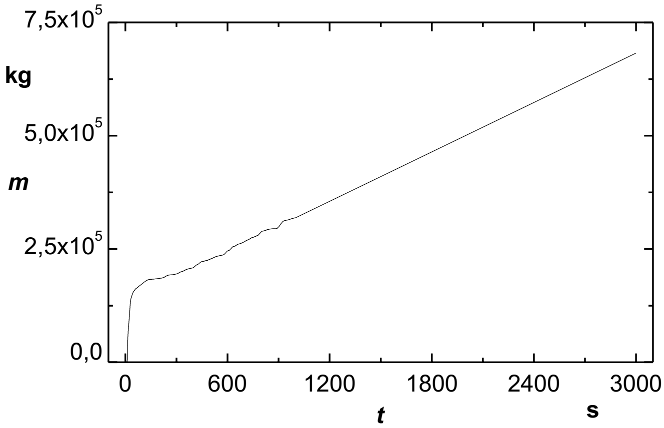
During the post-reflood period of a LB LOCA, an RCS mass balance exists with the break and emergency core-cooling system (ECCS) injection flow rates balanced [10]. For both coolant sources (from both ends of the break), the break mass flow rate between *t* = 1000 s and *t* = 3000 s was set equal to the average value between *t* = 500 s and *t* = 1000 s. A RCS energy balance is achieved by the injection of cold ECCS liquid, core heat addition, and removal of warm fluid at the break. Since the ECCS liquid is subcooled and the cold-leg velocities are small, we may assume that steam from the core is condensed within the cold leg and liquid flows out of the break [10].

According to the results of the RELAP5/MOD2 simulation, the pressure in the primary system sistemu ustali na popoplavno vrednost 3,4 bar, ki je dosežena približno pri *t* = 750 s. Za oba vira je bila vrednost specifične entalpije hladiva pri *t* = 1000 s izbrana enaka povprečni vrednosti med *t* = 800 s in *t* = 1000 s, in entalpiji nasičene kapljevine pri 3,4 bar med *t* = 1500 s in *t* = 3000 s. Vrednosti med *t* = 1000 s in *t* = 1500 s so bile določene z linearno interpolacijo.

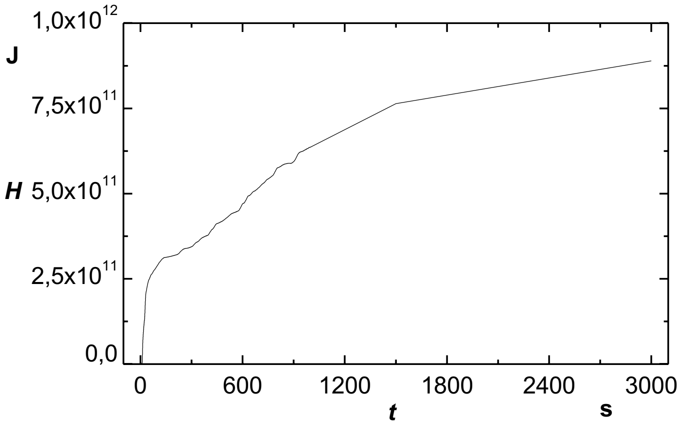
Slika 2 prikazuje skupno maso hladiva, dovedeno iz reaktorskega hladilnega sistema s tokom skozi zlom, medtem ko slika 3 prikazuje pripadajočo skupno dovedeno entalpijo (entalpija nasičene kapljevine je definirana kot 0 J pri temperaturi 273,15 K).

settles to a post-reflood value of about 3.4 bar, which is reached at *t* = 750 s approximately. For both sources, the value of the coolant specific enthalpy at *t* = 1000 s was set equal to the average value between *t* = 800 s and *t* = 1000 s, and to the liquid saturation enthalpy at 3.4 bar between *t* = 1500 s and *t* = 3000 s. Values between *t* = 1000 s and *t* = 1500 s were calculated by linear interpolation.

Figure 2 shows the cumulative coolant mass input from the RCS trough break flow, whereas figure 3 shows the corresponding cumulative enthalpy input (the liquid saturation enthalpy is defined as 0 J at 273.15 K).



Sl. 2. *Skupna masa hladiva, dovedena s tokom skozi zlom (t - čas, m - masa)*
Fig. 2. *Cumulative coolant mass input through break flow (t - time, m - mass)*



Sl. 3. *Skupna entalpija hladiva, dovedena s tokom skozi zlom (t - čas, H - entalpija)*
Fig. 3. *Cumulative coolant enthalpy input through break flow (t - time, H - enthalpy)*

3 REZULTATI IN RAZPRAVA

Razprava v tem poglavju se nanaša na notranjost jeklene stavbe zadrževanega hrama (brez upoštevanja kolobarjastega medprostora), razen če je navedeno drugače.

3.1 Tlak v ozračju zadrževalnega hrama

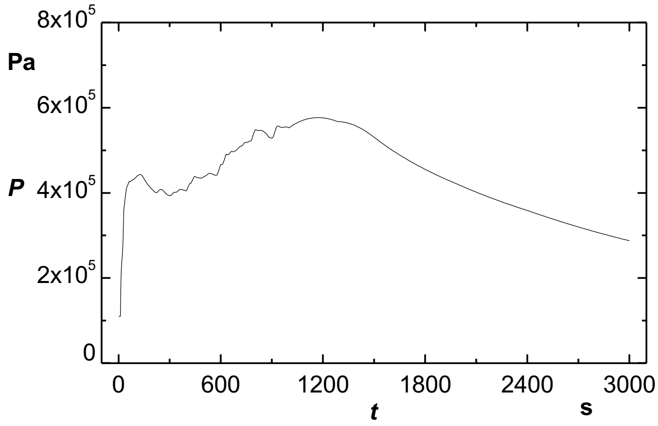
Slika 4 prikazuje tlak v ozračju celic zadrževalnega hrama (razlike v tlaku med različnimi celicami so zanemarljive). Takoj po nastanku zloma

3 RESULTS AND DISCUSSION

Unless stated otherwise, the discussion in this section refers to the interior of the containment steel vessel, thus excluding the annulus.

3.1 Pressure in containment atmosphere

Figure 4 shows the pressure of the atmosphere in the containment cells (pressure differences between different cells are negligible).



Sl. 4. *Tlak v ozračju celic zadrževalnega hrama (t - čas, P - tlak)*
Fig. 4. *Pressure in containment cells' atmosphere (t - time, P - pressure)*

se tlak skoraj hipoma dvigne, kar je posledica naglega dotoka mase in energije hladiva (sl. 2, 3). Po rahlem znižanju se tlak ponovno zviša. Nihanja tlaka so posledica nihanj pretoka skozi zlom in specifične entalpije. Tlak doseže največjo vrednost 5,8 bar približno v času 1200 s, ko se začne počasi zniževati.

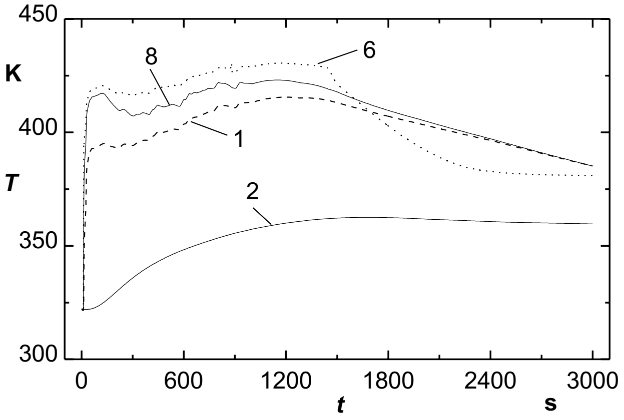
3.2 Temperatura ozračja zadrževalnega hrama

Slika 5 prikazuje temperaturo ozračja v glavnem predelku zadrževalnega hrama (celici 1 in 8), v predelku južnega uparjalnika (celica 6) in v medprostoru (celica 2). Do najvišje temperature (z največjo vrednostjo 430 K) prihaja v celici 6, kjer je postavljen vir hladiva (tok skozi zlom iz reaktorskega hladilnega sistema). Temperatura v glavnem predelku kaže podoben vzorec obnašanja kakor tlak. Temperatura je nekoliko višja v celici 8, ki je povezana s celico 6 prek tokovnih poti. Do zvišanja temperature v medprostoru (celica 2) pride zgolj zaradi prevoda toplote skozi jekleno steno zadrževalnega hrama.

Immediately after the occurrence of the break, the pressure rises sharply, which is due to the sudden inflow of coolant mass and energy (see figs. 2 and 3). After a slight drop, the pressure continues to rise. Pressure oscillations are due to oscillations of break mass flow and specific enthalpy. The pressure reaches a maximum of 5.8 bar at about 1200 s, after which it starts slowly to decrease.

3.2 Temperature in containment atmosphere

Figure 5 shows the atmosphere temperature in the containment main compartment (cells 1 and 8), south steam generator compartment (cell 6) and annulus (cell 2). The highest temperature (with a maximum value of 430 K) occurs in cell 6, where the coolant source (break flow from RCS) is located. The temperature in the main compartment exhibits a similar pattern of behavior to the pressure. The temperature is slightly higher in cell 8, which is connected to cell 6 through flow paths. The temperature rise in the annulus (cell 2) is caused solely by heat transfer through the containment vessel's steel wall.



Sl. 5. *Temperatura ozračja v nekaterih celicah zadrževalnega hrama (t - čas, T – temperatura); številke označujejo celice*
Fig. 5. *Atmosphere temperature in some containment cells (t - time, T - temperature); numbers indicate cells*

3.3 Porazdelitev hladiva v zadrževalnem hramu

Hladivo v zadrževalnem hramu izvira predvsem iz dveh virov: toka skozi zlom in prh zadrževalnega hrama. Tok skozi zlom iz reaktorskega hladilnega sistema nastaja iz hladiva, navzočega pred zlomom, in hladiva, vbrizganega prek sistema za zasilno hlajenje sredice. Hladivo iz zbiralnika vode za menjavo goriva je razpoložljivo za sistem za zasilno hlajenje sredice med celotnim simulirnim prehodnim pojavom. Prhe zadrževalnega hrama črpajo hladivo iz zbiralnika vode za menjavo goriva vse do časa 1285 s, ko preidejo na obtočni način in črpajo hladivo iz zbiralnika, ki se nahaja na dnu celice 6.

Kakor lahko vidimo na sliki 6, je masa hladiva, ki je dovedena s tokom skozi zlom v časovnem obdobju od 0 s do 3000 s, približno štirikrat večja od neto dovedene mase prek prh (iz zbiralnika vode za menjavo goriva).

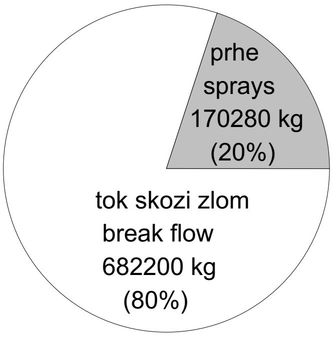
Slika 7 prikazuje porazdelitev hladiva v zadrževalnem hramu. Večina hladiva je v obliki kapljevine v bazenih na dnu celic. Pomemben delež je navzoč v ozračju v obliki pare in razpršene kapljevine, medtem ko je delež, ki se nahaja kot plast kondenzata na toplotnih konstrukcijah, za red velikosti manjši. Vendar lahko pomembnost kondenzacije pare na konstrukcijah opazimo na sliki

3.3 Coolant distribution in containment

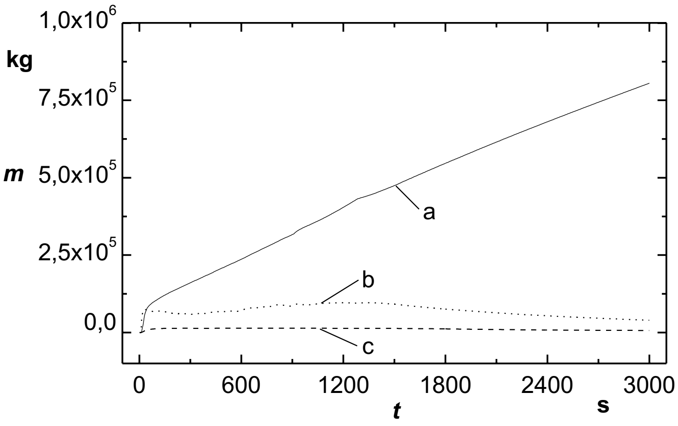
Coolant in the containment originates mainly from two sources: break flow and containment sprays. Break flow from the RCS results from coolant present before the break and coolant injected by the ECCS. Coolant from the refueling water storage tank (RWST) is available for the ECCS throughout the simulated transient. Containment sprays draw coolant from the RWST until t = 1285 s when they switch to recirculation mode and draw coolant from the sump, which is located at the bottom of cell 6.

As can be seen in figure 6, the mass of the coolant input through the break flow in the time interval from 0 s to 3000 s is about four times higher than the net mass of coolant input through sprays (from RWST).

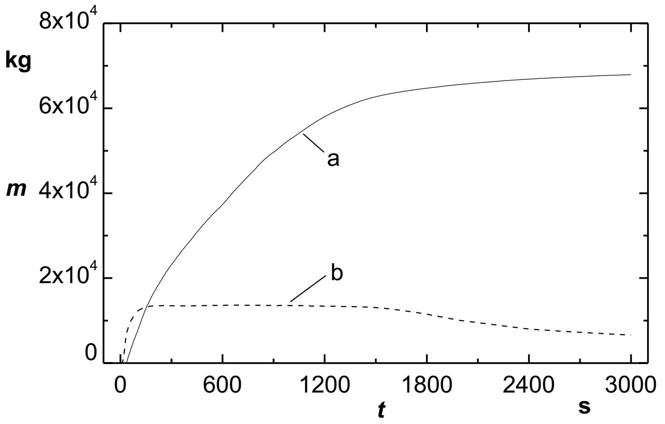
Figure 7 shows the coolant distribution in the containment. Most of the coolant is located as liquid in the pools on the cell floors. A significant fraction is present in the atmosphere as vapor and dispersed liquid, whereas the fraction located as condensate film on heat structures is an order of magnitude smaller. However, the importance of vapor condensation on structures can be seen in figure 8,



Sl. 6. *Vir hladiva, prisotnega v zadrževalnem hramu v času t = 3000 s*
Fig. 6. *Origin of coolant present in the containment at t = 3000 s*

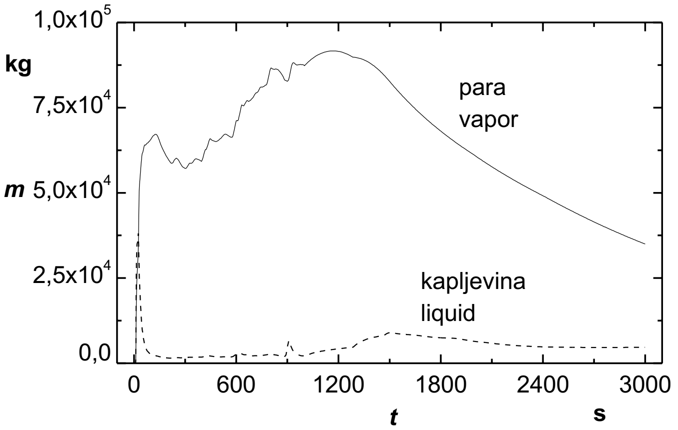


Sl. 7. *Masa hladiva v zadrževalnem hramu (t - čas, m - masa); a - bazeni kapljevine na dnu celic, b - para in kapljevina v ozračju celic, c - kondenzat na toplotnih strukturah*
Fig. 7. *Coolant mass in containment (t - time, m - mass); a - liquid pools on cell floors, b - vapor and liquid in cells' atmosphere, c - condensate on heat structures*



Sl. 8. *Kondenzat hladiva v zadrževalnem hramu (t - čas, m - masa); a - skupna masa kondenzata, ki je odtekel s toplotnih konstrukcij, b - preostali kondenzat na toplotnih konstrukcijah*

Fig. 8. *Coolant condensate in containment (t - time, m - mass); a - cumulative runoff condensate from heat structures, b - remaining condensate on heat structures*



Sl. 9. *Masa hladiva v ozračju celic zadrževalnega hrama (t - čas, m - masa)*

Fig. 9. *Coolant mass in containment cells' atmosphere (t - time, m - mass)*

8, ki kaže, da znatna količina kondenzata odteka v bazene kapljevine.

Slika 9 prikazuje porazdelitev hladiva v ozračju zadrževalnega hrama. Večina hladiva je v obliki pare. Večji del kapljevine, ki priteče v ozračje hrama z velikim masnim tokom mešanice kapljevine in pare skozi zlom med prvimi 20 s nezgode, se zelo hitro usede v bazene na dnu celic.

3.4 Porazdelitev energije v zadrževalnem hramu

V času med 0 s in 3000 s je bila večina entalpije dovedena s tokom skozi zlom in le manjši delež z delovanjem prh zadrževalnega hrama (sl. 10). Glavni cilj omejitvenih ukrepov je odvajanje notranje energije iz ozračja zadrževalnega hrama ter iz celotnega hrama. Večina notranje energije je bila odvedena iz hrama z delovanjem ventilatorskih hladilnikov in le majhen del s prevodom toplote skozi jekleno steno hrama (sl. 11).

Slika 12 prikazuje porazdelitev notranje energije v zadrževalnem hramu v času t = 3000 s. Večji del energije je v toplotnih konstrukcijah in v

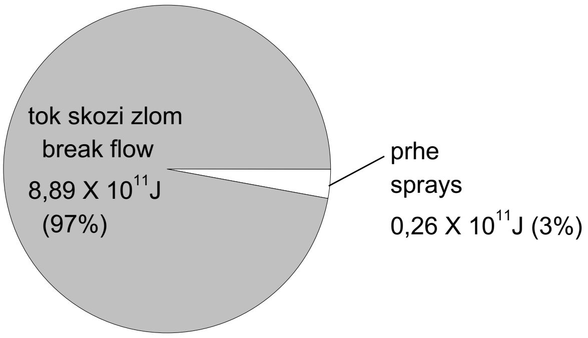
which shows that a considerable amount of condensate runs off into liquid pools.

Figure 9 shows the coolant distribution in the containment atmosphere. Most of the coolant is present as vapor. Most of the liquid, which flows into the containment atmosphere with the high liquid-vapor-mixture flow rate during the first 20 s of the accident, drops very quickly into pools on the cell floors.

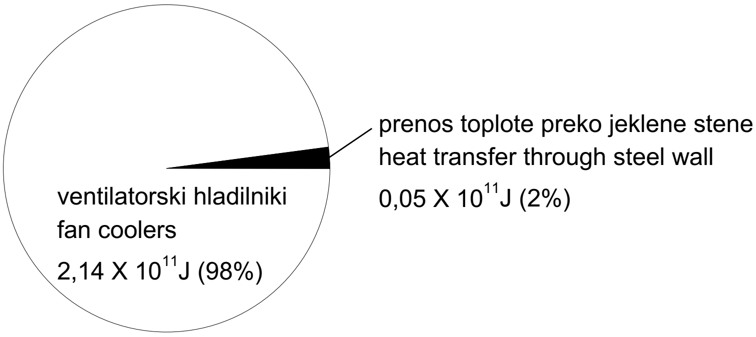
3.4 Energy distribution in containment

Most of the enthalpy from 0 s to 3000 s was introduced via the break flow and only a small fraction by the action of containment sprays (fig. 10). The main purpose of mitigating actions is to remove internal energy, first from the containment atmosphere, and then from the entire containment. Most of the internal energy was removed from the containment by the action of fan coolers and only a small part by heat conduction through the containment vessel's steel wall (fig. 11).

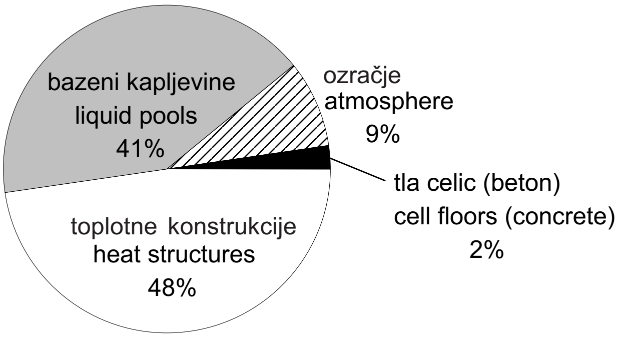
Figure 12 shows the internal energy distribution in the containment at time t = 3000 s. Most of the energy is contained in the heat structures and the



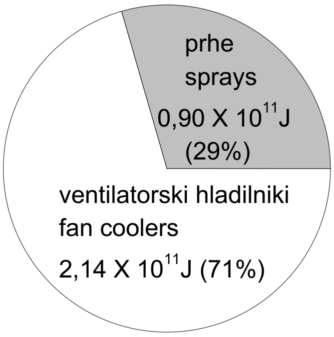
Sl. 10. *Dovedena entalpija v zadrževalni hram od t = 0 s do t = 3000 s*
Fig. 10. *Enthalpy input in containment from t = 0 s to t = 3000 s*



Sl. 11. *Odvedena notranja energija iz zadrževalnega hrama od t = 0 s do t = 3000 s*
Fig. 11. *Internal energy output from the containment from t = 0 s to t = 3000 s*



Sl. 12. *Porazdelitev notranje energije v zadrževalnem hramu v času t = 3000 s*
Fig. 12. *Internal energy distribution in the containment at t = 3000 s*



Sl. 13. *Notranja energija, odvedena iz ozračja zadrževalnega hrama s prhami in ventilatorskimi hladilniki od t = 0 s do t = 3000 s*
Fig. 13. *Internal energy removed from containment atmosphere by sprays and fan coolers from t = 0 s to t = 3000 s*

bazenih kapljevine na dnu celic, medtem ko je precej manjši delež v ozračju hrama in betonskih tleh celic. Toplotne konstrukcije in bazeni kapljevine tako prek procesov prenosa toplote in snovi absorbirajo znaten delež dovedene toplotne energije ter na ta način omejujejo obremenitve hrama.

Slika 13 ponuja primerjavo med učinki varnostnih sistemov pri odvajanju notranje energije iz ozračja zadrževalnega hrama. V obdobju med 0 s in 3000 s je bilo več ko dvakrat več energije odvedene z ventilatorskimi hladilniki kakor s prhami zadrževalnega hrama.

4 SKLEPI

S termohidravličnim računalniškim programom CONTAIN so bili simulirani pojavi v zadrževalnem hramu dvozančnega tlačnovodnega reaktorja med prvimi 3000 s velike izlivne nezgode. Rezultati kažejo naslednje:

1. Tlak v ozračju zadrževalnega hrama doseže največjo vrednost 5,8 bar 1200 s po nastanku zloma.
2. Temperatura ozračja zadrževalnega hrama doseže ustrezno največjo vrednost 430 K.
3. Po začetnem izpustu iz reaktorskega hladilnega sistema je večina hladiva v zadrževalnem hramu v bazenih kapljevine, večina hladiva v ozračju pa je navzoča v obliki pare.
4. Toplotne konstrukcije in bazeni kapljevine učinkujejo omejitveno na obremenitve zadrževalnega hrama, ker na koncu simulirnega prehodnega pojava vsebujejo skoraj 90 odstotkov notranje energije.

liquid pools at cell floors, whereas a much smaller fraction is contained in the containment atmosphere and the concrete cell floors. Thus, through heat- and mass-transfer processes, heat structures and liquid pools absorb a considerable fraction of the thermal energy introduced into the containment and provide a mitigating effect with respect to containment loads.

Figure 13 provides a comparison between the effects of engineered safety features in removing the internal energy from the containment atmosphere. In the interval from 0 s to 3000 s, more than twice as much energy was removed by fan coolers than by containment sprays.

4 CONCLUSIONS

Phenomena in the containment of a two-loop pressurized water reactor during the first 3000 s of a large-break loss-of-coolant accident were simulated with the CONTAIN thermal-hydraulic computer code. The results show the following:

1. The pressure in the containment atmosphere attains a maximum value of 5.8 bar 1200 s after the occurrence of the break.
2. The temperature of the containment atmosphere attains a corresponding maximum value of 430 K.
3. After the initial release from the reactor coolant system, most of the coolant in the containment is located in liquid pools and most of the coolant in the containment atmosphere is present as vapor.
4. Heat structures and liquid pools provide a mitigating effect with respect to containment loads as they contain almost 90% of the internal energy at the end of the simulated transient.

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