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Sinteza orodij za analizo človeške napake po metodi analize spoznavne zanesljivosti in napak ter analize drevesa odpovedi

The Synthesis of Human-Error Analysis Using the Cognitive Reliability and Error Analysis Method and Fault-Tree Analysis

Janja Zupančič - Jure Marn

V pričujočem prispevku je bila obravnavana sinteza orodij, ki so uporabljana za oceno človeških napak (analiza spoznavne zanesljivosti in napak - ASZN - CREAM) in tehničnih odpovedi (drevo napak) na tak način, da je moč dobljene rezultate smiselno primerjati. Sinteza je bila opravljena za obstoječo rektifikacijsko kolono. Predlagane in predstavljene so izboljšave na osnovi dobljenih rezultatov.

(Ključne besede: metode CREAM, verjetnost napak, verjetnost okvar, drevo odpovedi)

In this paper we have looked at the synthesis of tools used for human-error analysis (Cognitive Reliability and Error Analysis Method - CREAM) and technical error or device error (fault tree) in such a way that a comparison between the results is possible. The synthesis was performed for an existing rectification system (column). Possible improvements are shown and suggested.

(Keywords: CREAM methods, human probability, failure probability, fault tree analysis)

0 UVOD

Optimizacija procesov, povečevanje dobička, manjšanje stroškov, zlasti stroškov dela, so povzročili umik običajnih pripomočkov, ki so prispevali k zmanjšanju ali odpravi vplivov pomanjkljivega znanja. Na drugi strani je razvoj svetovno nevarnih sistemov za proizvodnjo energije in objektov procesne tehnike, zlasti s področja kemije, povzročil potrebo po manjšanju verjetnosti nezgod na človeštvu še sprejemljivo raven, ki se pogosto bliža frekvenci 1×10^{-5} dogodka na leto, kar prevedeno pomeni eno nezgodo v 100.000 letih obratovanja posameznega objekta. Za uporabnika ali operaterja pomeni taka verjetnost zanemarljivo tveganje.

V tem prispevku želimo prikazati možnost povezave med metodologijo ovrednotenja verjetnosti napake kot človekovega prispevka k odpovedi zahtevnega procesnega sistema in metodologijo ovrednotenja verjetnosti okvare kot tehnološkega prispevka k odpovedi procesnega objekta. Prednost prikazane metode je v enakovredni obravnavi nezgod in okvar ter v številski oceni verjetnosti odpovedi zahtevnega procesnega sistema.

Verjetnostna varnostna analiza na področju tehnoloških sistemov[1] v procesnem strojništvu je dobro razvita. Na tem področju je tudi pri nas moč najti več prispevkov, ki sodijo v zakladnico svetovne

0 INTRODUCTION

The optimization of processes, the increase of profit, and the decrease of costs, in particular labor costs, have resulted in an end to classical ways of decreasing or eliminating effects that occur due to a lack of knowledge. In addition, the evolution of globally dangerous systems for energy production and process engineering installations, in particular in the area of chemistry, caused the drive toward a lower accident probability that was at a level acceptable to the public, usually of the order of 1×10^{-5}, i.e. one accident in 100,000 years of operation for a particular installation. For both user and operator such a low frequency usually amounts to a negligible risk.

This paper deals with the possibility of a connection between the methodology of the accident probability evaluation of the human contribution to the failure of a complex-process installation, on the one hand, and the methodology of the evaluation of the technological contribution to failure of the same installation. The advantage of the method presented below is in the transformation of both types of information into comparable quantities, and the better assessment of complex-process system failure.

The probabilistic safety analysis of technological systems[1] in process engineering is well established. There are several studies in this area available in Slovenian professional literature: works znanosti, zlasti deli Kožuha ([1] in [2]). Večje težave pa so pri opredelitvi vpliva, ki ga imajo na delovanje kompleksnih sistemov ljudje.

V pričujočem prispevku zato poskušamo dvoje: ponoviti verjetnostno varnostno analizo odpovedi z uporabo analize dreves dogodkov, dobro znanih iz številnih del ([3] in [4]), najti je moč še številne druge avtorje in nadalje, to analizo nadgraditi z uporabo sodobne metodologije na področju analize vpliva človeških napak. Pri tem nimamo namena zadovoljiti zgolj z opisom mogočih posledic, temveč želimo vpliv človeških napak tudi številsko izraziti, s tem pa prepričati morebitne uporabnike[2], da bi predstavljeno metodologijo pričeli rutinsko uporabljati za svoje redno delo.

1 TEORETIČNA IZHODIŠČA

Človeške napake pomenijo 60 do 90 odstotkov vseh sistemskih napak.V zadnjih 40 letih se delež nezgod, katerih vzrok je človeška napaka, zvečuje. To ne pomeni, da povzročamo ljudje čedalje več napak, ampak da prihajajo s tehnološkim razvojem vedno bolj do izraza. Soodvisnost je prikazana na sliki 1 po [5]. Z uvajanjem sistemov nadzora kakovosti vse do sistema popolne kakovosti namreč prihaja do redkejših lomov strojev, človeška zanesljivost pa je ostala približno nespremenjena[3].

To spoznanje lahko spreminja žarišče dosedanjih verjetnostnih varnostnih analiz na področju zahtevnih tehnoloških sistemov iz analiz, ki so se zlasti ukvarjale z verjetnostjo odpovedi posameznega dela sistema, v analize, ki se ukvarjajo z verjetnostjo napačnih odločitev vpletenih na vseh stopnjah procesov (oz. organizacijski faktor). Poglobljena analiza zahtevnih tehnoloških sistemov

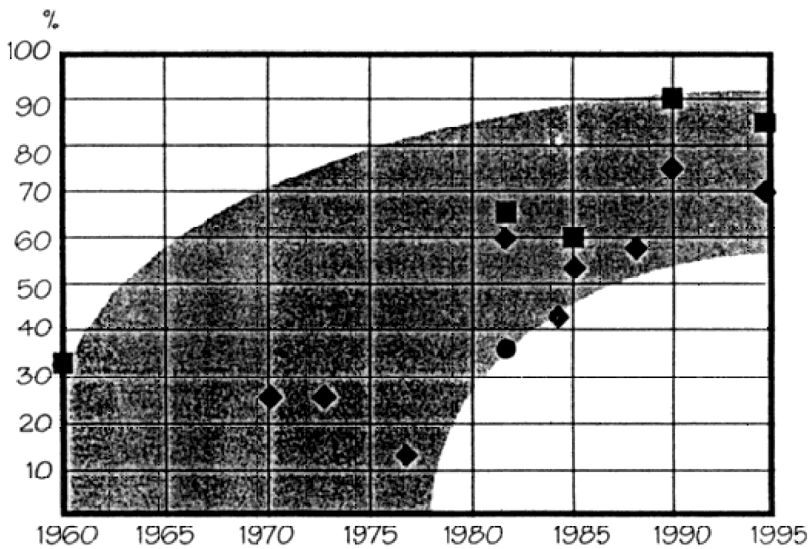
such as Kožuh ([1] and [2]). However, it is harder to find such contributions in the area of human-error analysis effecting complex engineering systems.

In this contribution we have tried to achieve two objectives: first, to repeat a well-established probabilistic safety analysis using the fault-tree-analysis method known from several contributions ([3] and [4]), and several other authors and second, to augment this analysis with a human-error analysis using modern methodology in this area. Further more, in addition to qualitatively describing possible consequences we have strived to quantify the effects of these errors, thereby convincing the users[2] of this information to start using such a methodology in their day-to-day operations.

1THEORETICAL BACKGROUND

Human errors represent 60–90% of all system failures. Over the past 40 years the ratio of accidents caused by human factors to all accidents has steadily increased. This does not mean that people are less careful, rather it means that technological progress is eliminating mechanical errors. This codependency was shown by [5], whose figure is reproduced as Figure 1. Modern quality systems such as Total Quality Management (TQM) have resulted in a reduction of mechanical failures, while human reliability has tended to stay constant unless influenced by training or other methods[3].

This conclusion can change the focus of to-date probabilistic safety analyses in the area of complex technological systems from analyses mainly dealing with the probability of failures to particular parts of a system to analyses dealing with the probability of erroneous decisions of all those involved in various levels of processes (the so-called organizational factor). The in-depth analysis of



Sl. 1. *Delež nezgod, katerih vzrok je človeška napaka* [5]
Fig. 1. *Fraction of human-error-induced accidents [5]*

tako še naprej ostaja v osti varnostnih analiz, zlasti na področju latentnih in zato premalo opazovanih napak [6]. Avtorja ugotavljava, da je bilo v začetku veliko zanimanje za tehnološko zanesljivost (v 70.), potem so spoznali, da je ključen človek (v 80.), in nato, da je pomembna organizacija (v 90 letih prejšnjega stoletja).

V nadaljevanju je najprej opisan problem, nato pa prikazana uporaba metodologije drevesa odpovedi (znane tudi pod imenom drevo napak), zatem uporaba metode spoznavne (oz. miselne) zanesljivosti in analize napak [5] na sistemu rektifikacijske kolone in nazadnje sinteza obeh metod ter primerjava med verjetnostjo nezgode in okvare s predlogom odprave.

complex technological systems still remains at the cutting edge of safety analyses, in particular for latent and therefore not-enough-observed errors [6]. The authors note that interest has shifted from an initial interest in technological reliability (1970s) to human-error analysis (1980s), and finally to organizational aspects of reliability (1990s).

The problem will be briefly discussed below, and this will be followed by the use of the methodology of failure-tree analysis, and then the use of [5] applied to the system of a rectification column, and finally the synthesis of both methods and a comparison between the probability of error and accident with a suggestion for system remedies.

2 OPIS PROBLEMA

Poglavitni namen dela je določitev verjetnosti tehnične (mehanske) in človeške napake rektifikacijskega sistema, katere posledica bi bil trenutni oziroma stalni izpust tekočinske mešanice. Obe vrsti izpusta bi bili iz vidika ekonomike procesa in parametrov okoljske varnosti nesprejemljivi, zato je treba določiti ne le verjetnost odpovedi temveč tudi posamezne vplivne parametre, ki na morebitno napako vplivajo. Številska vrednost prispevka napake posameznega vplivnega parametra, v okviru predpostavk, podaja tudi vrstni red, ki ga je smiselno upoštevati pri odpravi napak. Tako je moč v okviru prispevkov tehničnih napak ugotoviti potrebo po zamenjavi posameznih kritičnih delov in smiselno frekvenco preventivnih pregledov, v okviru prispevkov človeških napak pa tista področja, na katerih je primerno izvesti dodatno izobraževanje ljudi, ki so neposredno vpeti v proces obratovanje rektifikacijske kolone. Pri tem je smiselno poudariti še, da imata izobraževanje in trening omejitev in verjetnosti napake ne moremo poljubno zmanjšati [11].

Za določitev verjetnosti tehnične napake rektifikacijskega sistema je bila uporabljena metoda drevesa napak. Verjetnost človeške napake je bila vrednotena z osnovno in razširjeno metodo ASZN. Verjetnost človeške napake je bila vključena v drevo napak za trenutni in stalni izpust in hkrati opravljena analiza vpliva verjetnosti človeške napake na skupno verjetnost napake pri obeh izpustih.

2 PROBLEM DESCRIPTION

The basic goal of this work is the quantification of technical (mechanical) and human error during the continuous operation of a rectification system that causes instantaneous and continuous releases of a fluid mixture. Both types of leaks are unacceptable from the viewpoint of the economy of the process and ecological safety parameters; therefore, not only the probability of failure needs to be assessed but also the important parameters influencing the failures. A quantitative assessment of a particular failure mode also forms the basis for the mitigation of the factors leading to this failure: first the parameters leading to the most probable failure mode need to be investigated, followed by the second most probable, etc. given that the damage to life, people, and property is similar. This methodology enables one to establish which parts of the machinery are most likely to fail and therefore schedule preventive maintenance; and which areas should be addressed when training people involved in the operation of the rectification system. At the same time it should be noted that the effects of education and training are limited and that the probability of human error cannot be lowered indefinitely [11].

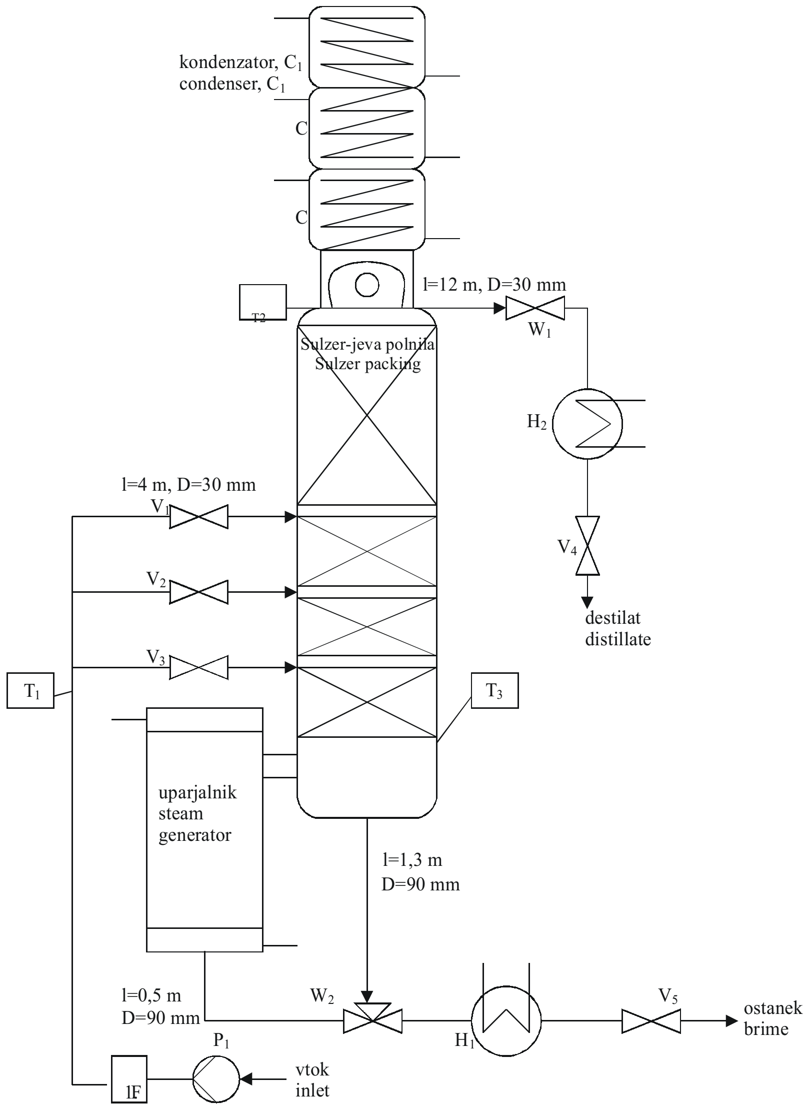
Fault-tree analysis was used for the evaluation of the technical error of the rectification system. The probability of human error was assessed using the basic and extended CREAM method. Then, the probability of human error was included in the fault trees for instantaneous and continuous releases and analyses of human-error influence on the total probability for both cases was performed.

2.1 Opis delovanja sistema

V rektifikacijski koloni, osrednji napravi rektifikacijskega sistema, poteka postopek ločevanja zmesi aceton - izopropanol - voda na podlagi različnih hlapljivosti navzočih sestavin. Ločevanje komponent poteka pri temperaturah vrelišča, pri čemer slika 2 prikazuje shemo rektifikacijskega sistema, ki je sestavljen iz rektifikacijske kolone, uparjalnika in kondenzatorjev.

2.1 Description of system operation

The process of separating acetone-isopropanol-water occurs within a rectification column forming the main part of a rectification system. The process is based on the different volatilities of the individual components. The separation occurs at the boiling temperatures of the components. The system is comprised of the rectification column, an evaporator and a condenser, and is shown in Fig. 2.



Sl. 2. *Shema rektifikacijskega sistema*
Fig. 2. *Schematic of the rectification system*

S črpalko napajalno zmes doziramo s strani v kolono. Z merilnikom pretoka uravnavamo pretok napajalne zmesi.

V koloni zmes ločujemo v lažje hlapni aceton in težje hlapno zmes izopropanol - voda. Ta se nabira na dnu kolone, kjer intenzivno vre. Za razvoj hlapov skrbi uparjalnik, skozi katerega kroži težje hlapna zmes. Hlapi iz uparjalnika se dvigujejo po koloni navzgor in na svoji poti prihajajo na površini polnil v stik s padajočo napajalno zmesjo. Zaradi intenzivnega stika med dvigajočimi hlapi in padajočo zmesjo pride do intenzivne toplotne in snovne izmenjave med njima. Iz padajoče zmesi se uparja del lažje hlapne komponente, iz dvigajočih hlapov kondenzira del težje hlapne komponente. Težje hlapljiva zmes se nabira na dnu kolone. Aceton se dviga proti vrhu kolone skozi refluksno glavo v kondenzator.

V kondenzatorju aceton kondenzira. Nastali destilat se zbira v refluksni glavi kolone. Del destilata se kot refluks preliva nazaj v kolono,

The mixture is introduced into the system using the pump. The flow into the system is adjusted in accordance with the flowmeter reading.

Inside the column the mixture is separated into acetone, which boils at a low temperature, and a mixture of isopropanol and water. The latter accumulates at the bottom of the column, where it boils intensively. The vapors are primarily formed within the evaporator, through which the heavier mixture circulates. The vapors from the evaporator rise through the column and are brought into contact with the falling input mixture. Due to the intensive contact between both flows an intensive heat and mass transfer takes place. As a result, the most volatile compound evaporates while the heavier compounds condense and flow back to the bottom of the column. The acetone rises to the top of the column through the reflux head into the condenser.

The acetone condenses inside the condenser. The resulting condensate accumulates in the reflux head of the column. Part of the liquid flows back into the column while del pa odteka iz kolone skozi regulacijski ventil za uravnavanje refluksnega razmerja skozi hladilnik destilata v rezervoar. Pretok destilata uravnavamo z regulacijskim ventilom tako, da temperatura v glavi kolone ne naraste nad nastavljeno vrednost, ki je tik nad vreliščem acetona. Pretok težje hlapne zmesi iz dna kolone kot destilacijski preostanek krmilimo z odjemnim regulacijskim ventilom, tako da je nivo nespremenljiv. Temperatura vrelišča lažje hlapne sestavine - acetona je 56,5 °C, težje hlapne - izopropanola pa 80,3 do 82 °C.

- Sestava vhodne zmesi: aceton (75 ut. %), izopropanol (15 ut. %), voda (10 ut. %).
- Ciljna sestava destilata: aceton (95,0 ut. %), izopropanol (3,0 ut. %), voda (2,0 ut. %).
- Sestava destilacijskega preostanka: aceton (največ 5,0 ut. %), izopropanol - voda (95,0 ut. %).

Iz dolgoletnih izkušenj operaterja so v obratu, kjer obravnavana kolona deluje, postavili naslednje delovno pravilo: najmanj 95 ut. % acetona v destilatu je zagotovljeno s stalnim vzdrževanjem temperatur T_2=56-57 °C v refluksni glavi kolone in T_3=80 °C na dnu kolone. Dejavnosti operaterja pri pripravi, vklopu, obratovanju in izklopu rektifikacijske kolone so opisane v preglednici 3.

3 IDENTIFIKACIJA TEHNIČNIH ODPOVEDI IN ANALIZA Z METODO DREVESA ODPOVEDI

V literaturi [7] je moč tehnične odpovedi razdeliti na tiste, ki imajo za posledico trenutni izpust (zaradi sesutja oziroma porušitve uparjalnika/kolone/kondenzatorja, prelom cevi) in tiste, katerih posledica je stalni izpust (poškodba plašča uparjalnika/kolone/kondenzatorja, poškodba cevi). To razdelitev smo upoštevali tudi v pričujočem prispevku. V nadaljevanju tako najprej identificiramo in analiziramo odpovedi s posledico trenutnega izpusta in nato odpovedi s posledico stalnega izpusta.

Uporaba in izdelava drevesa odpovedi je dobro znana. Najti je moč več avtorjev, v konkretni analizi pa smo se naslonili na delo [8]. Izračun verjetnosti za vmesne in glavni dogodek so za vse primere izračunani s t.i. Booleanovo algebro:

<u>vezje ALI:</u>

$\lambda_G=\lambda_1+\lambda_2-(\lambda_1 x \lambda_2)$ … če vezje povezuje dva dogodka (1)

$\lambda_G=1-[(1-\lambda_1)x\ldots x(1-\lambda_n)]$ … če vezje povezuje *n* dogodkov (2)

<u>vezje IN:</u>

$\lambda_G=\lambda_1 x \lambda_2 x \ldots x \lambda_n$ (3).

λ_x … verjetnost dogodka

Verjetnosti osnovnih dogodkov za rektifikacijski sistem ločevanja mešanice aceton-izopropanol - voda, ki smo jih povzeli po [7], so bile

another part of the liquid flows from the column through the control valve enabling the control of the reflux ratio through the condensate cooler into the reservoir. The actual flow of the liquid is controlled in such a fashion that the temperature within the reflux head does not rise above a preset value that is just above the acetone's boiling point. The flow of the heavier compound from the bottom of the column (bottom product) as well as the distillation bottom product is manipulated by the control valve in order to obtain an approximately constant level. The boiling point of the lighter compound, acetone, is 56.5°C, the boiling point of the heavier isopropanol is 80.3–82 °C.

- The input fluid is comprised of acetone (75% w.), isopropanol (15% w.), and water (10% w.).
- The desired distillate contains acetone (95% w.), isopropanol (3 % w.), water (2% w.)
- The distillation bottom-product contains acetone (5% w. max.), isopropanol-water (95% w.)

To achieve the best result the following rule has been established, based on several years' worth of observation: a minimum of 95% w. of acetone in the distillate is ensured with a constant temperature T_2=56–57 °C in the reflux head of the column and T_3=80 °C in the bottom of the column. The activities of the operator during preparation – turning on and turning off the rectification column – are described in Table 3.

3 IDENTIFICATION OF TECHNICAL FAILURES AND THE FAULT-TREE ANALYSIS

The literature [7] distinguishes between technical failures that result in an instantaneous release as a result of evaporator, column, condenser, or tube failure, and technical failures that result in a continuous release (damage to the shell of the evaporator, column, condenser, or tube). This division was also used in this study. Below, we identify and analyze the failures that result in an instantaneous release, and then the failures that result in a continuous release.

The use of a failure tree is well known. There are several authors who have explored this method in detail; however, this analysis was based on work by [8]. The computation of the probability for the top and intermediate events are calculated using the so-called Boolean algebra, as follows:

<u>OR gates:</u>

$\lambda_G=\lambda_1+\lambda_2-(\lambda_1 x \lambda_2)$ … if the gate connects two events (1)

$\lambda_G=1-[(1-\lambda_1)x\ldots x(1-\lambda_n)]$ … if the gate connects several (*n*) events (2)

<u>AND gates:</u>

$\lambda_G=\lambda_1 x \lambda_2 x \ldots x \lambda_n$ (3).

λ_x … probability of event

The probabilities of the top events for the rectification system for separating acetone-isopropanol-water were taken from [7] and adjusted

Preglednica 1. *Verjetnosti osnovnih dogodkov opisanega rektifikacijskega sistema*
Table 1. *Basic events probability of described rectification system*

DOGODEK EVENT	VERJETNOST DOGODKA PROBABILITY OF EVENT
prelom napajalne cevi uparjalnika (*D*=90 mm, *l*=0,5 m) reboiler feed line rupture (D=90 mm. l=0.5 m)	$1{,}3x10^{-7}$ /leto (year)
puščanje napajalne cevi uparjalnika (*D*=90 mm, *l*=0,5 m) reboiler feed line leak (D=90 mm. l=0.5 m)	$2{,}7x10^{-6}$ /leto (year)
prelom napajalne cevi kolone (*D*=30 mm, *l*=4 m) column feed line rupture (D=30 mm. l=4 m)	$3{,}5x10^{-6}$ /leto (year)
puščanje napajalne cevi kolone (*D*=30 mm, *l*=4 m) column feed line leak (D=30 mm. l=4 m)	$3{,}5x10^{-5}$ /leto (year)
prelom odvodne cevi iz dna kolone (*D*=90 mm, *l*=1,3 m) column bottom discharge line rupture (D=90 mm. l=1.3 m)	$3{,}4x10^{-7}$ /leto (year)
puščanje odvodne cevi iz dna kolone (*D*=90 mm, *l*=1,3 m) column bottom discharge line leak (D=90 mm. l=1.3 m)	$6{,}9x10^{-6}$ /leto (year)
prelom odvodne cevi iz vrha kolone (*D*=30 mm, *l*=12 m) column top discharge line rupture (D=30 mm. l=12 m)	$1{,}0x10^{-5}$ /leto (year)
puščanje odvodne cevi iz vrha kolone (*D*=30 mm, *l*=12 m) column top discharge line leak (D=30 mm. l=12 m)	$1{,}0x10^{-4}$ /leto (year)
sesutje uparjalnika/kolone/kondenzatorja column/reboiler/condenser rupture	$6{,}5x10^{-6}$ /leto (year)
puščanje plašča uparjalnika/kolone/kondenzatorja column/reboiler/condenser shell leak	$1{,}0x10^{-5}$ /leto (year)

preračunane glede na dolžine dejanskih cevi in so prikazane so v preglednici 1.

3.1 Trenutni izpust

Shema drevesa odpovedi za trenutni izpust je prikazana na sliki 3. Na vrhu je glavni dogodek (“top event”), katerega verjetnost ocenjujemo, pod njim pa tisti dogodki, ki na verjetnost odpovedi vplivajo. Z vezjem ALI poudarimo, da se dogodek (odpoved) nad vezjem ALI zgodi, če se zgodi katerikoli od dogodkov, ki jih vezje ALI povezujejo, z vezjem IN pa, da se dogodek nad vezjem IN zgodi, če se zgodijo vsi dogodki, ki so med seboj povezani z vezjem IN.

Že ta del kaže, da rektifikacijski sistem ni v zadostni meri opremljen z varnostnimi sistemi, če seveda so verjetnosti odpovedi posameznega podsistema nesprejemljive, saj bo verjetnost odpovedi celotnega sistema kvečjemu višja od verjetnosti odpovedi posameznega podsistema.

3.2 Stalni izpust in rezultati analize drevesa odpovedi

Shema drevesa odpovedi za stalni izpust je prikazana na sliki 4. Preglednica 2 kaže rezultate za verjetnost trenutnega in kontinuiranega izpusta v obeh primerih, izračunane z enačbama (1) in (2) za posamezne primere s slik 3 in 4.

4 IDENTIFIKACIJA ČLOVEŠKIH NAPAK Z UPORABO OSNOVNE IN RAZŠIRJENJE METODE CREAM

V nadaljevanju prikazujemo identifikacijo človeških napak in njihovo analizo z uporabo

for the actual lengths of the pipes. The results are shown in Table 1.

3.1 Instantaneous release

The failure-tree schematic for an instantaneous release is shown in Fig. 3. On the top there is an event, the probability of whhich one wishes to estimate. Below the top event there are events that influence the top event. An OR gate connects events where each event connected occurring causes the event above the gate to occur while an AND gate connects events where all events connected occurring causes the event above the gate to occur.

The rare use of AND gates in the presented case shows that the rectification system is not sufficiently equipped with safety features (provided that failures of subsystems are not acceptable) as the probability of failure of the total system could only be higher than the probability of failure of a particular subsystem.

3.2 Continuous release and the results of the fault-tree analysis

The fault-tree schematic for a continuous release is shown in Fig. 4. Table 2 shows results for the probability of instantaneous and continuous releases in both cases calculated using Eqs. (1) and (2) for the cases in Figs. 3 and 4.

4 IDENTIFICATION OF HUMAN ERRORS USING BASIC AND EXTENDED CREAM METHODS

Below, we examine the identification of human errors and their analysis using the basic and extended osnovne in razširjene metode ASZN, ki jo povzemamo po [5], in sicer najprej z osnovno metodo, ki jo dogradimo še z razširjeno metodo.

CREAM methodology by [5].

4.1 Analiza po osnovni metodi ASZN

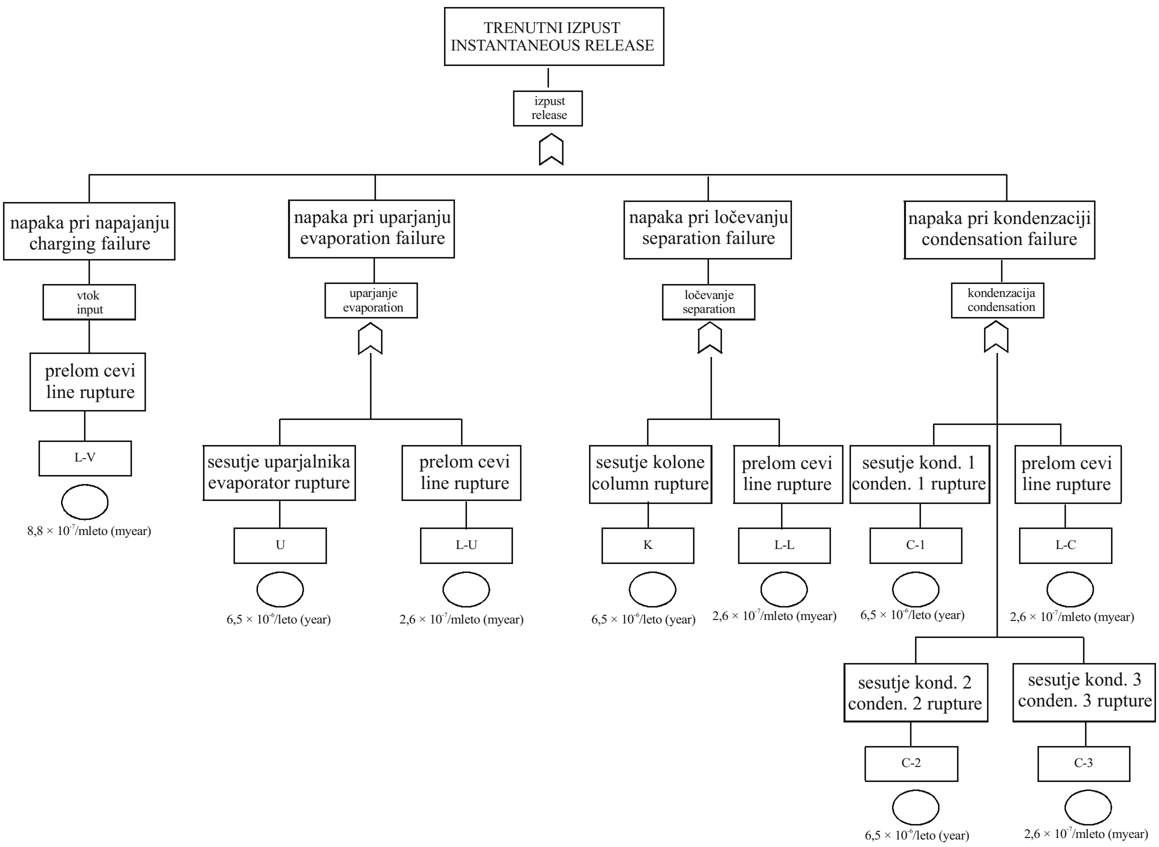
Osnovna metoda sestoji iz naslednjih treh stopenj:
- opis naloge ali dela naloge, ki ju analiziramo in opravimo tako, da posamezno nalogo razčlenimo na njene sestavne dele, podobno kakor je to za verjetnost odpovedi, opravljeno z uporabo drevesa odpovedi (preglednica 3),
- ocena splošnih pogojev dela[4], pri čemer za vsakega od predstavljanih pogojev dela izberemo primerno vrednost (preglednica 4),
- določitev verjetnega načina nadzora[5] (preglednica 5).

4.1 Analysis using the basic CREAM method

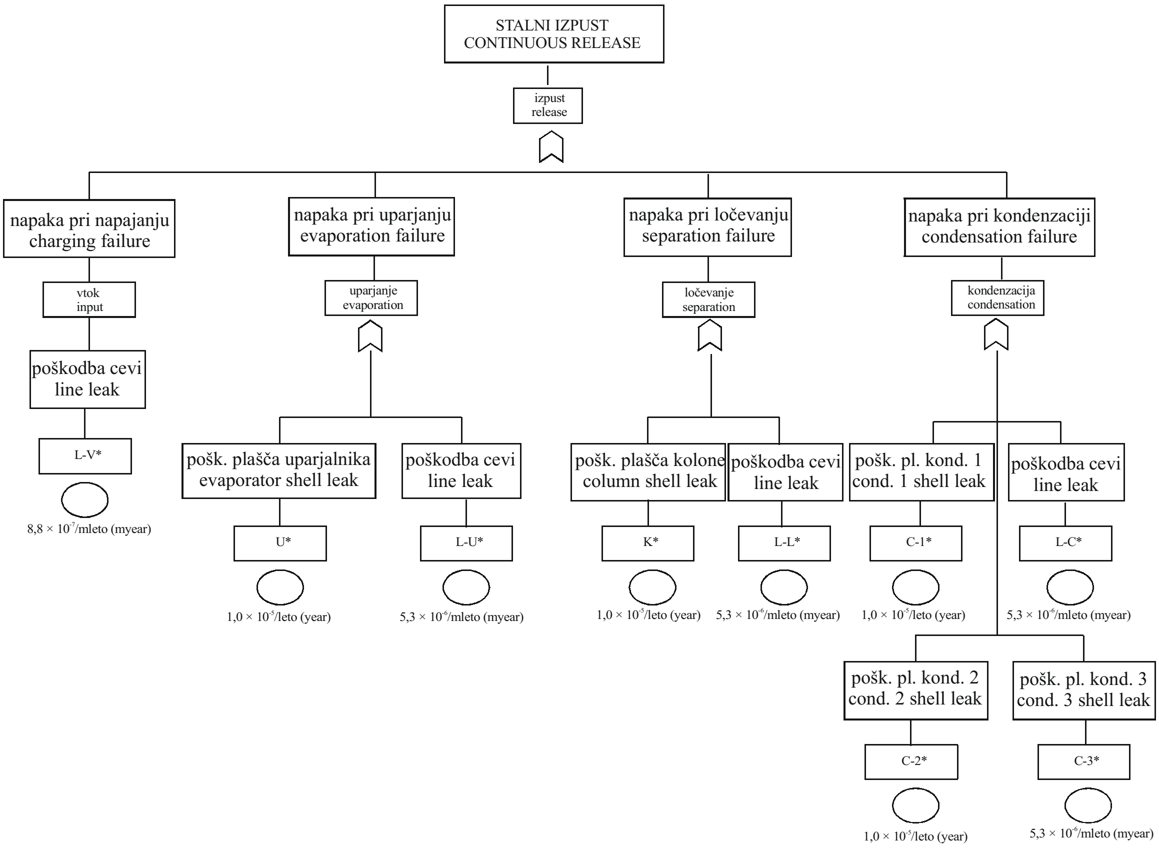
The basic method comprises the following three levels:
- description of the task or part of the task subject to analysis which is performed by breaking down particular tasks into their components in a similar fashion as done with failures using the fault-tree analysis, Table 3,
- assessment of common performance conditions[4] where a suitable value for each of the conditions of work is selected, Table 4,
- selection of probable control mode[5] , Table 5.

Preglednica 2. *Rezultati analize za trenutni in stalni izpust*
Table 2. *Results of analysis for instantaneous and continuous release*

NAPAKA FAILURE	VERJETNOST NAPAKE - p PROBABILITY OF FAILURE - p
trenutni izpust instantaneous release	$4{,}6x10^{-5}$
stalni izpust continuous release	$2{,}0x10^{-4}$



Sl. 3. *Drevo napak - trenutni izpust*
Fig. 3. *Fault tree – instantaneous release*



Sl. 4. *Drevo napak - stalni izpust*
Fig. 4. *Fault tree – continuous release*

V preglednici 3 je prikazano zaporedje dejavnosti pri pripravi, vklopu, obratovanju in izklopu rektifikacijskega sistema. Vidimo lahko, da so identificirane zlasti aktivnosti, katerih odsotnost bi povzročila napake v delovanju (primer: če so povezave med kolono in rezervoarji za destilat in destilacijski ostanek odprte, ima to negativne posledice za končni rezultat procesa). Iz navedenega je jasno razvidna potreba po obstoju tehnoloških postopkov, ki se jih operaterji zahtevnih procesnih sistemov držijo pri nadzoru delovanja teh sistemov.

Splošni pogoji dela dajo obširno in dobro strukturirano bazo za karakterizacijo razmer, v katerih izvajamo določeno nalogo. Za vsako vrsto delovnih pogojev je treba določiti ustrezno stopnjo. Vsaki stopnji ustreza pričakovan vpliv na zanesljivost dela, kakor je določeno v preglednici 4, povzeti po [5]. Pri tem so s krepkim tiskom označene vrednosti, ki smo jih upoštevali za izračun obravnavane rektifikacijske kolone.

Verjeten način nadzora določimo z oceno splošnih pogojev dela in določitvijo pričakovanega vpliva na zanesljivost izvedbe. Oceno splošnih pogojev dela prikažemo kot trojico [∑zmanjšan, ∑brez posebnosti, ∑izboljšan]. Slika 5 prikazuje povezavo med splošnimi pogoji dela in načinom nadzora. Način nadzora določimo glede na polje, v katerem je presečišče vrednosti ∑izboljšan in ∑zmanjšan [5].

Table 3 shows activities during the preparation, operation, and turning off of the rectification system. We see that the activities, the lack of which could cause errors during the operation, are noted (i.e. if the connections between the column and reservoirs for distillate remain open this is detrimental to the final result of the process). Therefore, a need for clearly defined guidelines for system control is shown.

Common performance conditions give a broad and well-structured basis for the characterization of conditions under which a particular task is performed. For each type of performance conditions one needs to define an appropriate level. Each level is associated with performance reliability, as defined in Table 4, according to Hollnagel [5], 1998. In Table 4 the conditions used for the actual calculations are written in bold.

The probable control mode is defined using an assessment of common performance conditions and selecting the expected influence on the reliability of performance. Common performance conditions are shown as a triplet [Σreduced, Σnot significant, Σimproved]. Fig. 5 depicts the relationship between the common performance conditions and the control mode. The control mode is defined according to the intersection of Σreduced and Σimproved [5].

Preglednica 3. *Zaporedje dejavnosti pri pripravi, vklopu, obratovanju in izklopu rektif. sistema*
Table 3. *Sequence of activities for preparing, start, operation and stopping of the rectification system*

OZNAKA MARK	CILJ GOAL	DEJAVNOST ACTIVITY
1.0	Priprava sistema Preparing of the system	
1.1		Preverimo, ali so odprte povezave med kolono in rezervoarji za destilat in destilacijski ostanek. Check if connections between column and tanks of destillate and distillatory residue are open.
1.2		Zapremo ventile za odvzem destilata in destilacijskega ostanka. Close valves for destillate and distillatory residue taking away.
2.0	Vklop sistema Start of the system	
2.1		Vključimo črpalko za kroženje glikola v kondenzatorjih. Start the pump for glycol circulation in condensers.
2.2		Vklopimo napajalno črpalko in napolnimo uparjalnik z mešanico topil. Start the feeder pump and fill up reboiler with components mixture.
2.3		Ko mešanica topil prekrije grelnik uparjalnika, odpremo ventil za gretje uparjalnika. When components mixture cover reboiler heater, open valve for reboiler heating.
3.0	Obratovanje sistema Operation of the system	
3.1		Kolona mora vsaj 30 min delovati pri popolnem refluksu brez napajanja. The column has to operate at least 30 minutes by full reflux without feeding.
3.2		Odpremo ventil za odvzem destilata in destilacijskega ostanka. Open valves for destillate and distillatory residue.
3.3		Napajalno črpalko naravnamo na pretok 300 l/h. Feeder pump set for flow 300 l/h.
3.4		Temperaturo v refluksni glavi uravnavamo z ventilom za odvzem destilata na 56 °C. Control temperature in reflux head with valve for destillate taking away at 56°C.
3.5		Temperaturo na dnu kolone uravnavamo z ventilom za odvzem destilacijskega ostanka na 80 °C. Control temperature in column bottom with valve for distillatory residue taking away at 80 °C.
4.0	Izklop sistema Stopping of the system	
4.1		Izklopimo napajalno črpalko. Stop feeder pump.
4.2		Zapremo ventil za gretje uparjalnika. Close valve for reboiler heating.
4.3		Zapremo ventil za odvzem destilacijskega ostanka. Close valve for distillatory residue taking away.
4.4		Odpremo ventil za odvzem destilata. Open valve for destillate taking away.
4.5		Izklopimo črpalko za kroženje glikola v kondenzatorjih. Stop pump for glycol circulation in condensers.

Ob koncu osnovne metode je treba določiti območje zanesljivosti za vsakega od načinov nadzora, ki so uporabni v primeru obravnavanega rektifikacijskega sistema.

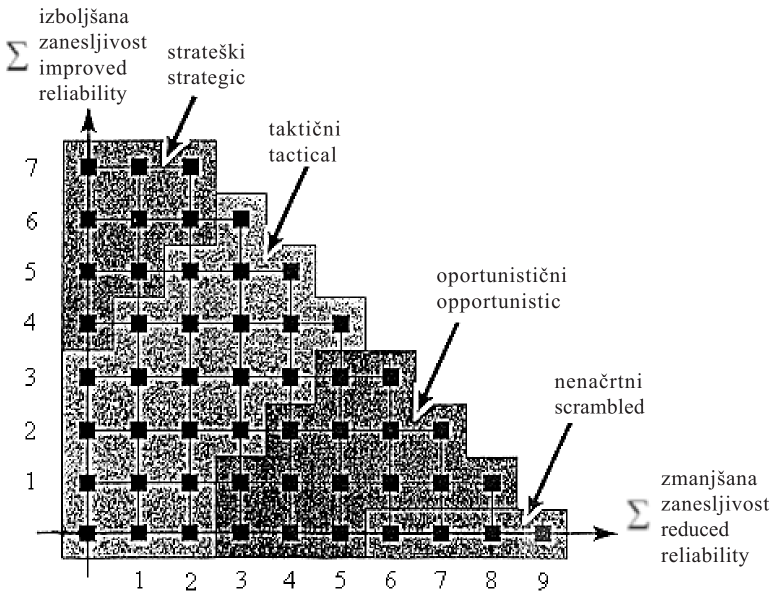
Za obravnavani sistem smo ugotovili, da zanj velja trojka [∑zmanjšan, ∑brez posebnosti, ∑izboljšan] = [0,5,4]. Ugotovimo lahko, da je presečišče vrednosti ∑zmanjšan in ∑izboljšan v polju, kjer je način nadzora strateški. Preglednica 5 kaže zanesljivostno območje za strateški način nadzor:

The final result of the basic method is the interval of reliability for each of the control modes used in the case of the rectification system as analyzed in this contribution.

For the system analyzed in this contribution we found the triplet [Σreduced, Σnot significant, Σimproved] = [0,5,4] to be valid. This gives a strategic control mode area of intersection between Σreduced and Σimproved. Table 5 presents the reliability interval for the strategic control mode as:

Preglednica 4. *Splošni pogoji dela in pričakovan vpliv na zanesljivost dela za obravnavani sistem*
Table 4. *Common performance conditions and expected effect on performance reliability for relevant system*

VRSTA DELOVNIH RAZMER COMMON PERFORMANCE CONDITIONS	OPIS EVALUATION	STOPNJA LEVEL	PRIČAKOVAN VPLIV NA ZANESLJIVOST DELA EXPECTED EFFECT ON PERFORMANCE RELIABILITY
Primerna organiziranost	kakovost podpore in namenjena sredstva organizacije, za opravljanje naloge; vključujoč komunikacijski sistem, sistem varstva pri delu	zelo učinkovit	izboljšan
		učinkovit	**brez posebnosti**
		neučinkovit	zmanjšan
		pomanjkljiv	zmanjšan
Adequacy of organisation	The quality of the support and resources provided by the organisation for the task being performed. This includes commu. system, Safety Management System.	very efficient	improved
		efficient	**not significant**
		inefficient	improved
		deficient	improved
Delovne razmere	osvetljenost prostora, bleščanje na zaslonih, hrup alarmov, motnje iz procesa, …	ugoden	izboljšan
		znosen	**brez posebnosti**
		neznosen	zmanjšan
Working conditions	Ambient lighting, glare on screens, noise from alarms, interruptions from the task, etc.	advantageous	improved
		compatible	**not significant**
		incompatible	improved
Primerna zaščita človeka pred strojem in operativna podpora	kakovost zaščite človeka pred strojem, informacije, dosegljive na nadzornih ploščah, računalniško vodenje	v pomoč	izboljšan
		primeren	brez posebnosti
		znosen	**brez posebnosti**
		neprimeren	zmanjšan
Adequacy of MMI and operational support	The quality of of the MMI, control panels, workstations.	supportive	improved
		adequate	not significant
		tolerable	**not significant**
		inappropriate	improved
Razpolaganje s postopki	razpolaganje s postopki in načrti, ki vključujejo operativna in nepričakovana stanja	**primeren**	**izboljšan**
		sprejemljiv	brez posebnosti
		neprimeren	zmanjšan
Availability of procedures/planes	The availability of prepared guideance for the work to be carried out, emergency proced..	**appropriate**	**improved**
		acceptable	not significant
		inappropriate	improved
Število hkratnih nalog	število nalog, ki jih mora delavec opraviti ali biti pozoren v istem času	pod zmožnostmi	brez posebnosti
		primerno zmožnostim	**brez posebnosti**
		nad zmožnostmi	zmanjšan
Number of simultaneous goals	The number of tasks or goals operators must attend to.	fewer than capacity	not significant
		matching curr. capacity	**not significant**
		more than capacity	improved
Razpoložljiv čas	čas, ki je na voljo za izvedbo naloge	**primeren**	**izboljšan**
		začasno neprimeren	brez posebnosti
		stalno neprimeren	zmanjšan
Available time	The time available to complete the work.	**adequate**	**improved**
		temporarily inadequate	not significant
		continuously inadequate	improved
Čas dneva	čas, v katerem je naloga opravljena	**dnevni čas**	**brez posebnosti**
		nočni čas	zmanjšan
Time of day	The time at which the task is carried out.	**day-time**	**not significant**
		night-time	improved
Primerna usposobljenost in izkušnje	raven in kakovost usposobljenosti operaterja, seznanitev z novo tehnologijo, ponavljanje starih spretnosti, stopnja operaterjeve izkušenosti	**primeren, zelo izkušen**	**izboljšan**
		primeren, omejeno izk.	brez posebnosti
		neprimeren	zmanjšan
Adequacy of training and preparation	The level of readiness for the work. Includes familiarisation to new technology, refreshing old skills, the level of operational experience.	**adequate, very experience**	**improved**
		adequate, lim. experience	not significant
		inadequate	improved
Kakovost sodelovanja v skupini	kakovost sodelovanja članov skupine, stopnja zaupanja, splošno počutje članov v skupini	**zelo učinkovit**	**izboljšan**
		učinkovit	brez posebnosti
		neučinkovit	brez posebnosti
		pomanjkljiv	zmanjšan
Crew collaboration quality	The quality of the collaboration. between crew members, the level of trust, the general social climate among crew members.	**very efficient**	**improved**
		efficient	not significant
		inefficient	not significant
		deficient	improved



Sl. 5. *Povezava med splošnimi pogoji dela in načinom nadzora [5]*
Fig. 5. *Relations between common performance conditions and control modes by [5]*

Preglednica 5. *Način nadzora in zanesljivostno območje [5]*
Table 5. *Control modes and probability intervals [5]*

NAČIN NADZORA CONTROL MODE	ZANESLJIVOSTNO OBMOČJE (VERJETNOST NAPAKE) RELIABILITY INTERVAL (PROBABILITY OF ACTION FAILURE)
strateški strategic	$0{,}5x10^{-5} < p < 1{,}0x10^{-2}$
taktični tactical	$1{,}0x10^{-3} < p < 1{,}0x10^{-1}$
oportunistični opportunistic	$1{,}0x10^{-2} < p < 0{,}5$
nenačrtni scrambled	$1{,}0x10^{-1} < p < 1{,}0$

$$0{,}5x10^{-5} < p < 1{,}0x10^{-2}$$

Ker je verjetnost človeške napake reda velikosti verjetnosti odpovedi rektifikacijskega sistema oz. je večja, je bilo treba analizo nadaljevati z razširjeno metodo CREAM.

4.2 Analiza z razširjeno metodo ASZN

Namen razširjene metode ASZN [5] je, da natančneje ovrednotimo posamezne prispevke k skupni človeški napaki in jo uporabimo takrat, ko je človeška napaka enakovredna ali pomembnejša od tehnične napake, ovrednotene po osnovni metodi ASZN.

V postopku izvedbe razširjene metode ASZN opravimo naslednje dejavnosti:
- določimo poznavalne dejavnosti[6], preglednica 6,
- identificiramo najverjetnejše napake poznavalne funkcije[7], preglednica 7,
- določimo verjetnost napake za vsako verjetno napako poznavalne funkcije za rektifikacijski sistem, preglednica 8,

As the probability of human error exceeds that of technical failure we continued the analysis with the extended CREAM methodology.

4.2 Extended CREAM methodology analysis

The extended Cognitive Reliability and Error Analysis Method (Extended CREAM) was designed by Hollnagel [5] as a tool to improve quantification of particular contributions to common human error and is used when the human-error probability assessed with basic CREAM equals or is greater than the technical failure probability.

In order to perform the extended CREAM the following activities should be undertaken:
- define cognitive demands[6], Table 6,
- identify cognitive function failures[7], Table 7,
- define cognitive failure probability, Table 8,

- določimo uravnane verjetnosti napak poznavalnih funkcij[8] za rektifikacijski sistem, preglednica 10.

Tako določeno vrednost napake lahko nato vključimo v drevo odpovedi in jo obravnavamo enako kakor smo obravnavali verjetnost okvare (napake iz tehničnih vzrokov).

Najprej smo na podlagi generičnih poznavalnih dejavnosti definirali poznavalne dejavnosti z zahtevami poznavanja za rektifikacijski sistem. Ugotovimo lahko, da je za rektifikacijski sistem največja zahteva po izvajanju, temu pa sledita opazovanje in razlaga. Preglednica 6 prikazuje poznavalne dejavnosti z zahtevami poznavanja za rektifikacijski sistem.

V nadaljevanju določimo najverjetnejše napake poznavalnih funkcij, uporabljenih za obravnavani rektifikacijski sistem, kar je prikazano v preglednici 7.

V nadaljevanju določimo še nominalne verjetnosti napak poznavalnih funkcij. Te lahko določimo na temelju lastnih opazovanj ali na temelju dosegljivih podatkov iz literature. V konkretnem primeru smo verjetnosti povzeli po [5], ki podaja osnovne vrednosti ter skrajne meje območij.

Iz vpliva splošnih delovnih pogojev na nominalno verjetnost napake poznavalne funkcije za rektifikacijski sistem določimo splošni uravnalni faktor (SUF) kot zmnožek posameznih uravnalnih faktorjev (UF[9]), kar storimo na podlagi utežnih količnikov uravnalnih faktorjev v skladu z razširjeno metodologijo ASZN. Izračun SUF je prikazan v preglednici 9.

Končna vrednost uravnane verjetnosti napake poznavalnih funkcij (UVNPF) je zmnožek skupnega uravnalnega faktorja in nominalne verjetnosti napake poznavalnih funkcij (NVNPF). Uravnane verjetnosti napak poznavalnih funkcij za rektifikacijski sistem so prikazane v preglednici 10.

V drevesi odpovedi za trenutni (sl. 3) in stalni izpust (sl. 4) so vključeni osnovni dogodki, ki so posledica človeških napak. Drevo odpovedi s tehničnimi in človeškimi napakami za trenutni izpust je na sliki 6. V drevesi odpovedi so vključene samo človeške napake, ki imajo za posledico trenutni ali stalni izpust tekočinske mešanice iz rektifikacijskega sistema.

5 SINTEZA VERJETNOSTI NEZGODE (ČLOVEŠKE NAPAKE) IN OKVARE (TEHNIČNE NAPAKE) V DREVESU ODPOVEDI

Na obravnavani način smo dobili vrednosti za verjetnosti človeških (nezgod) in mehanskih (okvar) napak, ki jih je moč uvrstiti v drevo odpovedi. Na sliki 6 je prikazano drevo odpovedi za trenutni izpust, na sliki 7 pa drevo odpovedi za stalni izpust. Prednost prikazanega je prav v uravnoteženju (deanimaciji[1]) objektivnih dogodkov (okvar) in subjektivnih dogodkov z objektivnimi posledicami (nezgod).

Zdaj je mogoče z uporabo že prikazane Booleove algebre ponovno ovrednotiti vse rezultate z upoštevanjem in brez upoštevanja človeških napak,

- define adjusted cognitive failure probability[8], Table 10.

The final result is a quantified human-error probability, which can be included in a fault tree and treated as any other failure probability to arrive at a final combined value for failure probability.

In order to arrive at the final result, we first define the cognitive demands based on generic cognitive demands. For our case, the execute cognitive demand was most frequently followed by observation and interpretation. The demands are summarized in Table 6.

Then we defined the cognitive function failures most likely to occur in the system at hand.The results are summarized in Table 7.

Further, we define the nominal cognitive failure probability. This can be defined based on our own observation or on published results. In our case we relied on the values of [5] who published basic values and upper and lower limits.

Based on the effect of common performance conditions on cognitive function failures for the rectification system under observation we can define a common weighting factor as a product of weighting factors[9] using the process shown in Table 9.

The final value of the adjusted cognitive failure probability is the product of a common weighting factor and the nominal cognitive failure probability. These values are shown in Table 10.

As a result, we have modified the fault trees for instantaneous (Fig.3) and continuous (Fig. 4) releases to include adjusted cognitive failure probabilities for both cases, shown in Fig. 6 for the instantaneous release case, and Fig. 7 for the continuous release case.

5 SYNTHESIS OF HUMAN-ERROR AND TECHNICAL FAILURE PROBABILITIES IN A FAULT TREE

In the preceding sections we have shown the process of obtaining human-error and technical failure probabilities. The results can be inserted in a fault tree in order to compare the influence of either component. Fig. 6 shows a fault tree for instantaneous release, and Fig. 7 for continuous release. The advantage of the presented synthesis is in the deanimation[10] of the objectively perceived events and the subjectively perceived human errors resulting in objectively perceived consequences of human errors (i.e. accidents)

Now, we can re-evaluate the results already

Preglednica 6. *Poznavalne dejavnosti z zahtevami poznavanja rektifikacijskega sistema*
Table 6. *Cognitive activity with cognitive demand for rectification system*

#	DEJAVNOST ACTIVITY	POZNAVALNA DEJAVNOST COGNITIVE ACTIVITY	O	IN	N	I
1.1	Preverimo, ali so odprte povezave med kolono in rezervoarji za destilat in destilacijski ostanek. Check if connections between column and tanks of destillate and distillatory residue are open.	Preveri Verify	*	*		
1.2	Zapremo ventile za odvzem destilata in destilacijskega ostanka. Close valves for destillate and distillatory residue taking away.	Izvedi Execute				*
2.1	Vključimo črpalko za kroženje glikola v kondenzatorjih. Start the pump for glycol circulation in condensers.	Izvedi Execute				*
2.2	Vklopimo napajalno črpalko in napolnimo uparjalnik z mešanico topil. Start the feeder pump and fill up reboiler with components mixture.	Izvedi Execute				*
2.3	Ko mešanica topil prekrije grelnik uparjalnika, odpremo ventil za gretje uparjalnika. When components mixture cover reboiler heater, open valve for reboiler heating.	Krmili Control	*			*
3.1	Kolona mora vsaj 30 min delovati pri popolnem refluksu brez napajanja. The column has to operate at least 30 minutes by full reflux without feeding.	Nadzoruj Monitor	*	*		
3.2	Odpremo ventil za odvzem destilata in destilacijskega ostanka. Open valves for destillate and distillatory residue.	Izvedi Execute				*
3.3	Napajalno črpalko naravnamo na pretok 300 l/h. Feeder pump regulate at flow 300 l/h.	Izvedi Execute				*
3.4	Temperaturo v refluksni glavi uravnavamo z ventilom za odvzem destilata na 56 °C. Control temperature in reflux head with valve for destillate taking away at 56°C.	Krmili Control	*			*
3.5	Temperaturo na dnu kolone uravnavamo z ventilom za odvzem destilacijskega ostanka na 80 °C. Control temperature in column bottom with valve for distillatory residue taking away at 80 °C.	Krmili Control	*			*
4.1	Izklopimo napajalno črpalko. Stop feeder pump.	Izvedi Execute				*
4.2	Zapremo ventil za gretje uparjalnika. Close valve for reboiler heating.	Izvedi Execute				*
4.3	Zapremo ventil za odvzem destil. ostanka. Close valve for distillatory residue taking away.	Izvedi Execute				*
4.4	Odpremo ventil za odvzem destilata. Open valve for destillate taking away.	Izvedi Execute				*
4.5	Izklopimo črpalko za kroženje glikola v kond. Stop pump for glycol circulation in condensers.	Izvedi Execute				*

Oznake: O – opazovanje, IN – interpretacija, N – načrtovanje, I – izvedba
Mark: O – observation, IN – interpretation, N – planning, I – execution

prikazanih v preglednici 2. Rezultati so prikazani v preglednici 11.

Ugotovimo lahko, da človeške napake v mejah postavljenih predpostavk ne vplivajo na verjetnost trenutnega izpusta, skoraj za faktor 25 pa povečajo verjetnost stalnega izpusta.

shown before with and without the human errors shown in Table 2. The results are shown in Table 11.

We deduce that human errors do not influence (within the limits of the assumptions) instantaneous release while they increase the probability of continuous release almost 25 fold.

Preglednica 7. *Verjeten način napak poznavalnih funkcij rektifikacijskega sistema*
Table 7. *Potential cognitive function failures for rectification system*

#	POZNA-VALNA DEJAVNOST COGNITIVE ACTIVITY	opazovanje observation			razlaga interpretation			načrtovanje planning		izvedba execution				
		O1	O2	O3	IN1	IN2	IN3	N1	N2	I1	I2	I3	I4	I5
1.1	Preveri Verify			*										
1.2	Izvedi Execute									*				
2.1	Izvedi Execute													*
2.2	Izvedi Execute										*			
2.3	Krmili Control			*										
3.1	Nadzoruj Monitor			*										
3.2	Izvedi Execute										*			
3.3	Izvedi Execute			*										
3.4	Krmili Control									*				
3.5	Krmili Control									*				
4.1	Izvedi Execute													*
4.2	Izvedi Execute													*
4.3	Izvedi Execute												*	
4.4	Izvedi Execute												*	
4.5	Izvedi Execute											*		

Ob analizi verjetnosti stalnega izpusta ugotovimo, da z vidika človeške napake nanjo vplivajo naslednje vrste napak poznavalne funkcije:
- brez izpolnitve
- napačna izpolnitev (2x).

Bistveno vprašanje, ki se zastavi operaterju rektifikacijskega sistema, je tedaj, kako napake zmanjšati ali odpraviti. Kar se tiče okvar, so postopki znani in preskušeni ter zaobseženi v načelih obvladovanja kakovosti. Glede nezgod pa bi bilo najprej smiselno ugotoviti, ali bi bilo nezgode moč omejiti tako, da bi jih iz potencialnih nezgod prekvalificirali v potencialne okvare, da bi torej razosebili njihov vir. To bi bilo najpreprosteje moč storiti z avtomatizacijo posameznih elementov delovanja rektifikacijskega sistema - torej zamenjavo človeške podpore s strojno podporo. Ker pa namen tega prispevka ni predlagati dejanske izvedbene tehnike, temveč le prikazati orodje in metodologijo za objektivno analizo sicer subjektivnih vprašanj, se s tem nismo bolj poglobljeno ukvarjali.

Glede same verjetnosti človeške napake pa menimo, da jo bo brez prekvalifikacije oz. zamenjave človeka z napravo moč najbolj zmanjšati v primeru

Further analysis of the continuous release shows that the following cognitive function failures are the main contributors to the human error:
- missed action
- action of the wrong type (2x)

The main question which the operator needs to answer is how to reduce or eliminate failures. As far as technical failures are concerned there are a number of procedures that are known under the umbrella of quality management. As far as human errors are concerned they should first be deanimated by switching them (conceptually and actually) from potential accidents into potential failures. This can be achieved by changing the human involvement with devices such as the automation of elements of the rectification system. As this is beyond the scope of this study we did not further explore the actual switch but it should, in our opinion, be performed at some point in the future.

Regarding human error itself, and short of changing the human operator with a device, the following actions should be performed to reduce failure rates:
- produce and use quality procedures and technical guidelines for operation,

Preglednica 8. *NVNPF osnovnih napak poznavalnih funkcij rektifikacijskega sistema*
Table 8. *Nominal Cognitive Failur Probabilities (NCFP) of basic cognitive function failures for rectification system*

#	DEJAVNOST ACTIVITY	VRSTA NAPAKE ERROR MODE	NVNPF NCFP
1.1	Preverimo, ali so odprte povezave med kolono in rezervoarji za destilat in destilacijski ostanek. Check if connections between column and tanks of destillate and distillatory residue are open.	O3 brez opazovanja observation not made	$7,0x10^{-2}$
1.2	Zapremo ventile za odvzem destilata in destilacijskega ostanka. Close valves for destillate and distillatory residue taking away.	I1 napačna izpolnitev action of wrong type	$3,0x10^{-3}$
2.1	Vključimo črpalko za kroženje glikola v kondenzatorjih. Start the pump for glycol circulation in condensers.	I5, brez izpolnitve missed action	$3,0x10^{-2}$
2.2	Vklopimo napajalno črpalko in napolnimo uparjalnik z mešanico topil. Start the feeder pump and fill up reboiler with components mixture.	I2 nepravočasna izpolnitev action at wrong time	$3,0x10^{-3}$
2.3	Ko mešanica topil prekrije grelnik uparjalnika, odpremo ventil za gretje uparjalnika. When components mixture cover reboiler heater, open valve for reboiler heating.	O3 brez opazovanja observation not made	$7,0x10^{-2}$
3.1	Kolona mora vsaj 30 min delovati pri popolnem refluksu brez napajanja. The column have to operate at least 30 minutes by full reflux without feeding.	O3 brez opazovanja observation not made	$7,0x10^{-2}$
3.2	Odpremo ventil za odvzem destilata in destilacijskega ostanka. Open valves for destillate and distillatory residue.	I2 nepravočasna izpolnitev action at wrong time	$3,0x10^{-3}$
3.3	Napajalno črpalko naravnamo na pretok 300 l/h. Feeder pump set for flow 300 l/h.	O3, brez opazovanja observation not made	$7,0x10^{-2}$
3.4	Temperaturo v refluksni glavi uravnavamo z ventilom za odvzem destilata na 56 °C. Control temperature in reflux head with valve for destillate taking away at 56°C.	I1 napačna izpolnitev action of wrong type	$3,0x10^{-3}$
3.5	Temperaturo na dnu kolone uravnavamo z ventilom za odvzem destilacijskega ostanka na 80 °C. Control temperature in column bottom with valve for distillatory residue taking away at 80 °C.	I1 napačna izpolnitev action of wrong type	$3,0x10^{-3}$
4.1	Izklopimo napajalno črpalko. Stop feeder pump.	I5, brez izpolnitve missed action	$3,0x10^{-2}$
4.2	Zapremo ventil za gretje uparjalnika. Close valve for reboiler heating.	I5, brez izpolnitve missed action	$3,0x10^{-2}$
4.3	Zapremo ventil za odvzem destilacijskega ostanka. Close valve for distillatory residue taking away.	I4, napačno zaporedje izpolnitev action out of sequence	$3,0x10^{-3}$
4.4	Odpremo ventil za odvzem destilata. Open valve for destillate taking away.	I4, napačno zaporedje izpolnitev action out of sequence	$3,0x10^{-3}$
4.5	Izklopimo črpalko za kroženje glikola v kondenzatorjih. Stop pump for glycol circulation in condensers.	I2, nepravočasna izpolnitev action at wrong time	$3,0x10^{-3}$

upravljanja rektifikacijske kolone:
- z izdelavo kakovostnih tehničnih navodil za delo in
- občasnim usposabljanjem upravljalca.

V navodila in usposabljanje je treba vključiti tudi neobičajne dogodke, katerih posledice so odvisne predvsem od hitre in prisebne reakcije upravljalca. Tudi sestava takih scenarijev je zunaj želenega dometa tega prispevka in pravzaprav spada v študij dela.

- education and training of the operator.

Procedures and guidelines should include unusual events, the consequences of which are primarily dependent on the rapid reaction of the operator. The scenarios, however, which could be included in this venue is outside of the scope of this study and should be performed by people involved in human-resources management.

Preglednica 9. *Vpliv splošnih delovnih razmer na nominalno verjetnost napake poznavalnih funkcij rektifikacijskega sistema*
Table 9. *Effects of common performance conditions on cognitive function failures for rectification system*

VRSTA DELOVNIH RAZMER COMMON PERFORMANCE CONDITION	STOPNJA LEVEL	1.1	1.2	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5
Primerna organiziranost Adequacy of organisation	učinkovit efficient	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Delovne razmere Working conditions	znosen compatible	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Primerna zaščita človeka pred strojem in operativna podpora Adequacy of MMI and operational support	znosen tolerable	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Razpolaganje s postopki Availability of procedures/planes	primeren appropriate	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
Število istočasnih nalog Number of simultaneous goals	primerno zmožnostim matching curr. capacity	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Razpoložljiv čas Available time	primeren adequate	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Čas dneva Time of day	dnevni čas day-time	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Primerna usposobljenost in izkušnje Adequacy of training and preparation	primeren, zelo izkušen adequate, very experience	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
Kakovost sodelovanja v skupini Crew collaboration quality	zelo učinkovit very efficient	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
SKUPNI URAVNALNI FAKTOR TOTAL INFLUENCE OF CPC		0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16

Preglednica 11. *Primerjava rezultatov analiz drevesa odpovedi z upoštevanjem in brez upoštevanja človeških napak*
Table 11. *Comparision of Fault-Tree Analyse results with and without including human errors*

KRITERIJ CRITERION	VERJETNOST DOGODKA PROBABILITY OF FAILURE	
	TRENUTNI IZPUST INSTANTANEOUS RELEASE	STALNI IZPUST CONTINUOUS RELEASE
TEHNIČNE NAPAKE TECHNICAL FAILURES	$4,6x10^{-5}$	$2,0x10^{-4}$
TEH. IN ČLOVEŠKE NAPAKE TECHNICAL AND HUMANS FAILURES	$4,6x10^{-5}$	$4,9x10^{-3}$

6 SKLEP

V pričujočem delu smo na kratko predstavili metodologijo, ki jo je po našem mnenju primerno upoštevati pri analizi delovanja zahtevnih sistemov. Najprej smo analizirali verjetnost napake trenutnega in stalnega izpusta iz rektifikacijskega sistema zaradi tehnične (mehanske) napake, kar smo storili z uporabo metode drevesa odpovedi in Booleove algebre.

Nato smo obravnavali sistem z vidika človeških napak ter ga analizirali z metodologijo ASZN.

Bistveni prispevek tega dela je v sintezi obeh vplivov, to je vpliv nezgod (človeške napake) in odpovedi (tehnične napake) v drevesu odpovedi. Po sintezi smo ugotovili, da človeška napaka na trenutni izpust bistveno ne vpliva (da je torej dominantna tehnična napaka), pač pa lahko bistveno vpliva na stalni izpust.

Analiza je pokazala še na glavne vire človeške napake, in sicer na napako, ki se pokaže kot neizpolnitev naloge in napačno izpolnitev naloge. Te napake je moč odpraviti z izdelavo dobrih tehničnih navodil za delo in občasnim usposabljanjem operaterja. Druga možnost je avtomatizacija tistih ponavljajočih se dejavnosti, ki bistveno prispevajo k verjetnosti nezgode.

6 CONCLUSION

This study deals mainly with methodology, which should, in our opinion, be used for an analysis of complex-system operation. First, the probability of technical failure for instantaneous and continuous releases was analyzed using fault-tree analysis and Boolean algebra.

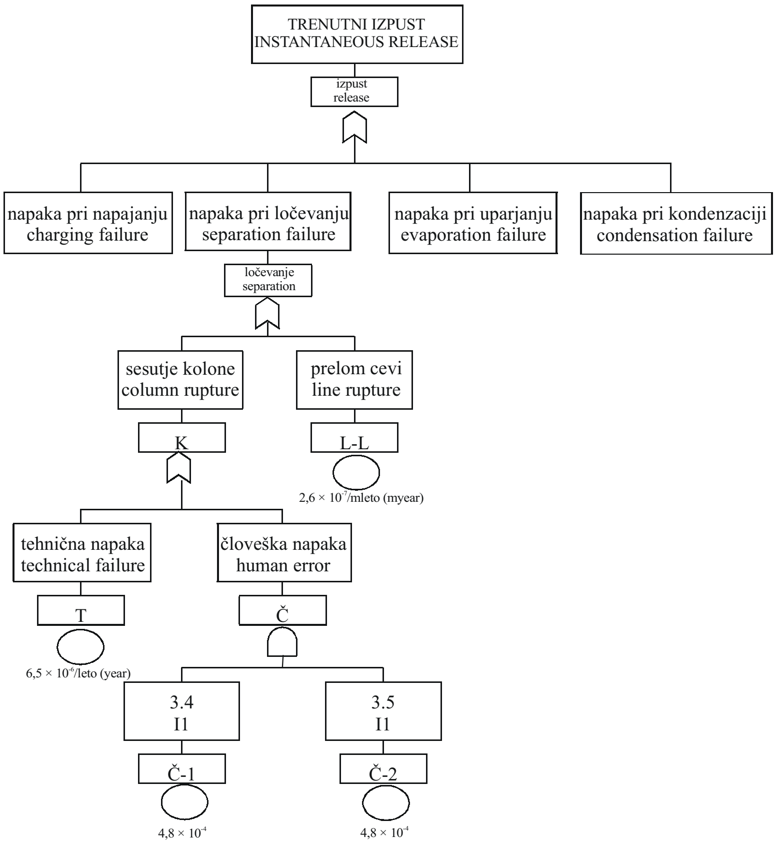
Then, the same system was presented from the human-error perspective and analyzed using CREAM methodology.

The main thrust of this work was in the synthesis of both methodologies, i.e. the influence of human errors and technical failures within the framework of the fault-tree analysis. The results have shown that human failure is almost negligible for instantaneous release, and of significance for continuous release.

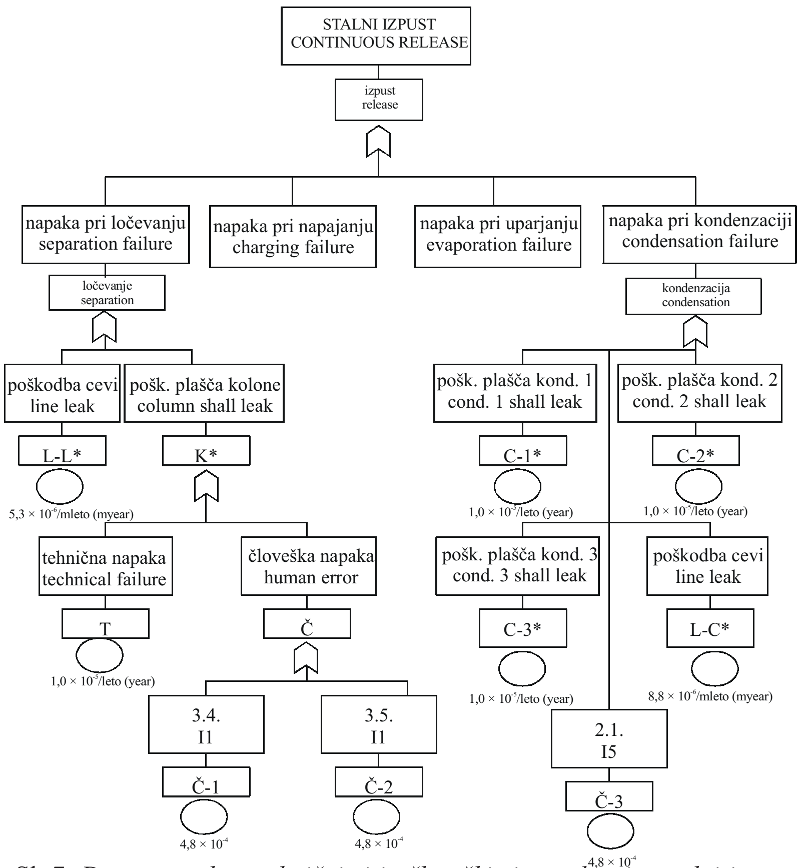
The analysis further identifies the main sources of human error as missed action and action of the wrong type. These errors could be mitigated using technical guidelines of sufficient quality and the periodic training of operators. The second possibility is switching the operations from human operator to activities operated using devices for those repetitive activities which could be the main contributors to the accidents as analyzed.

Preglednica 10. *Uravnane verjetnosti napak poznavalnih funkcij za rektifikacijski sistem*
Table 10. *Adjusted CFPs (ACFP) for rectification system*

#	DEJAVNOST ACTIVITY	VRSTA NAPAKE ERROR MODE	NVNPF NCFP	SUF WF	UVNPF ACFP
1.1	Preverimo, ali so odprte povezave med kolono in rezervoarji za destilat in destilacijski ostanek. Check if connections between column and tanks of destillate and distillatory residue are open.	O3 brez opazovanja observation not made	$7{,}0\text{x}10^{-2}$	0,16	$1{,}1\text{x}10^{-2}$
1.2	Zapremo ventile za odvzem destilata in destilacijskega ostanka. Close valves for destillate and distillatory residue taking away.	I1 napačna izpolnitev action of wrong type	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
2.1	Vključimo črpalko za kroženje glikola v kondenzatorjih. Start the pump for glycol circulation in condensers.	I5 brez izpolnitve missed action	$3{,}0\text{x}10^{-2}$	0,16	$4{,}8\text{x}10^{-3}$
2.2	Vklopimo napajalno črpalko in napolnimo uparjalnik z mešanico topil Start the feeder pump and fill up reboiler with components mixture.	I2, nepravočasna izpolnitev action at wrong time	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
2.3	Ko mešanica topil prekrije grelnik uparjalnika, odpremo ventil za gretje uparjalnika. When components mixture cover reboiler heater, open valve for reboiler heating.	O3 brez opazovanja observation not made	$7{,}0\text{x}10^{-2}$	0,16	$1{,}1\text{x}10^{-2}$
3.1	Kolona mora vsaj 30 min delovati pri popolnem refluksu brez napajanja. The column have to operate at least 30 minutes by full reflux without feeding.	O3 brez opazovanja observation not made	$7{,}0\text{x}10^{-2}$	0,16	$1{,}1\text{x}10^{-2}$
3.2	Odpremo ventil za odvzem destilata in destilacijskega ostanka. Open valves for destillate and distillatory residue.	I2 nepravočasna izpolnitev action at wrong time	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-3}$
3.3	Napajalno črpalko naravnamo na pretok 300 l/h. Feeder pump set for flow 300 l/h.	O3 brez opazovanja observation not made	$7{,}0\text{x}10^{-2}$	0,16	$1{,}1\text{x}10^{-2}$
3.4	Temperaturo v refluksni glavi uravnavamo z ventilom za odvzem destilata na 56 °C. Control temperature in reflux head with valve for destillate taking away at 56°C.	I1 napačna izpolnitev action of wrong type	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
3.5	Temperaturo na dnu kolone uravnavamo z ventilom za odvzem destilacijskega ostanka na 80 °C. Control temperature in column bottom with valve for distillatory residue taking away at 80 °C.	I1 napačna izpolnitev action of wrong type	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
4.1	Izklopimo napajalno črpalko. Stop feeder pump.	I5, brez izpolnitve missed action	$3{,}0\text{x}10^{-2}$	0,16	$4{,}8\text{x}10^{-3}$
4.2	Zapremo ventil za gretje uparjalnika. Close valve for reboiler heating.	I5, brez izpolnitve missed action	$3{,}0\text{x}10^{-2}$	0,16	$4{,}8\text{x}10^{-3}$
4.3	Zapremo ventil za odvzem destilacijskega ostanka. Close valve for distillatory residue taking away.	I4, napačno zaporedje izpol. action out of sequence	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
4.4	Odpremo ventil za odvzem destilata. Open valve for destillate taking away.	I4, napačno zaporedje izpol. action out of sequence	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$
4.5	Izklopimo črpalko za kroženje glikola v kondenzatorjih. Stop pump for glycol circulation in condensers.	I2, nepravočasna izpolnitev action at wrong time	$3{,}0\text{x}10^{-3}$	0,16	$4{,}8\text{x}10^{-4}$



Sl. 6. *Drevo napake s tehničnimi in človeškimi napakami – trenutni izpust*
Fig. 6. *Synthesis of human error and fault-tree analysis – instantaneous release*



Sl. 7. *Drevo napake s tehničnimi in človeškimi napakami – stalni izpust*
Fig. 7. *Synthesis of human error and fault-tree analysis – continuous release*

[1] Z mehanskimi sistemi imamo v mislih vse sisteme, ki niso odvisni od človeškega odziva, ne glede na to, za kakšne sisteme gre - sem spadajo npr. cevi, ventili, tlačne posode, zvari ipd.
[2] Med uporabnike štejemo menedžerje, zavarovalnice, sodne izvedence, tehnologe in druge, ki za svoje odločitve uporabljajo podatke o verjetnosti ali možnosti okvare ali porušitve posamezne naprave.
[3] Glede na krajšanje dobe, ki je potrebna za doseganje družbeno sprejemljive spretnosti pri ravnanju s stroji in višanje števila nosilcev tako pridobljene izobrazbe je ta predpostavka konzervativna.
[4] Z izrazom splošni pogoji dela po [5] označujemo obširen in dobro strukturiran temelj za označevanje pogojev, pri katerih naj bi se delo izvajalo. Osnovna predpostavka njihove uporabe je, da so medsebojno odvisni in da zato preprost seštevek ne pomeni še skupne ocene splošnih pogojev dela. V posledici medsebojne odvisnosti mora biti skupna ocena izračunana tako, da upošteva način medsebojne odvisnosti.
[5] Sklepni korak osnovne metode je določitev verjetnega načina nadzora na podlagi kombinacije števila posameznih vplivnih parametrov (od 9 skupnih), ki so bodisi zmanjšani, niso spremenjeni, ali izboljšani ([Σ zmanjšan, Σ brez posebnosti, Σ izboljšan]), pri čemer trojka [9,0,0] opiše najmanj zaželeno stanje, trojka [0,2,7] pa najbolj želeno stanje.
[6] Z izrazom poznavalne dejavnosti [5] označujemo posamezne poznavalne (prepoznavalne, kognitivne) dejavnosti, ki so značilne za vsakega od korakov iz osnovne metode. Te posamezne dejavnosti so uporabljene za gradnjo poznavalnega profila (*Cognitive Profile*) za bistvene segmente opravila, osnovane na funkcijah (t.i poznavalnih funkcijah), ki so opisane s poznavalnim (kognitivnim) modelom. Poznavalne funkcije so uporabljene za prepoznavanje posameznih poznavalnih dejavnosti (npr. z opazovanjem kot funkcijo opravimo dejavnost verifikacije ali dejavnost spremljanja).
[7] Z izrazom napake poznavalne funkcije so [5] označene napovedane napake, do katerih lahko pride pri izvedbi poznavalnih funkcij (npr. pri opazovanju kot funkciji lahko pride do napak opazovanja, ki imajo lahko neposredni vpliv na poznavalne dejavnosti, npr. na spremljanje).
[8] Različne napake poznavalnih funkcij imajo različen učinek na končni rezultat, zato je posamezne napake poznavalne funkcije treba primerno utežiti.
[9] Uravnalni faktor po [5] iz [9], ki za učinek posamezne poznavalne funkcije na posamezno poznavalno aktivnost določa utež. Ta izvira iz izkušenj in znaša za nevtralni položaj 1.0, za položaj, ki izboljšuje stanje manj ko 1 in za položaj, ki stanje slabša, več ko 1. Tako npr. primerna dostopnost načrtov in postopkov pomeni 20% zmanjšanje verjetnosti napake (uravnalni faktor 0,8), sprejemljiva dostopnost pomeni nevtralno stanje (UF=1,0), neprimerna dostopnost pa 100% povečanje verjetnosti napake (UF=2). Značilna za tako porazdelitev je penalizacija, ki kaznuje slabšanje položaja in posledično vnaša konzervativnost v določanje UF.
[10] *Deanimation*, po Raven, J., osebna komunikacija.

[1] With mechanical or technological systems one describes all systems that are not directly dependent on human response without regard to actual systems - such as piping, valves, pressure vessels, welds etc.
[2] Such as insurance companies, managers, court experts, system engineers and others on a need-to-know basis regarding the probability of failure.
[3] This is a conservative assumption given the reduction in time needed for qualification as a machinist and inflation in the number of graduates of technical schools.
[4] Common performance conditions were suggested by Hollnagel [5] to describe well-structured foundation for description of conditions for work performance. The basic assumption of their use is common interdependence and the fact that a simple sum does not equal common performance conditions. Interdependence also requires taking into account its mode.
[5] The final step of the basic method is the evaluation of a probable control mode based on the combination of a number of important parameters (numbering 9) which can either be reduced, are not significant, or are improved [Σ reduced, Σ not significant, Σ improved] where the triplet [9,0,0] stands for least-desirable situation, and the triplet [0,2,7] for most-desirable situation.
[6] Hollnagel [5] defines the cognitive demands that are characteristic for each of the basic method steps. These demands are used to build a cognitive profile for important segments of a particular action and are based on a cognitive function. These functions are used for either recognizing a particular cognitive demand (e.g. with observation as a function the activity of monitoring is made).
[7] Cognitive function failures Hollnagel [5] describes potential failures that can occur during the execution of cognitive functions (i.e. observation as a function can result in observation failures, and these failures may directly influence execution).
[8] Different cognitive failures may have a different influence on the final result, which requires different weights to be applied to cognitive functions.
[9] Hollnagel [5] has adopted weighting factors from Williams [9] who defines the weight for the effect of each particular cognitive function on cognitive demand. The weight (weighting factor) is based on experience and equals 1.0 for neutral (not significant) position, less than 1 for improvements, and more than 1 for reduction. For example, good access to plans and procedures means a 20% reduction in probability of error (i.e. weight of 0.8), while adequate access means not significant position with a weight of 1.0, and inadequate access increase for 100%, i.e. a weight of 2.0. This method means penalization of worsening of position and results in a conservative weight definition.
[10] From Raven, J., personal communication.

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Izviren kombiniran večfazni model mešalne faze eksplozije pare

An Original Combined Multiphase Model of the Steam-Explosion Premixing Phase

Matjaž Leskovar - Borut Mavko

V večfaznem toku so lahko faze razporejene tako, da večfaznega toka ni mogoče obravnavati niti samo z modeli proste površine niti samo z modeli večfaznega toka. Takšno porazdelitev faz srečujemo na primer pri izotermnih preskusih mešalne faze eksplozije pare, kjer razpršene kroglice prodirajo v vodo, medfazna ploskev voda - zrak pa se ne razprši in ostane ostra. Pri modeliranju izotermnih mešalnih preskusov so običajno obravnavane vse tri faze, to so voda, zrak in kroglice, enakovredno z modeli večfaznega toka. Tako je obravnavana medfazna ploskev voda - zrak kot razpršen tok mehurčkov zraka v vodi oziroma kapljic vode v zraku, kar je fizikalno neustrezna slika in zaradi togih medfaznih sklopitvenih členov tudi numerično težko rešljiva naloga. Zato smo si zamislili, da bi izotermni mešalni proces obravnavali z izvirnim kombiniranim večfaznim modelom, pri katerem bi kroglice obravnavali kot običajno z modelom večfaznega toka, medtem ko bi medfazno ploskev voda - zrak obravnavali z modelom proste površine.

Z razvitim kombiniranim večfaznim modelom smo simulirali izotermni preskus Q08, ki so ga izvedli na napravi QUEOS. Najbolj problematičen del simuliranja izotermnega mešalnega preskusa je pravilna napoved plinskega stebra, ki se oblikuje med prodiranjem kroglic v vodo. Da bi bolje spoznali, kako se plinski steber oblikuje, smo opravili obsežno parametrično analizo (velikost mreže, začetno debelino medfazne ploskve voda - zrak, gostoto vode, položaj vključitve medfazne sklopitve gibalne količine). Ugotovili smo, da se plinski steber oblikuje tako kakor pri preskusu le, če v modelu medfazno trenje kroglic na vodni gladini obravnavamo na poseben način, ki upošteva nezveznost prehoda zrak - voda.

(Ključne besede: tok večfazni, modeli večfazni, eksplozija parne, metode z nivojsko funkcijo, simuliranje)

In multiphase flow, different phase distributions can occur that cannot be adequately modeled with just free-surface models or with just multiphase models. Such a distribution of phases occurs, for example, in isothermal steam-explosion premixing experiments, where dispersed spheres penetrate the water and the water-air surface remains sharp. A common practice when modeling isothermal premixing experiments is to treat all three phases involved – the water, the air and the spheres' phase – equally, with multiphase flow models. In this way the water-air surface is treated as a dispersed flow of bubbles in water or droplets in air, which is a physically incorrect picture and because of very strong momentum-coupling terms also numerically not an easily solvable problem. Therefore, we decided to develop an original, combined multiphase model, where the spheres are treated, as is usual, with a multiphase flow model, whereas the water-air surface is treated with a free-surface model.

The QUEOS isothermal premixing experiment Q08 was simulated with the developed combined multiphase model. A crucial part in isothermal premixing experiment simulations is the correct prediction of the gas chimney, which forms during the spheres' penetration into the water. To get a better understanding of the gas-chimney formation an extensive parametric analysis (mesh size, initial water-air surface thickness, water density, interfacial momentum-coupling starting position) was performed. We established that the right gas-chimney formation can be obtained if a special spheres' drag treatment at the water-air surface, which considers the discontinuous air-water transition, is incorporated into the model.

(Keywords: multiphase flow, multiphase models, steam explosion, level set methods, simulations)

0 UVOD

Porazdelitev faz v večfaznem toku je lahko različna. Tako so lahko faze na primer razporejene v večja območja, ki so med seboj ločena z gladko medfazno

0 INTRODUCTION

In multiphase flow different phase distributions can occur, these range from unmixed-phase distributions, where the phases are arranged ploskvijo (npr. stratificiran tok). Takšne večfazne tokove opisujemo z modeli proste površine, ki temeljijo na reševanju Navier-Stokesovih enačb ob upoštevanju medfaznih robnih pogojev. Drugo skrajnost pomenijo večfazni tokovi z razpršenimi fazami (npr. mehurčkast tok), pri katerih je medfazno ploskev praktično nemogoče spremljati in jih zato opisujemo z modeli večfaznega toka, ki temeljijo na manj natančnih povprečenih Navier-Stokosovih enačbah. Med tema obema skrajnostma (ločene faze – razpršene faze) obstajajo še številne porazdelitve faz, ki jih ni mogoče obravnavati niti samo z modeli proste površine niti samo z modeli večfaznega toka. Te porazdelitve faz lahko razdelimo v dve skupini. Prvo skupino predstavljajo tiste porazdelitve faz, pri katerih so faze razpršene le na določenih območjih, medtem ko so drugje ločene z gladko medfazno ploskvijo [1]. Takšna porazdelitev faz se pojavi na primer v kasnejši fazi razvoja Kelvin-Helmholtzove nestabilnosti. Drugo skupino pa predstavljajo tiste porazdelitve faz, pri katerih so nekatere faze ločene z gladko medfazno ploskvijo, medtem ko so druge faze razpršene. Takšno porazdelitev faz srečamo na primer pri izotermnih preskusih mešalne faze eksplozije pare, pri katerih spuščajo različne curke hladnih kroglic v posodo, napolnjeno z vodo [2].

V tem prispevku bomo predstavili izvirni kombinirani večfazni model, ki smo ga razvili za modeliranje izotermnih preskusov mešalne faze parne eksplozije [3]. Nova zasnova obravnave večfaznih tokov je dovolj splošna, da jo je mogoče preprosto prilagoditi tudi za obravnavo vseh drugih porazdelitev faz druge obsežne skupine faznih porazdelitev.

1 MODELIRANJE VEČFAZNEGA TOKA

Pri modeliranju izotermnih mešalnih preskusov so običajno obravnavane vse faze, to so voda, zrak in kroglice, enakovredno z modeli večfaznega toka [4]. Ti modeli večfaznega toka temeljijo na predpostavki, da vsaka faza z določeno fazno verjetnostjo kot oblak zaseda celotno simulirno območje in da so faze med seboj povezane z medfaznimi sklopitvenimi členi.

Značilnost izotermnih mešalnih preskusov je, da ostaneta voda in zrak med celotnim preskusom ločena z gladko medfazno ploskvijo, kakor je shematično prikazano na sliki 1, kjer so predstavljene tri mrežne celice. Indeksa *a* in *w* označujeta fazi zraka in vode, $\Delta\vec{\mathbf{v}}_{aw}$ pa je razlika vektorjev hitrosti zraka in vode. Pri modelu večfaznega toka opisujemo medfazno ploskev voda - zrak kot razpršen tok mehurčkov zraka v vodi oz. kapljic vode v zraku (sl. 1), kar je fizikalno neustrezna slika. Ker so medfazni sklopitveni členi gibalne količine v razpršenih tokovih, pri katerih je razmerje gostot faz veliko, togi, so pri izrecnih numeričnih metodah potrebni zelo majhni časovni koraki, pojavijo pa se tudi težave s konvergenco [5]. Poleg tega se medfazna ploskev voda - zrak numerično razprši zaradi numerične difuzije

in larger regions separated by a smooth interface (for example, stratified flow), to mixed distributions, where the phases are dispersed and it is practically impossible to track the phase interfaces (for example, bubbly flow). In between there is a variety of phases' distributions, which cannot be adequately modeled with just free-surface models, which are based on Navier-Stokes equations that consider the interface boundary conditions, or just with multiphase flow models, which are based on less accurate, averaged Navier-Stokes equations. In general, these phase distributions can be classified in two groups. The first group comprises cases where the phases are only dispersed in some domains, whereas elsewhere the phase interfaces are smooth [1]. Such a phase distribution occurs, for example, at a late stage of the Kelvin-Helmholtz instability. The second group comprises cases where some phases are separated with a smooth interface, whereas the other phases are dispersed. Such a phase distribution occurs, for example, in isothermal steam-explosion premixing experiments, where different jets of cold spheres are injected into a water pool [2].

In this paper an original combined multiphase model developed for isothermal steam-explosion premixing experiments modeling will be presented [3]. This new concept of multiphase-flow treatment is general enough for it to be easily adapted to all other cases of phase distribution of the comprehensive second-phase distributions group.

1 MULTIPHASE FLOW MODELING

A common practice in isothermal premixing experiments modeling is to treat all three phases involved – the water, the air and the spheres' phase – equally with multiphase flow models [4]. These multiphase flow models are based on the assumption that each of the phases occupies, with a given phase-presence probability, the whole simulated region as a cloud, and that the phases interact through interfacial coupling terms.

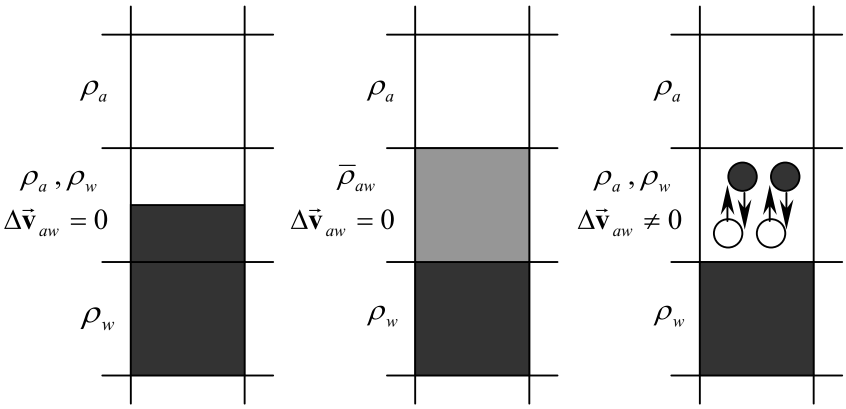
The special feature of isothermal premixing experiments is that the water and air phases remain separated by a free surface during the whole experiment, as shown schematically in Figure 1, where three mesh cells are presented. The indices *a* and *w* correspond to the air and water phases and $\Delta\vec{\mathbf{v}}_{aw}$ is the difference between the air- and water-velocity vectors. In the multiphase flow model the water-air surface is treated as a dispersed flow of air bubbles in water or water droplets in air (Fig. 1), which is a physically uncorrect picture. Since the interfacial momentum coupling terms in dispersed flows of fluids with high density ratios are very stiff, convergence problems occur and in explicit numerical methods extremely small time steps have to be used [5]. In addition, since in multiphase flow models

[6], ker pri modelih večfaznega toka medfazni ploskvi ne posvečamo posebne pozornosti. Zato smo se odločili, da bomo medfazno ploskev voda - zrak obravnavali z modelom proste površine in tako odpravili vse omenjene pomanjkljivosti obravnave medfazne ploskve z modelom večfaznega toka, ki ni primeren za takšne probleme.

Pri modelih proste površine uporabljamo za zasledovanje stične površine posebne algoritme, na stični površini pa vzamemo povprečne lastnosti faz (sl. 1). Ker se faze ne mešajo, zadošča za opis večfaznega toka eno hitrostno polje. Formalno lahko zato vodo in zrak obravnavamo kot eno, združeno fazo z nezveznimi faznimi lastnostmi na medfazni ploskvi voda - zrak in tako lahko izotermni mešalni potek obravnavamo kot navidez dvofazen tok razpršenih kroglic v kontinuumu združene faze voda - zrak. To je bistvo izvirnega kombiniranega večfaznega modela, pri katerem kroglice obravnavamo z modelom večfaznega toka, združeno fazo voda - zrak pa z modelom proste površine.

no special attention is given to the phases' interface, the water-air surface numerically spreads due to numerical diffusion [6]. Therefore, we decided to treat the water-air surface with a free-surface model and suppress, in this way, all the mentioned drawbacks of treating the phases' interface with multiphase flow models, which are not suited for such problems.

In free-surface models special interface-tracking algorithms are used, and since the phases do not mix the phases' flow is described with only one velocity field. At the phase interfaces the average phase properties are taken (Fig. 1). In this way the water and air phases can be regarded as a single, joint phase with discontinuous phase properties at the water-air interface, and consequently the isothermal premixing process can be treated as a quasi two-phase flow of dispersed spheres in the continuous joint water-air phase. This is the essence of the original combined multiphase model, where the spheres are treated with a multiphase flow model and the joint water-air phase with a free-surface model.



Sl. 1. *Obravnava medfazne ploskve voda - zrak pri modelu proste površine in modelu večfaznega toka*
Fig. 1. W*ater-air surface treatment in the free-surface model and the multiphase flow model*

2 METODA Z NIVOJSKO FUNKCIJO

Vsako fazo v tako definiranem navidez dvofaznem toku, razpršeno fazo kroglic in kontinuum združene faze voda - zrak, smo opisali s kontinuitetno in gibalno enačbo, kar je opisano v [7] in [8]. Medfazno ploskev voda - zrak smo določevali z metodo z nivojsko funkcijo [9], ki je namenjena reševanju problemov s stično površino in se v zadnjih letih veliko uporablja. Pri metodi z nivojsko funkcijo modeliramo medfazno ploskev kot ničelno izohipso $\phi = 0$ gladke nivojske funkcije, ki je definirana na celotnem obravnavanem območju kot $\phi(\vec{\mathbf{r}}, t = 0) = \pm d(\vec{\mathbf{r}})$, kjer je $d(\vec{\mathbf{r}})$ najmanjša razdalja do medfazne ploskve pri začetnem času $t = 0$. Glavne lastnosti nivojske funkcije so, da je v področju ene faze pozitivna, v področju druge faze negativna in da je gladka. Časovni razvoj lege medfazne ploskve določujemo z enačbo nivojske funkcije:

2 THE LEVEL-SET METHOD

Each phase in the so-defined quasi two-phase flow – the dispersed spheres' phase and the continuum joint water-air phase – was described using the continuity and momentum equations as explained in [7] and [8]. The water-air surface was determined using the front-capturing level-set method [9], which was developed for free-surface problems and has been widely used in recent years. In the level-set method the phases' interface is modeled as the zero set $\phi = 0$ of a smooth signed normal distance function, defined on the entire physical domain as $\phi(\vec{\mathbf{r}}, t = 0) = \pm d(\vec{\mathbf{r}})$, where $d(\vec{\mathbf{r}})$ is the signed minimum distance from the two-fluid interface at the initial time $t = 0$. The interface position is determined by solving the Hamilton-Jacobi-type level-set equation on the whole domain:

$$\frac{\partial \phi}{\partial t} + (\vec{\mathbf{v}} \cdot \nabla)\phi = 0 \qquad (1),$$

ki pomika ničelno izohipso nivojske funkcije tako, kakor se premika stična površina. Ker je ϕ gladka funkcija, v nasprotju z gostoto združene faze voda - zrak, ki je na medfazni ploskvi nezvezna, numerično reševanje enačbe nivojske funkcije (1) ni problematično. Gostota združene faze voda - zrak je določena z nivojsko funkcijo kot:

which moves the zero level of ϕ in exactly the same way as the actual two-fluid interface moves. Since ϕ is a smooth function, unlike the density of the joint water-air phase, which undergoes a jump at the water-air interface, the level-set equation (1) is more easily solved numerically. The density of the joint water-air phase is determined from the level-set function as:

$$\rho(\phi) = \begin{cases} \rho_w , & \phi > 0 \\ (\rho_w + \rho_a)/2 , & \phi = 0 \\ \rho_a , & \phi < 0 \end{cases} \qquad (2).$$

Če bi predpis (2) uporabljali dosledno, bi dobili stopničast, nezvezen potek gostote in pojavile bi se nestabilnosti, ki bi bile še posebej izrazite pri velikih razmerjih gostot. Zato je priporočljivo potek gostote na medfazni ploskvi nekoliko zgladiti z:

If this prescription (2) were to be used in a straightforward way a graded solution would result and instabilities would occur, especially for large density ratios. Therefore, it is recommendable to smooth the density at the interface as:

$$\rho(\phi) = \begin{cases} \rho_w , & \phi > \varepsilon \\ \frac{(\rho_w + \rho_a)}{2} + \frac{(\rho_w - \rho_a)}{2}\left(\frac{\phi}{\varepsilon} + \frac{1}{\pi}\sin\left(\frac{\pi\phi}{\varepsilon}\right)\right), & |\phi| \le \varepsilon \\ \rho_a , & \phi < -\varepsilon \end{cases} \qquad (3),$$

kjer je ε izbrana debelina medfazne ploskve. Pri naših izračunih smo za debelino medfazne ploskve vzeli priporočeno vrednost $\varepsilon = \frac{3}{2}\Delta h$, kjer je Δh mrežna razdalja.

Na začetku izračuna je vrednost ϕ enaka pozitivni oz. negativni najmanjši razdalji do medfazne ploskve, kasneje pa to ne drži več, saj enačba (1) nivojsko funkcijo spremeni. Da bi ohranili nespremenljivo debelino medfazne ploskve, moramo ϕ po vsakem časovnem koraku ponovno določiti tako, da zopet pomeni oddaljenost od medfazne ploskve. To izvedemo s tem, da poiščemo ustaljeno rešitev enačbe:

where ε is the chosen interface thickness. In our computations the recommended value $\varepsilon = \frac{3}{2}\Delta h$ was used, where Δh is the grid spacing.

It should be noted that while ϕ is initially a distance function it will not remain so at later times since the level-set equation (1) deforms it. To keep the interface thickness fixed in time the level-set function has to be reinitialized at each time step so that it remains a distance function. The reinitialisation is carried out by solving the equation:

$$\frac{\partial \phi}{\partial t} = sign(\phi_0)(1 - |\nabla\phi|), \quad \phi(\vec{\mathbf{r}},0) = \phi_0(\vec{\mathbf{r}}) \qquad (4),$$

kjer je ϕ_0 izračunana nivojska funkcija po času t. Rešitev enačbe (4) ima enak predznak in enako ničelno izohipso kakor ϕ_0 in ker rešitev izpolnjuje pogoj $|\nabla\phi| = 1$, je vrednost ϕ enaka pozitivni oz. negativni najmanjši razdalji do medfazne ploskve.

for the steady-state solution, where ϕ_0 is the calculated level-set function at time t. The solution of equation (4) will have the same sign and the same zero level-set as ϕ_0, and since it satisfies $|\nabla\phi| = 1$, it will be a distance function.

3 PARAMETRIČNA ANALIZA

S kombiniranim večfaznim modelom smo simulirali preskus Q08 [10], kakor je opisano v [8], vendar brez posebne obravnave medfaznega trenja kroglic na vodni gladini. Na sliki 2 so predstavljeni rezultati simuliranja. Slika prikazuje gostoto združene faze voda - zrak (črni obrisi), fazno verjetnost kroglic (sivi obrisi) in hitrostno polje združene faze voda - zrak v valjnem koordinatnem sistemu (r, z) v ekvidistančnih 25 ms dolgih časovnih razmikih. Kakor je razvidno na sliki, se začne plinski steber, ki nastane med prodiranjem kroglic v vodo, zapirati na vrhu stebra, kar ni v skladu z opažanji pri preskusih. Na

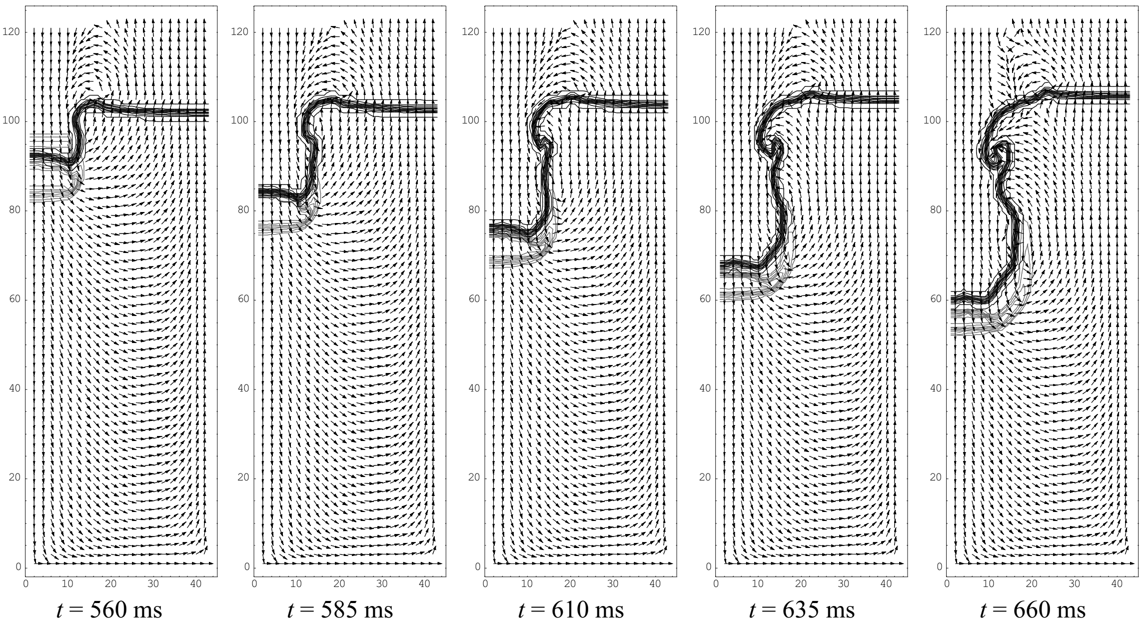
3 PARAMETRIC ANALYSIS

With the combined multiphase model the premixing experiment Q08 [10] was simulated, as described in [8], but without the special spheres' drag treatment at the water-air surface. The results of the simulation are presented in Figure 2. The figure shows the joint water-air phase density (black contours), the spheres' presence probability (gray contours) and the joint water-air phase velocity field in the cylindrical coordinate system (r, z) in equi-distant 25-ms-long time intervals. As seen in the figure, the gas chimney, which forms during the spheres' penetration into the water, starts to close at the top of the chimney, which is not in accordance with the experimental sliki 3 so prikazani posnetki vseh opravljenih izotermnih mešalnih preskusov QUEOS. Poleg preskusa Q08, ki smo ga simulirali, so predstavljeni še preskusi Q01, Q02, Q05 in Q06, ki se med seboj razlikujejo po premeru kroglic, snovi, iz katere so kroglice, in skupni masi kroglic [11]. Na vseh posnetkih je jasno vidno, da se plinski steber prične zapirati na sredini in ne na vrhu, tako kakor pri simuliranju.

Da bi ugotovili, zakaj so rezultati simuliranj kakovostno napačni, smo opravili obsežno parametrično analizo. Ker geometrijska oblika modela preskusa Q08, predstavljenega v [8], ni primerna za preprosto parametrično analizo vpliva velikosti mreže, smo parametrično analizo opravili v nekoliko

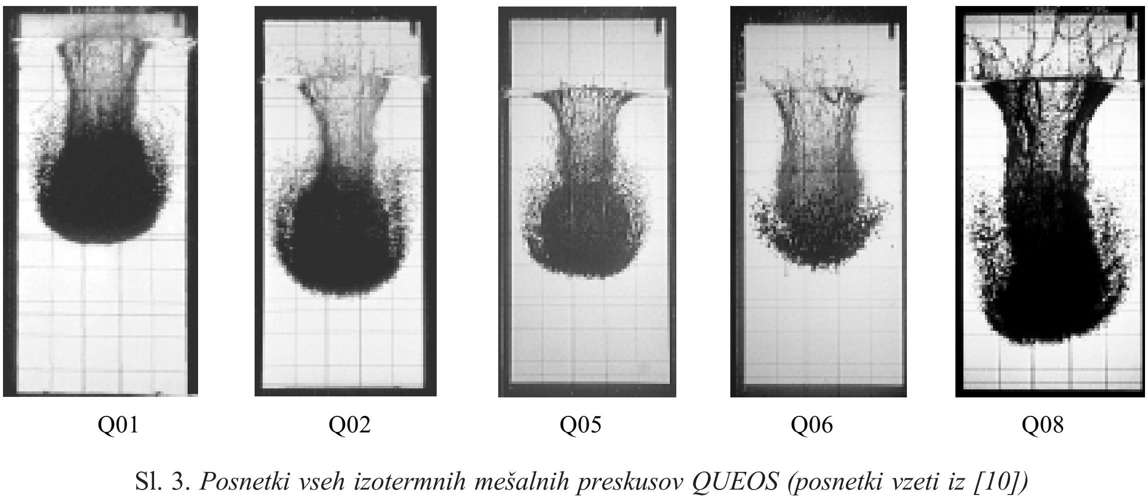
observations. The images of all the performed isothermal QUEOS premixing experiments are presented in Figure 3. Besides the simulated experiment Q08, experiments Q01, Q02, Q05 and Q06, where the spheres' diameter, spheres' material and spheres' total mass were varied, are also shown [11]. In all the images it is clear that the gas chimney starts to close in the middle, and not at the top as in the simulation.

To find out why the simulation results are qualitatively wrong a comprehensive parametric analysis was performed. Since the geometry of the model of experiment Q08, presented in [8], is not suited to a straightforward mesh-size-influence analysis, the parametric analyses were performed using a slightly different geometry (Figure 4). The spheres' jet radius



Sl. 2. *Gostota združene faze voda - zrak, fazna verjetnost kroglic in hitrostno polje združene faze voda - zrak ob različnih časih pri simuliranju preskusa Q08*

Fig. 2. *The joint water-air phase density, the spheres' phase-presence probability and the joint water-air phase velocity field at different times during the simulation of experiment Q08*



Sl. 3. *Posnetki vseh izotermnih mešalnih preskusov QUEOS (posnetki vzeti iz [10])*

Fig. 3. *Images of all isothermal QEUOS premixing experiments (images taken from [10])*

spremenjeni geometrijski obliki (sl. 4). Polmer curka kroglic smo zmanjšali z 9 cm na 8 cm in polmer posode z 41 cm na 40 cm. Tako so vse značilne dolžine modela večkrat deljive z 2, zaradi česar je parametrična analiza vpliva velikosti mreže lažje izvedljiva. Padajoče kroglice smo v model vključili z robnimi pogoji (RP), kar je opisano v [8].

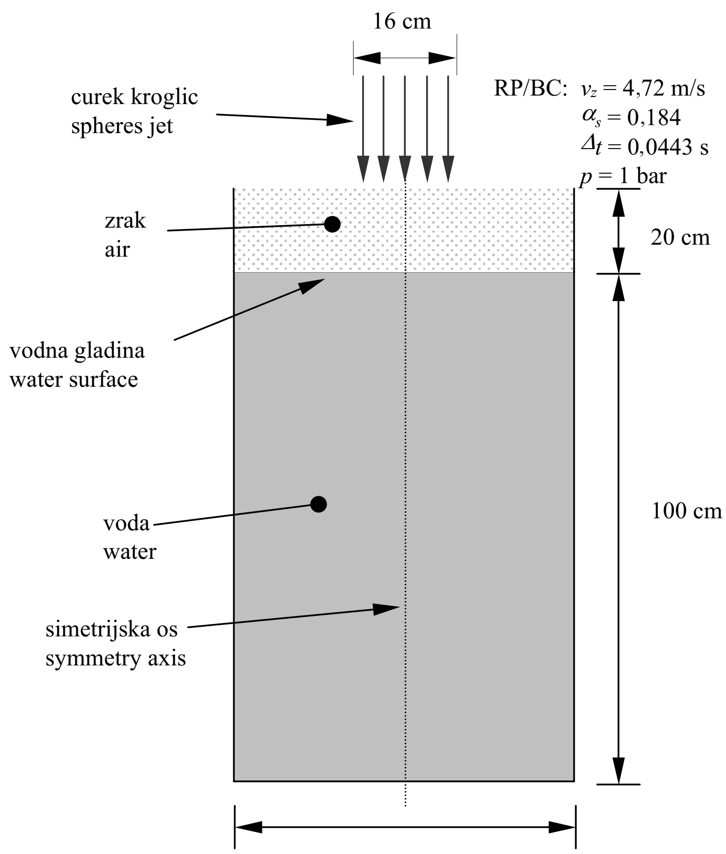
Najprej smo napravili analizo vpliva velikosti mreže, da bi ugotovili ali rezultati simuliranj konvergirajo k pravi fizikalni rešitvi. Kot osnovno mrežo, označeno z 1×, smo izbrali mrežo velikosti 40 × 120 točk. Tako je bila mrežna razdalja natančno 1 cm. Na sliki 5 so prikazani rezultati simuliranj, opravljenih na mrežah velikosti 0,5 × (20 × 60 točk), 1× (40 × 120 točk) in 2 × (80 × 240 točk). Kakor je razvidno s slik, rezultati simuliranj ne konvergirajo k pravi fizikalni rešitvi, ampak prav nasprotno – z zgoščevanjem mreže postaja nefizikalno zapiranje plinskega stebra na vrhu še bolj izrazito.

Da bi ugotovili, ali je razlog za takšno obnašanje nefizikalni zvezni prehod zrak - voda v modelu zaradi reševanja enačb z metodo končnih razlik, smo simuliranja opravili pri različnih začetnih debelinah ε medfazne ploskve voda - zrak, pri čemer je ε določen z enačbo (3). Ker je pri metodi z nivojsko funkcijo debelina medfazne ploskve vnaprej določena in nespremenljiva za vse lege medfazne ploskve (tudi

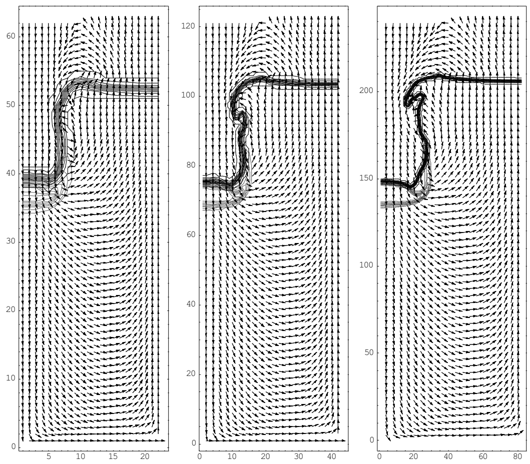
was reduced from 9 cm to 8 cm and the radius of the vessel from 41 cm to 40 cm. In this way all the characteristic dimensions of the model are more-times divisible by 2, which makes the mesh-size-influence analysis more straightforward. The falling spheres where introduced to the model with the boundary conditions (BC) as described in [8].

First the mesh-size-influence analysis was performed to establish whether the simulation results converge to the right physical solution. For the basic grid a mesh of 40 × 120 grid points, denoted with size 1×, was chosen. This meant that the grid spacing was exactly 1 cm. The results of the simulations performed on grid sizes 0.5 × (20 × 60 points), 1× (40 × 120 points) and 2 × (80 × 240 points) are presented in Figure 5. As can be seen in the figure, the results do not converge to the right physical solution. On the contrary, with the finer mesh the unphysical closing of the gas chimney at the top becomes even more pronounced.

To find out if the reason for this behavior is the unphysical, gradual air-water transition in the model due to the numerical finite-differences solving procedure, the simulations were performed for different initial water-air surface thicknesses, ε, defined according to equation (3). Since for the level-set method the interface thickness is predetermined and constant for all interface positions (also vertical) this parametric analysis was performed

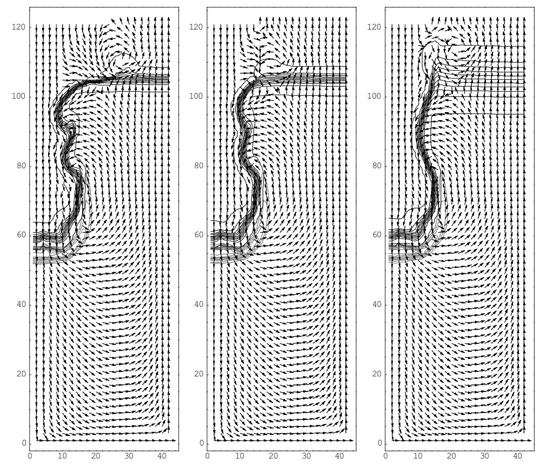


Sl. 4. *Shema modela, prilagojenega za parametrično analizo*
Fig. 4. *Scheme of the model used for the parametric analyses*



0,5x 1 x 2x

Sl. 5. *Rezultati simuliranj pri času 610 ms, opravljeni na različno velikih mrežah*
Fig. 5. *The simulation results at time 610 ms performed for different mesh sizes*



0xε 3xε 10xε

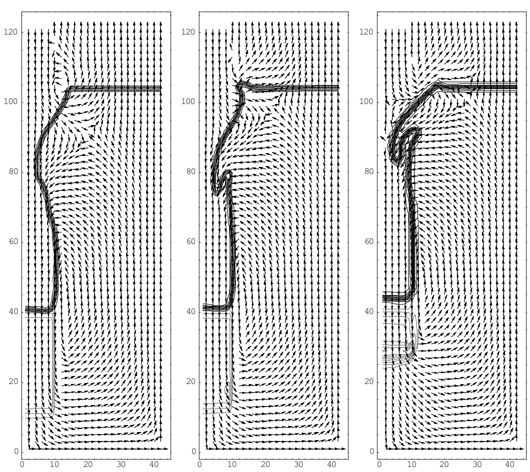
Sl. 6. *Rezultati simuliranj pri času 660 ms za različne začetne debeline medfazne ploskve voda - zrak*
Fig. 6. *The simulation results at time 660 ms for different initial water-air surface thicknesses*

navpično), smo pri tej parametrični analizi gostoto združene faze voda - zrak določevali z metodo velike ločljivosti. Rezultati simuliranj, ki so prikazani na sliki 6, so presenetljivi in v nasprotju z našimi pričakovanji. Izkazalo se je, da se pri najbolj blagem prehodu zrak - voda začne zračni steber zapirati na pravem mestu v sredini, tako kakor pri preskusih.

Da bi pojasnili to nenavadno obnašanje, smo analizirali vpliv gostote vode na rezultate simuliranj. Na sliki 7 so prikazani rezultati simuliranj za različne umetne gostote vode. Vidimo, da se pri najmanjši gostoti vode 2 kg/m^3, kar je le malo več od gostote zraka, začne zračni steber zapirati na sredini. To bi lahko bila razlaga, zakaj so rezultati pri najbolj blagem prehodu zrak - voda (sl. 6) kakovostno najboljši, saj je gostota združene faze voda - zrak v zgornji plasti

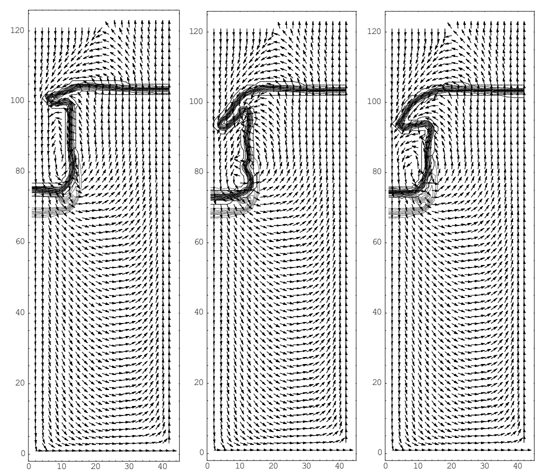
using the high-resolution method for the joint water-air phase-density determination. The results of the simulations, which are presented in Figure 6, are quite surprising, and the opposite of what we expected. It turned out that for the smoothest initial air-water transition the air chimney starts to close at the right place, in the middle, like the experimental observations.

To explain this strange behavior the influence of the water density on the simulation results was analyzed. The results of the simulations for different artificial water densities are presented in Figure 7. We can see that at the lowest water density, 2 kg/m^3, which is only slightly higher than the air density, the air chimney starts to close in the middle. This could explain why the results for the smoothest air-water transition (Fig. 6) are qualitatively the best, since in the upper



2 kg/m^3 10 kg/m^3 100 kg/m^3

Sl. 7. *Rezultati simuliranj pri času 660 ms za različne umetne gostote vode*
Fig. 7. *The simulation results at time 660 ms for different artificial water densities*



+1xΔh 0xΔh -1xΔh

Sl. 8. *Rezultati simuliranj pri času 610 ms za različne lege vključitve sklopitve gibalne količine*
Fig. 8. *The simulation results at time 610 ms for different momentum-coupling starting positions*

obsežne medfazne ploskve voda - zrak majhna in tako vrtinec nastane podobno kakor pri primeru z najmanjšo umetno gostoto vode (sl. 7).

Vendar, kaj je potem razlog za zapiranje zračnega stebra na vrhu? Dejansko je medfazna sklopitev gibalne količine kroglic med prostim padom skozi zrak precej majhna, potem pa se skokovito zveča, ko kroglice pričnejo prodirati v vodo. Da bi spoznali vpliv te skokovite spremembe medfazne sklopitve gibalne količine, smo napravili parametrično analizo, pri kateri smo sklopitev gibalne količine kroglic med prostim padom izklopili do določene globine. Rezultati simuliranj so prikazani na sliki 8. Medfazno sklopitev gibalne količine kroglic smo izklopili do ene mrežne razdalje nad vodno gladino ($+1 \times \Delta h$), do vodne gladine ($0 \times \Delta h$) in do ene mrežne razdalje pod vodno gladino ($-1 \times \Delta h$). Vidimo, da je zapiranje zračnega stebra na vrhu bolj izrazito, če je plast vode nad lego, kjer medfazna sklopitev gibalne količine kroglic prične vodo vleči navzdol, debelejša.

V modelu preskusa se lastnosti združene faze voda - zrak zaradi opisa s končnimi razlikami vedno spreminjajo postopoma in tako leži nad čisto fazo vode, kjer se medfazna sklopitev gibalne količine kroglic zveča na največjo vrednost, vedno neka prehodna plast z vmesno gostoto. Ta prehodna plast zaduši brizganje vode, ki se pojavi pri preskusih (sl. 3), in povzroči nefizikalno zapiranje zračnega stebra na vrhu (sl. 2). To zapiranje zračnega stebra je najizrazitejše na najgostejši mreži (sl. 5), kjer voda zaradi bolj podrobnega opisa ni več tako močno prisiljena k numerično odvisnemu kolektivnemu gibanju, debelina prehodne plasti pa je še vedno 1 cm.

Da bi odpravili to podedovano numerično pomanjkljivost modela, moramo v model vgraditi skokovito spremembo medfazne sklopitve gibalne količine kroglic na medfazni ploskvi zrak - voda, tako kakor je to dejansko, kar dosežemo s tem, da na skrajnem zgornjem območju prehodne plasti zrak - voda umetno povečamo medfazno sklopitev gibalne količine kroglic. To v praksi storimo najlažje tako, da v najvišji mrežni ravnini prehodne plasti zrak - voda, to je eno mrežno razdaljo Δh nad vodno gladino, medfazni koeficient trenja kroglic C pomnožimo z ustreznim faktorjem. Na sliki 9 so prikazani rezultati simuliranj, opravljenih z nespremenjenim ($1 \times C$) in pomnoženim koeficientom trenja kroglic ($10 \times C$, $20 \times C$). Kakor smo pričakovali, se začne zračni steber zapirati na pravem mestu v sredini, če v najvišji mrežni ravnini prehodne plasti zrak - voda koeficient trenja kroglic dovolj povečamo ($C^{up} \geq 10C$). Na sliki 11 je prikazan izračunani tlak v vodi, 250 mm nad dnom posode, za različne vrednosti koeficienta trenja kroglic C^{up}. S slik 11 in 9 je razvidno, da ima koeficient trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda zanemarljiv vpliv na rezultate simuliranj, če je dovolj velik ($C^{up} \geq 10C$). Zato smo v našem kombiniranem večfaznem

layer of the wide water-air interface the joint water-air phase density is low and so the vortex forms likewise in the lowest artificial water-density case (Fig. 7).

But why does the air chimney close at the top? In reality the spheres' momentum coupling during the free fall through the air is quite low and then abruptly rises when the spheres start to penetrate the water. To find out the influence of this abrupt momentum-coupling change a parametric analysis was performed, where the spheres' momentum coupling during the spheres' free fall was switched off until a certain depth. The results of these simulations are presented in Figure 8. The spheres' momentum coupling was switched off at one grid spacing over the water-air surface ($+1 \times \Delta h$), at the water-air surface ($0 \times \Delta h$) and at one grid spacing below the water-air surface ($-1 \times \Delta h$). It is clear that the air-chimney closing at the top is more pronounced if the water layer over the position, where the spheres' momentum coupling starts to drag the water down, is thicker.

In the experimental model the joint water-air phase properties always change gradually due to the finite differences' description and so there is always a transition layer with intermediate phases, density over the pure water phase, where the spheres' momentum coupling rises to its maximum value. This transition layer chokes the water splashing that is observed in the experiments (Fig. 3) and causes the unphysical air-chimney closing at the top (Fig. 2). This air-chimney closing at the top is most clearly demonstrated for the finest mesh (Fig. 5), where the water, due to the more detailed description, is not so strongly forced to the collective movement anymore, whereas the transition layer is still about 1-cm thick.

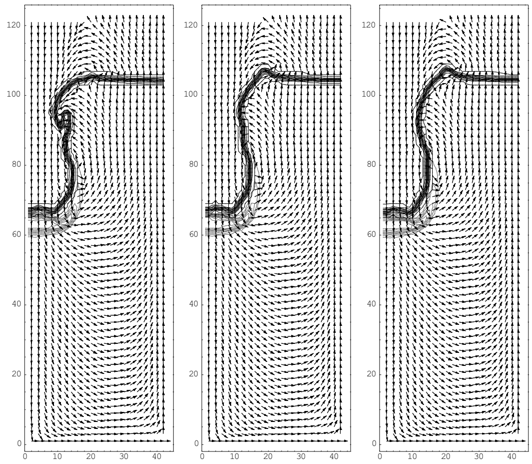
To overcome this inherent deficiency in the numerical model an abrupt increase in the spheres' momentum coupling at the water-air surface, as occurs in reality, has to be incorporated. This can be achieved if the spheres' momentum coupling at the upmost part of the air-water transition layer is artificially increased. This is most easily done if the spheres' interfacial drag coefficient C at the upmost mesh plane of the air-water transition layer, which is one grid spacing Δh over the water-air surface, is multiplied by a factor. The results of the simulations with the unmodified ($1 \times C$) and multiplied spheres' drag coefficient ($10 \times C$, $20 \times C$) are presented in Figure 9. As expected, the air chimney starts to close at the right place in the middle if the spheres' drag coefficient at the upmost mesh plane of the water-air transition layer is increased sufficiently ($C^{up} \geq 10C$). The calculated pressure in the water 250 mm above the bottom of the vessel is presented for different spheres' drag coefficients C^{up} in Figure 11. From Figs. 11 and 9 it is evident that the spheres' drag coefficient at the upmost mesh plane of the water-air transition layer has a negligible influence on the simulation results if it is large enough ($C^{up} \geq 10C$). So, in our modelu za koeficient trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda vzeli naslednjo od velikosti mrežne razdalje odvisno vrednost:

combined multiphase model at the upmost mesh plane of the water-air transition layer the following grid-dependent spheres' drag coefficient was chosen:

$$C^{up} = 10\frac{0{,}01\mathrm{m}}{\Delta h}C \qquad (5),$$

ki upošteva dejstvo, da je na gostejši mreži vpliv v eni mrežni ravnini povečanega koeficienta trenja kroglic manjši.

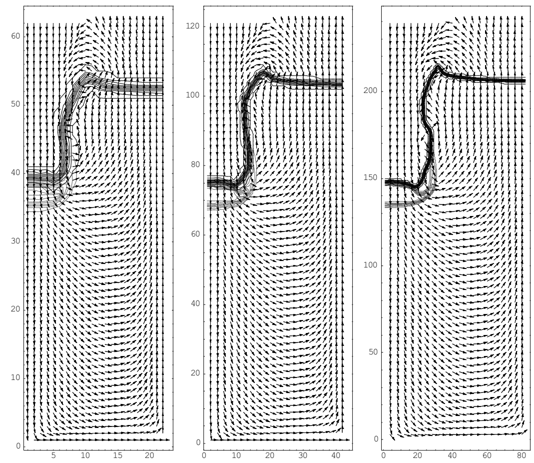
which takes into account the fact that on a finer grid the influence of the spheres' drag-coefficient increase in one mesh plane is lower.



1x *C* 10x *C* 20x *C*

Sl. 9. *Rezultati simuliranj ob času 635 ms za različne vrednosti koeficienta trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda*

Fig. 9. *The simulation results at time 635 ms for different spheres' drag coefficients at the upmost mesh plane of the water-air transition layer*



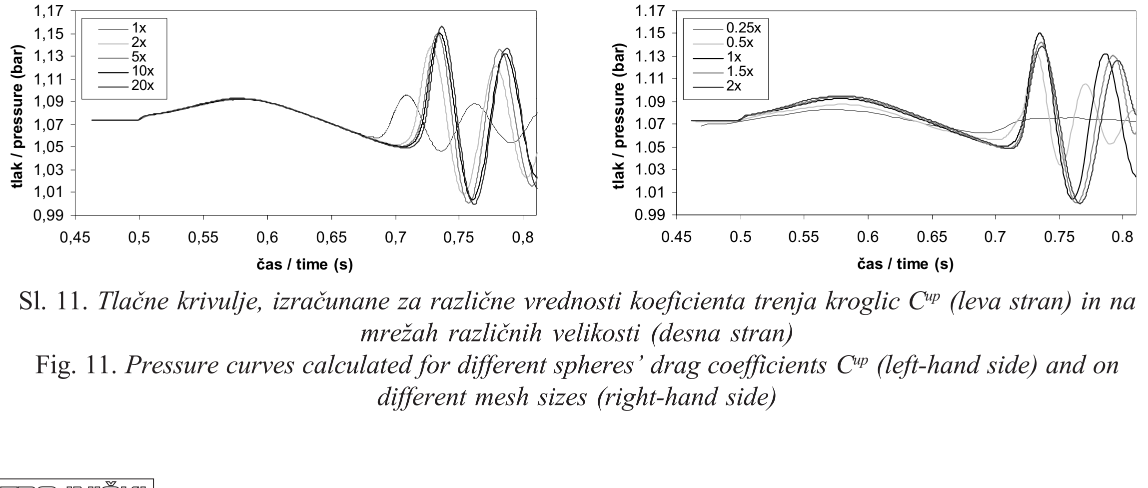
0,5x 1x 2x

Sl. 10. *Rezultati simuliranj ob času 610 ms na mrežah različnih velikosti, opravljenih s spremenjenim koeficientom trenja kroglic*

Fig. 10. *The simulation results at time 610 ms performed with the modified spheres' drag coefficient on different mesh sizes*

Na sliki 10 so prikazani rezultati simuliranj na mrežah različnih velikostih, opravljenih s spremenjenim koeficientom trenja kroglic (5). Vidimo, da se na vseh mrežah plinski steber razvije tako kakor v preskusih (sl. 3). Na sliki 11 so prikazane še tlačne krivulje, izračunane na mrežah različnih velikosti. Tlačne krivulje so sicer nekoliko odvisne od velikosti mreže tudi na gostejših mrežah (velikost mrež: 1x, 1,5x in 2x), vendar se to zgodi predvsem zaradi velike občutljivosti problema. Tako lahko sklepamo, da je osnovna mreža velikosti 1x z mrežno razdaljo 1 cm primerna za takšne vrste simuliranj.

The results of the simulations performed with the modified spheres' drag coefficient (Eq. 5) on different mesh sizes are presented in Figure 10. It is evident that the gas chimney develops like in the experiments (Fig. 3). The pressure curves calculated on different mesh sizes are presented in Figure 11. The pressure curves are also somewhat grid dependent on the finer meshes (mesh sizes: 1x, 1.5x and 2x), but that is mainly because of the very sensitive nature of the problem. We can conclude that the basic mesh size of 1x with the grid spacing of 1 cm is adequate for this type of simulation.



Sl. 11. *Tlačne krivulje, izračunane za različne vrednosti koeficienta trenja kroglic C^{up} (leva stran) in na mrežah različnih velikosti (desna stran)*

Fig. 11. *Pressure curves calculated for different spheres' drag coefficients C^{up} (left-hand side) and on different mesh sizes (right-hand side)*

Z razvitim kombiniranim večfaznim modelom z ustrezno spremenjenim koeficientom trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda (5) smo ponovno simulirali mešalni preskus Q08. Rezultati simuliranja so predstavljeni v prispevku [8].

With the developed combined multiphase model taking into account the modified spheres' drag coefficient at the upmost mesh plane of the water-air transition layer (Eq. 5) the premixing experiment Q08 was simulated once again. The results of the simulation were presented in the paper [8].

4 SKLEP

Predstavili smo novo zasnovo obravnave večfaznih tokov, to je opis s kombiniranim večfaznim modelom, in jo preskusili na primeru izotermnega preskusa mešalne faze eksplozije pare. Ključna zamisel opisa večfaznega toka s kombiniranim večfaznim modelom je, da obravnavamo faze, ki ostanejo ločene s prosto površino (voda in zrak) z modelom proste površine kot eno, združeno fazo z nezveznimi faznimi lastnostmi, medtem ko preostale faze (kroglice) obravnavamo kakor običajno z modelom večfaznega toka. Stično površino (voda - zrak) določamo z nivojsko funkcijo, ki se v zadnjih letih veliko uporablja.

Z razvitim izvirnim kombiniranim večfaznim modelom smo simulirali mešalni preskus Q08, ki so ga izvedli na napravi QUEOS. Rezultati simuliranj so pokazali, da se plinski steber, ki nastane med prodiranjem kroglic v vodo, začne zapirati na napačnem mestu na vrhu stebra. Ugotovili smo, da pride do tega zaradi zvezne spremembe gostote na medfazni ploskvi voda - zrak v modelu preskusa, saj je nad čisto fazo vode zaradi opisa s končnimi razlikami vedno prehodna plast z vmesno gostoto. Ta prehodna plast zaduši brizganje vode, do katerega pride pri preskusih med prodiranjem padajočih kroglic v vodo, in povzroči nefizikalno zapiranje zračnega stebra na vrhu.

To podedovano numerično pomanjkljivost modela smo odpravili s posebno obravnavo medfaznega trenja kroglic na vodni gladini, na kateri smo koeficient trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda ustrezno povečali in tako dosegli skokovito spremembo medfazne sklopitve gibalne količine kroglic na medfazni ploskvi zrak - voda, tako kakor je to dejansko. Opravljena parametrična analiza je pokazala, da ima koeficient trenja kroglic v najvišji mrežni ravnini prehodne plasti zrak - voda zanemarljiv vpliv na rezultate simuliranj, če je dovolj velik. Tako smo lahko določili optimalno vrednost spremenjenega koeficienta trenja kroglic. Konvergenčna analiza je pokazala, da je mrežna razdalja 1 cm primerna za takšne vrste simuliranj.

4 CONCLUSION

A new concept of multiphase flow treatment, the combined multiphase model formulation, was presented and applied to isothermal steam-explosion premixing experiments. The main idea of the combined multiphase model formulation is to treat the phases, which remain separated by a free surface (water and air), with a free-surface model as a single, joint phase with discontinuous phase properties, whereas the other phases (spheres) are treated, as is usual, with a multiphase flow model. The free surface (water-air) is determined with the front-capturing level-set method, which was widely used in recent years.

Using the developed, original, combined multiphase model the QUEOS isothermal premixing experiment Q08 was simulated. The simulation results showed that the gas chimney, which forms during the spheres' penetration into the water, starts to close at the wrong place at the top of the chimney. It was established that this happens because of the gradual change of the density at the water-air surface in the experimental model, since there is always a transition layer with intermediate phases' density over the pure water phase due to the finite differences' description. This transition layer chokes the water splashing observed in the experiments and causes the unphysical gas-chimney closing at the top.

This inherent deficiency of the numerical model was compensated with a special spheres' drag treatment at the air-water surface, where the spheres' drag coefficient at the upmost mesh plane of the water-air transition layer was appropriately increased and so an abrupt rise of the spheres' interfacial momentum coupling at the water-air surface, as occurs in reality, is achieved. The performed parametric analysis showed that the spheres' drag coefficient at the upmost mesh point of the water-air transition layer has a negligible influence on the simulation results if it is large enough. So, the optimum value of the modified spheres' drag coefficient could be established. The convergence analysis showed that a 1-cm grid spacing is appropriate for this kind of simulation.

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Simuliranje izotermnega QUEOS preskusa mešalne faze eksplozije pare Q08

Simulation of the Isothermal QUEOS Steam-Explosion Premixing Experiment Q08

Matjaž Leskovar - Borut Mavko

Mešalna faza eksplozije pare obsega interakcijo curka taline z vodo pred izbruhom eksplozije pare. Da bi bolje spoznali hidrodinamične procese med mešalno fazo eksplozije pare, izvajajo poleg "vročih" preskusov, pri katerih je pomembno uparjanje vode, tudi "hladne" izotermne preskuse.

Značilnost izotermnih preskusov mešalne faze eksplozije pare je, da se od vseh treh faz, to je vode, zraka in kroglic, z drugima dvema fazama pomešajo le kroglice, medtem ko ostaneta voda in zrak ločena z gladko medfazno ploskvijo. To dejstvo smo upoštevali pri razvoju izvirnega kombiniranega večfaznega modela mešalne faze eksplozije pare. Pri razvitem kombiniranem večfaznem modelu obravnavamo vodo in zrak z modelom proste površine kot eno, združeno fazo z nezveznimi faznimi lastnostmi na medfazni ploskvi voda - zrak, kroglice pa obravnavamo kot običajno z modelom večfaznega toka, pri katerem pomenijo kroglice razpršeno fazo, združena faza voda - zrak pa kontinuum, ki obdaja kroglice.

Razviti kombinirani večfazni model smo preverili na izotermnem preskusu Q08, ki so ga izvedli na napravi QUEOS. Simuliranja smo opravili z različnimi numeričnimi obravnavami medfazne ploskve voda - zrak (metoda z nivojsko funkcijo, metoda visoke ločljivosti, metoda "nazaj") za nestisljiv in stisljiv primer. Rezultate simuliranj smo primerjali med seboj in s podatki preskusa.

(Ključne besede: tok večfazni, modeli večfazni, eksplozija parne, metode z nivojsko funkcijo, simuliranje)

The premixing phase of a steam explosion covers the interaction of the melt jet with the water prior to any steam explosion occurring. To get a better insight into the hydrodynamic processes during the premixing phase, in addition to "hot" premixing experiments, where the water evaporation is significant, "cold" isothermal premixing experiments were also performed.

The special feature of isothermal premixing experiments is that three phases are involved – the water, the air and the spheres' phase – but only the spheres' phase mixes with the other two phases, whereas the water and air phases do not mix and remain separated by a free surface. Our idea was to treat the isothermal premixing process with an original, combined multiphase model. In the developed combined multiphase model the water and air phases are treated with a free-surface model as a single, joint phase with discontinuous phase properties at the water-air interface. The spheres are treated, as is usual, with a multiphase flow model, where the spheres represent the dispersed phase and the joint water-air phase represents the continuous phase.

The developed combined multiphase model was validated against the QUEOS isothermal premixing experiment Q08. A numerical analysis using different treatments of the water-air interface (level set, high-resolution, upwind) was performed for the incompressible and compressible cases and the results were compared with experimental measurements.

(Keywords: multiphase flow, multiphase models, steam explosion, level set methods, simulations)

0 UVOD

Med resno nezgodo v jedrski elektrarni, ko pride staljena sredica po različnih poteh v stik s hladilno vodo, lahko pride do eksplozije pare. Eksplozijo pare razdelimo na več faz. Prva, mešalna faza eksplozije pare je najbolj pomembna, ker določa začetne pogoje morebitne eksplozije pare in podaja

0 INTRODUCTION

During a severe reactor accident following core meltdown when the molten fuel comes into contact with the coolant water a steam explosion may occur. A steam explosion can be divided into more stages. The first stage, called premixing, is the most important since it provides the initial conditions for a possible steam explosion and največjo količino staljenega jedrskega goriva, ki bi lahko sodelovalo pri eksploziji. Da bi bolje spoznali hidrodinamične procese med prodiranjem taline v vodo, izvajajo poleg "vročih" preskusov, pri katerih je pomembno predvsem uparjanje vode, tudi "hladne" izotermne preskuse. Pri teh izotermnih preskusih mešalne faze eksplozije pare spuščajo različne curke hladnih kroglic v posodo, napolnjeno z vodo in opazujejo dogajanja [1].

Značilnost izotermnih preskusov mešalne faze eksplozije pare je, da se od prisotnih treh faz, to je vode, zraka in kroglic, s preostalima dvema fazama pomešajo le kroglice, medtem ko ostaneta voda in zrak ločena z gladko medfazno ploskvijo. To dejstvo smo upoštevali pri razvoju izvirnega kombiniranega večfaznega modela mešalne faze eksplozije pare. Pri razvitem kombiniranem večfaznem modelu obravnavamo vodo in zrak z modelom proste površine kot eno, združeno fazo z nezveznimi faznimi lastnostmi na medfazni ploskvi voda - zrak, kroglice pa obravnavamo kot običajno z modelom večfaznega toka, pri katerem pomenijo kroglice razpršeno fazo, združena faza voda - zrak pa kontinuum, ki obdaja kroglice [2].

determines the maximum quantity of melt, which might then be involved in the explosion. To investigate the mixing process associated with the melt penetration, in addition to "hot" premixing experiments, where the water evaporation is significant, "cold" isothermal premixing experiments were also performed to get a better insight into the hydrodynamic processes during the premixing phase. In these isothermal premixing experiments, different jets of spheres are injected in a water pool [1].

The special feature of isothermal premixing experiments is that three phases are involved – the water, the air and the spheres' phase – but only the spheres' phase mixes with the other two phases, whereas the water and air phases do not mix and remain separated by a free surface. Our idea was to treat the isothermal premixing process with an original combined multiphase model. In the developed combined model the water and air phases are treated with a free-surface model as a single, joint phase with discontinuous phase properties at the water-air interface. The spheres are treated, as is usual, with a multiphase flow model, where the spheres represent the dispersed phase and the joint water-air phase represents the continuous phase [2].

1 GLAVNE ENAČBE

1 GOVERNING EQUATIONS

Fazna verjetnost α_c in gostota ρ_c združene faze voda - zrak c sta definirani kot:

The phase presence probability α_c and the density ρ_c of the joint water-air phase c are defined as:

$$\alpha_c = \alpha_w + \alpha_a , \quad \rho_c = \frac{\alpha_w \rho_w + \alpha_a \rho_a}{\alpha_w + \alpha_a} \qquad (1),$$

kjer indeksa w in a označujeta fazi vode in zraka. S to definicijo lahko večfazen tok kroglic, vode in zraka obravnavamo kot navidez dvofazen tok razpršenih kroglic d v kontinuumu združene faze voda - zrak c.

Vsako fazo p v tako definiranem navidez dvofaznem toku smo opisali s kontinuitetno:

where the indices w and a correspond to the water and air phases. With this definition the multiphase flow of spheres, water and air can be described as a quasi two-phase flow of dispersed spheres d in the continuous joint water-air phase c.

Each phase p in the so-defined quasi two-phase flow is described using the continuity:

$$\frac{\partial}{\partial t}\left(\alpha_p \rho_p\right) + \nabla \cdot \left(\alpha_p \rho_p \vec{\mathbf{v}}_p\right) = 0 \qquad (2)$$

in gibalno enačbo:

and the momentum equation:

$$\rho_p \frac{\partial \vec{\mathbf{v}}_p}{\partial t} + \rho_p \left(\vec{\mathbf{v}}_p \cdot \nabla\right)\vec{\mathbf{v}}_p = -\nabla p + \rho_p \vec{\mathbf{g}} + \vec{\mathbf{M}}_p \qquad (3),$$

ki smo ju izpeljali s statističnim povprečenjem enofaznih enačb [3]. Pri tem smo medfazno sklopitveno silo $\vec{\mathbf{M}}$ definirali kot:

obtained by ensemble averaging the single-phase equations [3]. The interfacial friction force $\vec{\mathbf{M}}$ is defined as:

$$\vec{\mathbf{M}}_d = \vec{\mathbf{M}}_d^{drag} + \vec{\mathbf{M}}_d^{vm} + \vec{\mathbf{M}}_d^{lift} , \quad \alpha_c \vec{\mathbf{M}}_c = -\alpha_d \vec{\mathbf{M}}_d \qquad (4),$$

kjer silo medfaznega trenja računamo z [4]:

where the drag force is calculated from [4]:

$$\vec{\mathbf{M}}_d^{drag} = 0{,}44 \cdot \frac{3}{4}\frac{\rho_c}{d_d}\left|\vec{\mathbf{v}}_c - \vec{\mathbf{v}}_d\right|\left(\vec{\mathbf{v}}_c - \vec{\mathbf{v}}_d\right) \qquad (5),$$

silo navidezne mase z [4]:

the virtual mass force from [4]:

$$\vec{\mathbf{M}}_d^{vm} = 0.5\rho_c\left(\frac{D\vec{\mathbf{v}}_c}{Dt} - \frac{D\vec{\mathbf{v}}_d}{Dt}\right) \qquad (6)$$

in dvižno silo z [4]:

and the lift force from [4]:

$$\vec{\mathbf{M}}_d^{lift} = 0.5\rho_c\left(\vec{\mathbf{v}}_c - \vec{\mathbf{v}}_d\right)\times\left(\nabla\times\vec{\mathbf{v}}_c\right) \qquad (7).$$

Medfazno trenje kroglic na medfazni ploskvi voda - zrak smo določevali na poseben način, ki upošteva nezveznost prehoda zrak - voda, kakor je opisano v [5].

Tlačno enačbo za predpostavljeno skupno tlačno polje p smo izpeljali iz vsote kontinuitetne enačbe za stisljivo tekočino (2) po vseh fazah s projekcijsko metodo [6]:

The spheres' drag at the water-air surface was treated in a special way by considering the discontinuous air-water transition as described in [5].

The pressure equation for the assumed common pressure field p was derived from the sum of the compressible flow continuity equation (2) over all phases using the projection method [6]:

$$\sum_{p=1}^{2}\left(\frac{\alpha_p^{n+1}}{\rho_p^{n+1/2}}\frac{\partial\rho_p^{n+1/2}}{\partial p^n}\left(p^{n+1}-p^n\right)+\nabla\cdot\left(\alpha_p^{n+1}\vec{\mathbf{v}}_p^{n+1/2}\right)\Delta t-\nabla\cdot\left(\frac{\alpha_p^{n+1}}{\rho_p^{n+1/2}}\nabla p^{n+1}\right)\Delta t\right)=0 \qquad (8),$$

kjer je:

where:

$$\vec{\mathbf{v}}_p^{n+1/2} = \vec{\mathbf{v}}_p^n + \Delta t\left[-\left(\vec{\mathbf{v}}_p^n\cdot\nabla\right)\vec{\mathbf{v}}_p^n + \vec{\mathbf{g}} + \tfrac{1}{\rho_p^n}\vec{\mathbf{M}}_p^n\right], \quad \rho_p^{n+1/2} = \rho\left(\alpha_p^{n+1}, p^n\right) \qquad (9).$$

2 SIMULIRANJA PRESKUSA MEŠALNE FAZE

Za analizo izvirnega kombiniranega večfaznega modela smo izbrali preskus mešalne faze Q08, ki so ga izvedli na napravi QUEOS [7]. Pri tem preskusu so spuščali molibdenove kroglice premera 4,2 mm in skupne mase 10 kg z višine 1,3 m skozi cev v posodo v obliki kvadra z osnovno ploskvijo 70 cm x 70 cm in višino 138 cm, napolnjeno z vodo. Premer curka kroglic je bil 18 cm, hitrost kroglic na vodni gladini 5,12 m/s in fazna verjetnost kroglic 0,17. Višina vodne gladine v posodi je bila 100 cm, začetni tlak plina nad vodno gladino pa 0,975 bar.

Pri simuliranjih preskusa smo obravnavali le z vodo napolnjeni spodnji del posode in 20 cm debelo plast plina nad vodno gladino (sl. 1). Vse druge značilnosti preskusa smo upoštevali z ustreznimi robnimi pogoji.

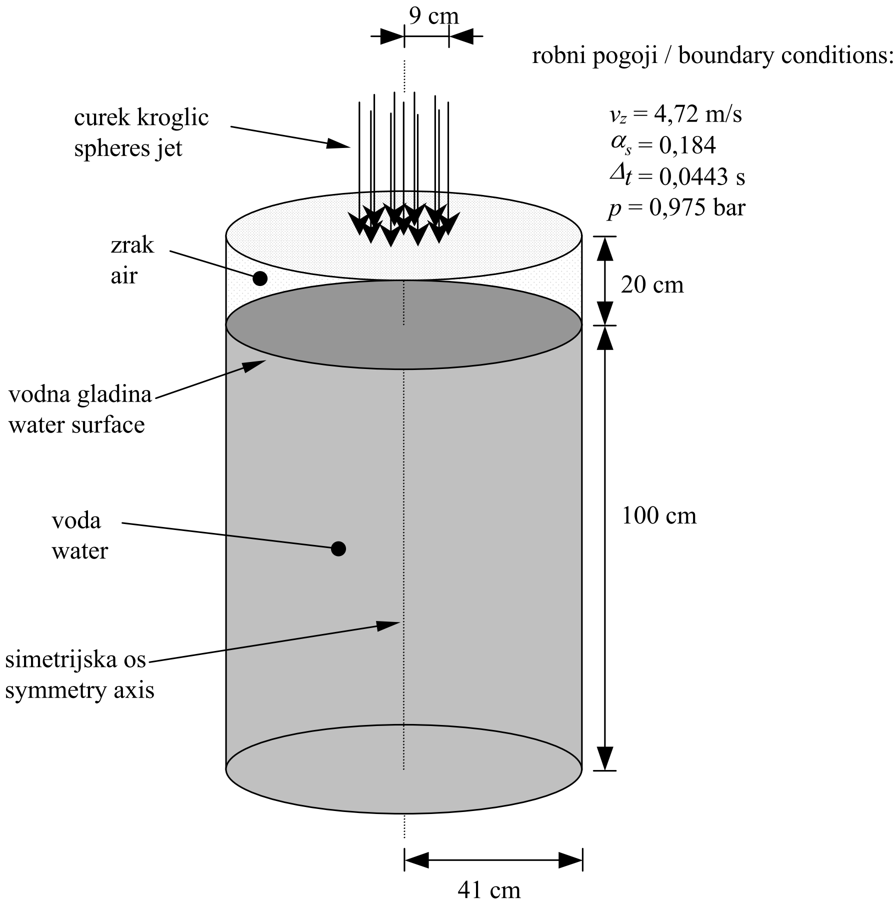
Predpostavili smo, da je plin nad vodno gladino zrak. V resnici je plin v posodi neznana mešanica vodne pare in neukapljivega argona. Simuliranja smo opravili v valjnem koordinatnem sistemu ob predpostavki osne simetričnosti problema. Ta predpostavka je le delno upravičljiva, saj porazdelitev kroglic predvsem na čelu curka ni osno simetrična zaradi sprostilnega mehanizma kroglic, pri katerem se simetrično odpreta dve ravni premični plošči [8]. Dejanski polmer valjaste posode modela (41 cm) smo določili tako, da sta se ujemali površini osnovnih ploskev modela in preskusa. Padajoči curek kroglic smo v model vključili z robnimi pogoji (RP). Robne vrednosti hitrostnega polja kroglic v_z in polja fazne verjetnost kroglic α_s na zgornjem robu simulirnega območja 20 cm nad vodno gladino smo določili posredno iz znanih

2 SIMULATIONS OF THE PREMIXING EXPERIMENT

The QUEOS premixing experiment Q08 was chosen for the analysis of the original combined multiphase model [7]. In this experiment molybdenum spheres with a diameter of 4.2 mm and a total mass of 10 kg were discharged from a height of 1.3 m through a tube into a water-filled vessel with an inner cross-section of 70 cm x 70 cm and a height of 138 cm. The spheres' jet diameter was 18 cm and the spheres entered the water at a velocity of 5.12 m/s and a phase-presence probability of 0.17. The water level in the vessel was 100 cm, and the initial gas pressure over the water surface was 0.975 bar.

In the experimental simulations only the part of the vessel filled with water together with a 20-cm-wide gas zone over the water surface was modeled (Figure 1). All other experimental features were taken into account with appropriate boundary conditions.

It was assumed that the gas over the water was air. In fact it was an unknown mixture of steam and non-condensable argon. The simulations were performed in the cylindrical coordinate system and assumed an axial symmetry for the problem. This was not really the case in the experiment since the release mechanism with two doors opening in opposite directions caused, especially at the front of the spheres' cloud, an initially non- axially symmetric distribution of the falling spheres [8]. To match the cross-sectional area of the vessel, an equivalent radius of 41 cm was used in the axially symmetric model. The falling spheres were introduced in the model with boundary conditions (BCs). The appropriate boundary conditions for the spheres' velocity v_z and the spheres' presence probability α_s at the upper edge of the simulation region 20 cm above the water surface were



Sl. 1. *Shema modela QUEOS preskusa Q08*
Fig. 1. *Schematic model of QUEOS experiment Q08*

povprečnih vrednosti na vodni gladini. Čas preleta curka kroglic Δt mimo zgornjega roba simulirnega območja smo določili iz razmerja znane celotne mase kroglic in izračunanega masnega toka kroglic [2].

Polja faznih verjetnosti in hitrostna polja faz smo računali z metodo velike ločljivosti [9], ki je drugega reda natančnosti. Metoda velike ločljivosti je temeljila na privetrni metodi prvega reda natančnosti in metodi Lax-Wendroff, ki je drugega reda natančnosti [10]. Tlačno enačbo smo reševali z metodo CGSTAB [6], ker hitro konvergira tudi za velika razmerja gostot posameznih faz [8]. Nezvezno gostoto združene faze voda - zrak smo določevali z metodo z nivojsko funkcijo [11], katero so razvili za reševanje problemov s prosto površino in se v zadnjih letih veliko uporablja. Simuliranja preskusov smo opravili na mreži velikosti 41 x 120 točk. Tako je bila mrežna razdalja točno 1 cm, kar je, kakor je pokazala konvergenčna analiza, primerno za takšne vrste simuliranj [5].

3 REZULTATI SIMULIRANJ

Da bi bolje spoznali prednosti razvitega kombiniranega večfaznega modela, pri katerem

determined from the known average values at the water's surface. The time interval Δt during which the spheres were falling through the upper boundary of the simulated region was established from the total spheres' mass and the calculated spheres' mass-flow rate [2].

The phases' presence probabilities and the phases' velocities were calculated using the second-order-accurate high-resolution method [9]. The high-resolution method was based on the first-order-accurate upwind method and the second-order-accurate Lax-Wendroff method [10]. The pressure equation was solved using the CGSTAB method [6], since it also converges quickly for high phase-density ratia [8]. The discontinuous density of the joint water-air phase was determined with the front-capturing level-set method [11], which was developed for free-surface problems and has been widely used in recent years. The experimental simulations were performed on a mesh with 41 x 120 grid points. The grid spacing was exactly 1 cm, which is adequate for this type of simulation, as the convergence analysis showed [5].

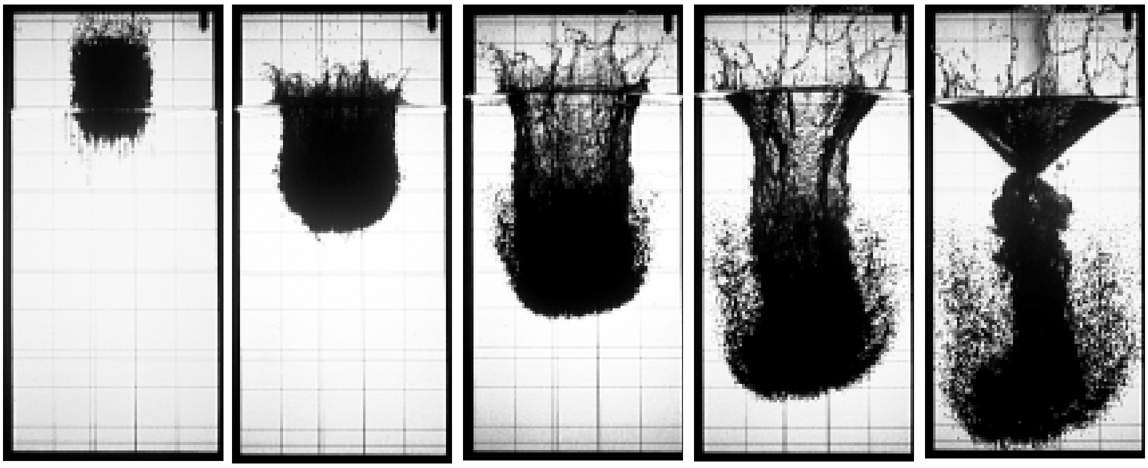
3 RESULTS OF THE SIMULATIONS

To get a better insight into the advantages of the developed combined multiphase model with the obravnavamo medfazno ploskev voda - zrak z metodo z nivojsko funkcijo (NF - LS), ki so jo razvili za reševanje problemov s stično površino, smo medfazno ploskev voda - zrak primerjalno določevali še z metodo velike ločljivosti (VL - HR), ki je drugega reda natančnosti, in privetrno metodo (PM - UW) prvega reda natančnosti.

Na sliki 2 so prikazani posnetki preskusa Q08, ki so jih napravili s hitro slikovno kamero ob osvetlitvi z zadnje strani. Čas posnetkov je merjen od sprostitve kroglic. Ker točni podatki niso bili na voljo, smo lahko čas posnetkov določili le približno. Na slikah je vidna referenčna mreža s celicami velikosti 10 cm x 10 cm, ki je pritrjena na notranjo stran okenskih šip posode. Ker so okna široka le 50 cm, je na vsaki strani in tudi na dnu posode zakrit 10 cm širok pas. Poudariti je treba, da pomeni večji del črno senčenega območja na posnetkih plinski steber in ne kroglic.

incorporated level-set (LS) method, which was developed for free-surface problems, the water-air surface was, for a comparison, also determined with the second-order-accurate high-resolution (HR) method and the first-order-accurate upwind (UW) method.

The images of experiment Q08 taken with a high-speed film camera with backlighting are presented in Figure 2. The time, which is measured after the release of the spheres, could only be determined approximately since no exact data was available. On the images the 10 cm x 10 cm reference grid mounted close to the inside of each of the vessel windows can be seen. Since the windows are only 50-cm wide, there is a 10-cm-wide zone on both sides and also on the bottom of the vessel, which is hidden. It should be stressed that most of the black shaded region on the images represents the gas chimney and not the spheres.



t =~520 ms t =~590 ms t =~650 ms t =~725 ms t =~775 ms

Sl. 2. *Posnetki preskusa Q08, napravljeni ob različnih časih (posnetki vzeti iz [7])*
Fig. 2. *Images of experiment Q08 taken at different times (images taken from [7])*

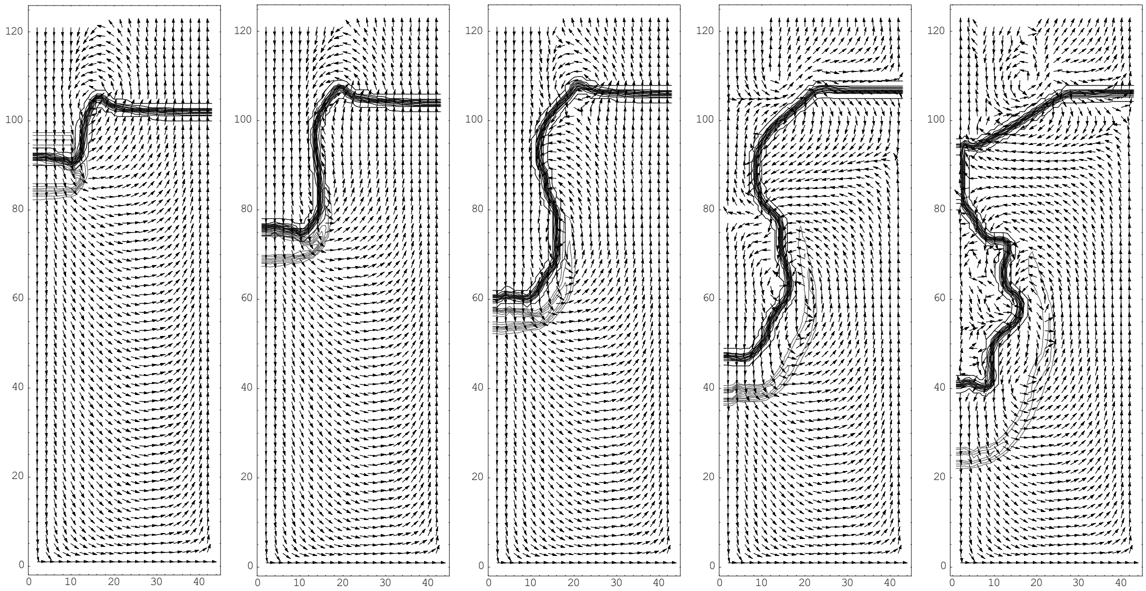
Na slikah 3 do 5 so predstavljeni rezultati simuliranj, opravljenih z metodami NF, VL in PM. Slike prikazujejo gostoto združene faze voda - zrak (črni obrisi), fazno verjetnost kroglic (sivi obrisi) in hitrostno polje združene faze voda - zrak v valjnem koordinatnem sistemu (r, z) v ekvidistančnih 50 ms dolgih časovnih razmikih. Čas je zaradi lažje primerjave merjen tako kakor pri preskusu po sprostitvi kroglic, to je 0,46 s pred začetkom simuliranja. Obrisi gostote združene faze voda - zrak (ρ_w = 997 kg/m^3, ρ_a = 1,2 kg/m^3) imajo vrednosti 2, 100, 200, ..., 800, 900, 996 kg/m^3, obrisi fazne verjetnosti kroglic pa imajo vrednosti 0,02; 0,05; 0,1; 0,15; itn. Hitrostno polje je predstavljeno z enotskimi vektorji, ki prikazujejo le smer vektorja hitrosti in ne tudi velikosti hitrosti, saj bi bile sicer slike nepregledne.

Kakor smo pričakovali, ostane medfazna ploskev voda - zrak ostra med celotnim simuliranjem le pri izračunu z metodo NF. Pri metodi VL, ki je drugega reda natančnosti, predvsem pa pri metodi PM prvega

The results of the simulations performed with the LS, HR and UW methods are presented in Figs. 3 to 5. The figures show the joint water-air phase density (black contours), the spheres' presence probability (gray contours) and the joint water-air phase velocity field in the cylindrical coordinate system (r, z) in equidistant 50-ms-long time intervals. The time is measured, as in the experiment, after the release of the spheres, i.e. 0.46 s before the start of the simulation. The joint water-air phase density (ρ_w = 997 kg/m^3, ρ_a = 1.2 kg/m^3) contours correspond to values 2, 100, 200, ... , 800, 900, 996 kg/m^3, and the spheres' presence probability contours correspond to the values 0.02, 0.05, 0.1, 0.15, etc. The velocity field is represented by unit vectors showing only the direction of the velocity vector but not the speed because the figures would be unclear.

As expected, the water-air surface remains sharp during the whole simulation only during the LS-method calculation. For the second-order-accurate HR method, and in particular for the first-order-reda natančnosti, se združena faza voda - zrak nefizikalno razprši zaradi numerične difuzije. Numerična difuzija je splošna skupna pomanjkljivost metod končnih razlik. Rezultati simuliranj, opravljenih z metodo NF (slika 3), se kakovostno razmeroma dobro ujemajo s posnetki preskusa (sl. 2).

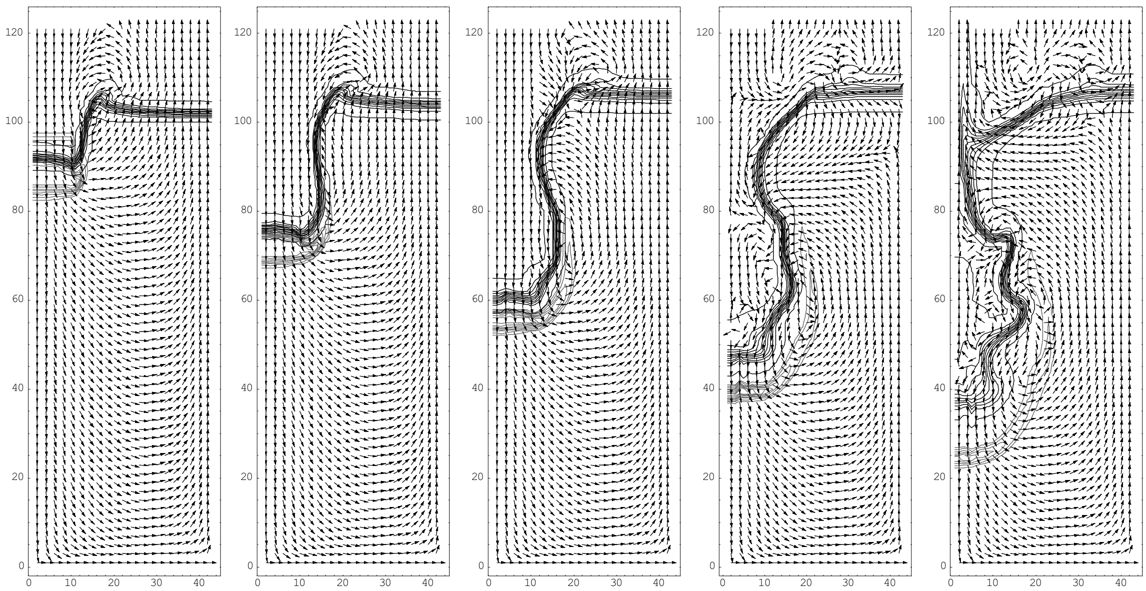
accurate UW method, the joint water-air phase unphysically mixes due to numerical diffusion, which is a common weakness of finite-differences methods. The simulation results performed with the LS method (Figure 3) agree qualitatively quite well with the images of the experiment (Figure 2).



t = 560 ms *t* = 610 ms *t* = 660 ms *t* = 710 ms *t* = 760 ms

Sl. 3. *Gostota združene faze voda - zrak, fazna verjetnost kroglic in hitrostno polje združene faze voda - zrak ob različnih časih pri izračunih z metodo NF*

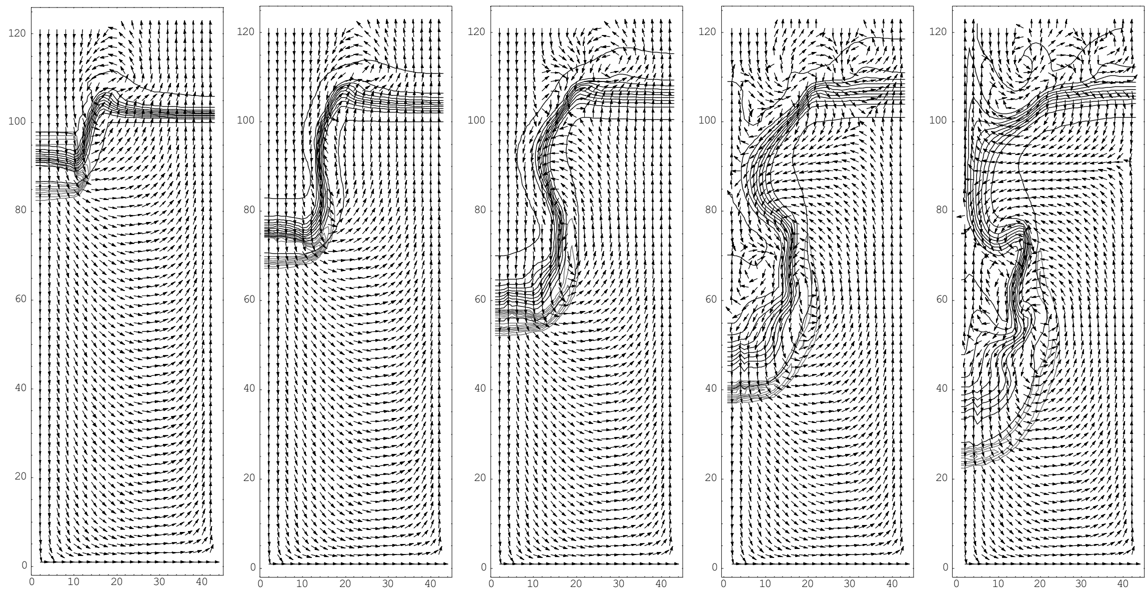
Fig. 3. *The joint water-air phase density, the spheres' phase-presence probability and the joint water-air phase velocity field at different times for the LS-method calculation*



t = 560 ms *t* = 610 ms *t* = 660 ms *t* = 710 ms *t* = 760 ms

Sl. 4. *Gostota združene faze voda - zrak, fazna verjetnost kroglic in hitrostno polje združene faze voda - zrak ob različnih časih pri izračunih z metodo VL*

Fig. 4. *The joint water-air phase density, the spheres' phase-presence probability and the joint water-air phase velocity field at different times for the HR-method calculation*



Sl. 5. *Gostota združene faze voda - zrak, fazna verjetnost kroglic in hitrostno polje združene faze voda - zrak ob različnih časih pri izračunih z metodo PM*

Fig. 5. *The joint water-air phase density, the spheres' phase-presence probability and the joint water-air phase velocity field at different times for the UW-method calculation*

Pri vseh simuliranjih smo spremljali tudi potek tlaka na različnih globinah. Na sliki 6 so prikazane izračunane tlačne krivulje skupaj s preskusnimi podatki. Tlaka *p3* in *p6* so merili v vodi ob steni posode v točkah 838 mm in 250 mm nad dnom posode. Porast tlaka 0,5 s po izpustu kroglic označuje začetek prodiranja čelnih kroglic v vodo, tlačni vrh po 0,76 s pa zapiranje plinskega stebra.

Pri prvem nizu simuliranj smo vse tri faze, to je vodo, zrak in kroglice, obravnavali kot nestisljive. Kakor je razvidno s slike 6, se ob zapiranju plinskega stebra pojavi tlačna konica, ki je najbolj izrazita pri izračunu z metodo NF, pri kateri ostane medfazna ploskev voda - zrak ostra, medtem ko se tlačna nihanja, ki se pojavijo pri preskusu, ne razvijejo. To kakovostno drugačno obnašanje tlaka kakor pri preskusu je posledica nestisljive obravnave zraka, saj je razlog za tlačna nihanja pri preskusu širjenje in krčenje velikega plinskega mehurja, ki se oblikuje po zaprtju plinskega stebra.

V drugem nizu simuliranj smo zato fazo zraka obravnavali kot stisljivo. Ker energijske enačbe nismo vključili v model, je bilo treba za stisljivost zraka določiti ustrezno vrednost. Stisljivost zraka je omejena z največjo, izotermno stisljivostjo in najmanjšo, adiabatno stisljivostjo. Preprosta ocena pokaže, da je prevod toplote v plinski mehur v enem nihajnem času zanemarljiv in da je zato adiabatna stisljivost zraka zelo dober približek:

During all the simulations the pressure at different levels was also traced. The calculated pressure curves are presented together with the experimentally measured values in Fig. 6. The pressures *p3* and *p6* were measured in the water at the vessel's wall, 838 mm and 250 mm from the bottom of the vessel. The pressure rise 0.5 s after the spheres' release indicates the entry of the first spheres into the water and the pressure peak after 0.76 s is the collapse of the gas chimney.

In the first set of simulations, all three phases – the water, the air and the spheres' phase – were treated as incompressible. As seen in Fig. 6, the pressure produces a spike when the gas chimney collapses, most pronounced for the LS method, where the water-air surface remains sharp, whereas the pressure oscillations, which were observed in the experiment, do not occur. This qualitatively different pressure behavior is due to the incompressible air treatment, since the reason for the pressure oscillations in the experiment is the expansion and compression of the whole, big, gas bubble, which forms after the gas-chimney collapse.

In the second series of simulations the air phase was therefore treated as compressible. Since the energy equation was not taken into account the correct air compressibility, which lies somewhere in the range bounded with the maximum isothermal and minimum adiabatic value, had to be determined. A simple estimation shows that the heat conduction in the gas bubble during one oscillation period is negligible and that, consequently, the adiabatic air compressibility is a very good approach:

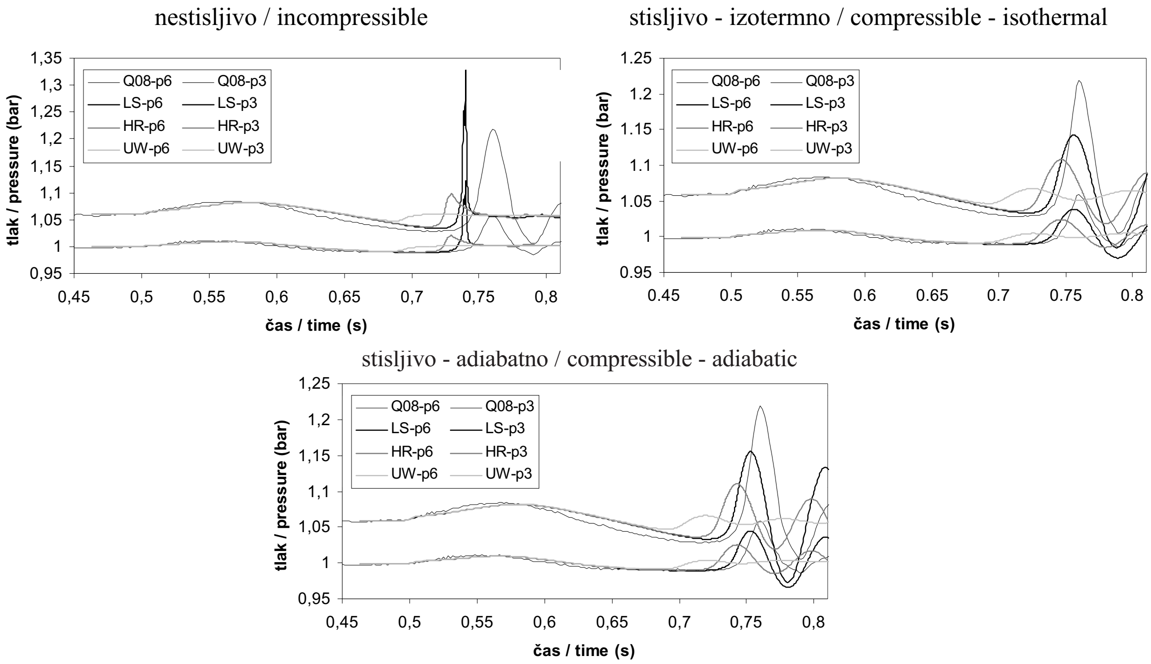
$$\frac{\Delta T_a}{\Delta T_{aw}} = \frac{\lambda_a \Delta t_{osc}}{\rho_a c_{pa} \Delta l_a^2} \approx \frac{10^{-2}\ \mathrm{W/Km} \cdot 10^{-1}\ \mathrm{s}}{1 \mathrm{kg/m^3} \cdot 10^3\ \mathrm{J/kgK} \cdot 10^{-2}\ \mathrm{m^2}} = 10^{-4} << 1 \qquad (10),$$

kjer so: ΔT_{aw} razlika temperature zraka v mehurju in temperature okolišne vode, ΔT_a sprememba temperature zraka v mehurju v enem nihajnem času Δt_{osc} zaradi prevoda toplote in Δl_a linearna izmera mehurja. Kljub temu smo simuliranja opravili tudi z izotermno stisljivostjo zraka, predvsem zato, da bi spoznali vpliv stisljivosti zraka na rezultate simuliranj.

Na sliki 6 je prikazan potek tlaka za oba stisljiva primera, pri katerih upoštevamo izotermno oz. adiabatno stisljivost zraka. Kakor smo pričakovali, se v stisljivih primerih pojavijo tlačna nihanja. Tlačna nihanja so najbolj izrazita pri metodi NF, pri kateri ostane medfazna ploskev voda - zrak ostra.

where ΔT_{aw} is the temperature difference between the air in the bubble and the surrounding water, ΔT_a is the temperature change of the air in the bubble during one oscillation period Δt_{osc} due to heat conduction and Δl_a is the linear dimension of the bubble. Despite that the simulations were also performed with the isothermal air compressibility, primarilly to establish the air compressibility's influence on the simulation results.

The pressure behavior in the compressible cases taking into account the isothermal and adiabatic air compressibility are presented in Fig. 6. As expected, in the compressible cases the pressure oscillations occur and are most pronounced for the LS method, where the water-air surface remains sharp.



Sl. 6. *Primerjava tlakov na različnih globinah (p3 in p6) pri izračunih z metodami NF, VL in PM za nestisljivo, izotermno in adiabatno stisljivost zraka s podatki preskusa Q08*

Fig. 6. *Comparison of pressures in the vessel at different levels (p3 and p6) between LS-, HR- and UW-methods calculations for the incompressible, isothermal and adiabatic air compressibility and the experimental measurements Q08*

Da bi simuliranja lažje primerjali med seboj, smo glavne rezultate simuliranj zbrali v preglednici 1. Za vsa predstavljena simuliranja so navedeni naslednji podatki: največji tlak *p6* (p_{max}), čas po katerem tlak doseže vrh (t_{pmax}) in časovni razmik med prvim tlačnim vrhom in dolom pri tlačnem nihanju ($\Delta t_{osc}/2$). Zaradi popolnosti in kot referenca so dodane tudi preskusne vrednosti, ki pa niso namenjene za resno primerjavo, saj so bile preskusne razmere, kar je opisano v 2. poglavju, nekoliko drugačne.

Potek tlaka se pri izračunih z metodami PM, VL in NF razlikuje zaradi različno izrazite razpršitve medfazne ploskve voda - zrak, ki jo povzročajo te numerične metode. Metoda PM prvega reda natančnosti povzroči največjo razpršitev (sl. 5) in zato

To make the comparison of the simulations easier the main results are assembled in table 1. The maximum pressure *p6* (p_{max}), the time when the pressure peak is reached (t_{pmax}) and the time between the first pressure maximum and minimum during the pressure oscillations ($\Delta t_{osc}/2$) are listed for all the presented simulations. The experimental values are also added for completeness and as a reference, but not for a rigorous comparison since the experimental conditions were somewhat different, as explained in section 2.

The reason for the various pressure behaviors for the UW-, HR- and LS-method calculations is the different extent of water-air surface-spreading these numerical methods produce. The first-order-accurate UW method produces the highest spreading (Fig. 5), so the

Preglednica 1. *Glavni rezultati nestisljivih in stisljivih simuliranj, opravljenih z metodami NF, VL in PM, skupaj s podatki preskusa Q08*
Table 1. *Main results of the incompressible and compressible simulations performed with the LS-, HR- and UW-methods together with the experimental measurements Q08*

	Simuliranje Simulation									preskus experiment Q08
	nestisljivo incompressible			stisljivo - izotermno compressible - isothermal			stisljivo - adiabatno compressible - adiabatic			
	NF/LS	VL/HR	PM/UW	NF/LS	VL/HR	PM/UW	NF/LS	VL/HR	PM/UW	
$p_{\max}$ (bar)	1,328	1,098	1,060	1,143	1,108	1,067	1,155	1,111	1,066	1,219
$t_{p\max}$ (s)	0,740	0,730	0,716	0,756	0,747	0,725	0,753	0,743	0,720	0,760
$\Delta t_{osc}/2\,(s)$	/	/	/	0,031	0,032	0,036	0,027	0,028	0,028	0,030

se začne zračni steber najhitreje zapirati. Ker se gostota medfazne ploskve voda - zrak spreminja najpočasneje, je povišanje tlaka najmanjše. Pri metodi VL je medfazna ploskev voda - zrak ostrejša (sl. 4) in zato je amplituda tlačnih nihanj večja. Tlačne spremembe so največje pri metodi NF, saj ostane medfazna ploskev voda - zrak ostra med celotnim simuliranjem (sl. 3), tako kakor je vidno tudi na posnetkih preskusa (sl. 2). Kakor smo pričakovali, vpliva stisljivost zraka neposredno na frekvenco tlačnih nihanj. Pri manjši, adiabatni stisljivosti zraka je frekvenca tlačnih nihanj višja (preglednica 1).

4 SKLEP

Predstavili smo izvirno obravnavo izotermnih preskusov mešalne faze eksplozije pare. Značilnost izotermnih mešalnih preskusov je, da jih ni mogoče ustrezno obravnavati niti izključno z modeli proste površine niti izključno z modeli večfaznega toka, saj se kroglice razpršijo, medtem ko ostane medfazna ploskev voda - zrak ostra. Zato smo se odločili razviti kombinirani večfazni model, pri katerem kroglice kot običajno obravnavamo z modelom večfaznega toka, medfazno ploskev voda - zrak pa z modelom proste površine.

Izvirni kombinirani večfazni model smo preverili na izotermnem preskusu mešalne faze eksplozije pare Q08, ki so ga izvedli na napravi QUEOS. Opravili smo številna primerjalna simuliranja, pri katerih smo medfazno ploskev voda - zrak določevali z različnimi numeričnimi postopki (NF, VL in PM), pri tem pa zrak obravnavali kot stisljiv oz. nestisljiv.

Po pričakovanju so rezultati simuliranj pokazali, da ostane medfazna ploskev voda - zrak ostra le pri izračunih z metodo NF in da je razpršitev medfazne ploskve voda - zrak največja pri izračunih z metodo PM prvega reda natančnosti. Posledično so tlačne spremembe največje pri metodi NF, kjer se gostota na medfazni ploskvi voda - zrak najhitreje spremeni. Tlačna nihanja, ki so se pojavila pri preskusu, smo dobili le v stisljivem primeru, saj so posledica nihanja ujetega plinskega mehurja. Ob upoštevanju predstavljenih pomanjkljivosti modela

air chimney starts to close the fastest in this calculation. Since the density of the spread water-air surface changes slowest the pressure rise is the lowest. The HR method produces a sharper water-air interface (Fig. 4); therefore, the amplitude of the pressure oscillations is greater. The pressure changes are the largest for the LS method since it keeps the water-air interface sharp during the whole simulation (Fig. 3), as was also observed in the experiment (Fig. 2). As expected, the air compressibility has a direct influence on the pressure oscillation frequency. At the lower adiabatic air compressibility the pressure oscillation frequency is higher (Table 1).

4 CONCLUSION

An original treatment of isothermal steam-explosion premixing experiments was presented. The special feature of isothermal premixing experiments is that they cannot be adequately modeled just with free-surface models or just with multiphase flow models, since the spheres disperse, whereas the water-air surface remains sharp. So we decided to develop a combined multiphase model, where the spheres are treated, as is usual, with a multiphase flow model, whereas the water-air surface is treated with a free-surface model.

The original combined multiphase model was validated using the QUEOS isothermal premixing experiment Q08. A number of simulations were performed in a comparison using different numerical methods for the water-air surface determination (LS, HR and UW) treating the air as compressible or incompressible.

As expected, the results of the simulations showed that the water-air surface remains sharp only for the LS-method calculations and that the first-order-accurate UW method produces the highest water-air surface spreading. Consequently, the pressure variations are the largest for the LS method, where the density at the water-air interface changes most rapidly. The pressure oscillations that were observed in the experiment could only be reproduced in the compressible case since they are the consequence of the entrapped gas bubble oscillations. The simulation results obtained with the LS preskusa, se rezultati simuliranj z metodo NF tako kakovostno kakor količinsko dobro ujemajo s podatki preskusa.

method agree, when the deficiencies of the presented experiment model are considered, qualitatively and quantitatively well with the experimental measurements.

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Vpliv računskega polmera obračanja goseničnega vozila na potrebno moč motorja pri obračanju

The Impact of a Fixed Kinematic Turning Radius of a Tracked Vehicle on the Engine Power required in a Turn

Vjekoslav Stojković - Dinko Mikulić

V prispevku je analiziran vpliv velikosti računskega polmera obračanja na potrebno moč motorja pri obračanju in na obremenjenost drsnih elementov mehanizma obračanja goseničnega vozila, ki ima mehanizem obračanja z več izračunanimi polmeri obračanja.

Definirani so parametri, ki opisujejo relativno spremembo potrebne moči motorja pri obračanju, relativno spremembo zavorne moči na drsnih elementih mehanizma obračanja in spremembo koeficienta koristnega delovanja mehanizma obračanja v odvisnosti od relativnega polmera obračanja.

Podana so priporočila za izbiranje računskih polmerov obračanja pri projektiranju mehanizma obračanja goseničnega vozila.

(Ključne besede: goseničarji, obračanje vozil, moči motorjev, mehanizmi obračanja)

This paper analyzes the impact of a fixed kinematic turning radius on the engine power required in a turn and on the load of friction elements in the turning mechanism of a tracked vehicle equipped with turning mechanisms that have several fixed kinematic turning radii.

Parameters describing the relative change of engine power in a turn, the relative change of braking power on the friction elements of the turning mechanism, and the change of efficiency coefficient of the turning mechanism depending on the relative turning radius are defined.

Recommendations regarding the choice of fixed kinematic turning radii, relating to the design of the turning mechanism of a tracked vehicle, are given.

(Keywords: tracked vehicles, turning radius, engine power, turning mechanism)

0 UVOD

Obračanje goseničnega vozila se doseže s spremembo hitrosti navijanja ene v primerjavi z drugo gosenico ob hkratnem oblikovanju različnih vlečnih sil na gosenicah ([1] in [2]). Dotikalni del gosenice dobiva ob vzdolžnem pomikanju pri obračanju še dodatno bočno premikanje po tleh. Zaradi vzdolžnih pomikov gosenice se pojavljajo odpori tudi pri gibanju vozila naravnost. Bočni pomiki gosenic povzročajo dodatne odpore zaradi bočnega trenja med gosenicami in tlemi, kakor tudi zaradi gnetenja, rezanja in premikov tal pod gosenicami. Zaradi tega se pojavi pri vstopu v obračanje goseničnega vozila porast skupnih odporov gibanja, zaradi česar se poveča obremenitev pogonskega motorja in pogonskega mehanizma, posledično pa tudi poveča obremenitev posameznih elementov v mehanizmih obračanja.

Obremenitev motorja in pogonskega mehanizma goseničnega vozila ter posameznih elementov v mehanizmih za obračanje je v veliki meri

0 INTRODUCTION

Turning a tracked vehicle is accomplished by changing the winding speed of one of its tracks with respect to the other, resulting in the simultaneous occurrance of different tractive forces on each track ([1] and [2]). The leaning part of the track, apart from the longitudinal, receives an additional lateral shift during the turn. Longitudinal shifts of the tracks induce the same kind of resistances as during rectilinear motion of the vehicle. Lateral shifts induce additional resistances due to lateral friction between the tracks and the ground and due to the compression, cutting and mixing of soil under the tracks. When a turn begins, the total resistance to motion of a tracked vehicle is increased, this causes an increased load on the engine and transmission, and therefore an increased load on the elements of the turning mechanisms.

The loads on the engine and transmission of a tracked vehicle, as well as on the elements of its turning mechanisms, significantly depend on the odvisna od velikosti t.i. računskega polmera obračanja R_p. Računski polmer obračanja je tisti polmer obračanja, ki se realizira ob fiksnem prenosnem razmerju pogonske verige do notranje gosenice in brez drsenja drsnih elementov v mehanizmih obračanja ([1] in [2]).

V tem prispevku je analiziran vpliv velikosti računskega polmera obračanja na potrebno moč motorja v obračanju in na obremenjenost drsnih elementov mehanizma obračanja na konkretnem primeru goseničnega vozila, ki ima mehanizme obračanja z več računskimi polmeri obračanja. Definirani so parametri, ki opisujejo relativno spremembo potrebne moči motorja pri obračanju, relativno spremembo zavorne sile na drsnih elementih mehanizma za obračanje in spremembo koeficienta koristnega delovanja mehanizma obračanja v odvisnosti od relativnega polmera obračanja. Na podlagi izvedene analize so dana priporočila za izbiranje računskega polmera obračanja.

1 DEFINIRANJE PARAMETROV ZA ANALIZIRANJE OBRAČANJA

Analizirano je obračanje goseničnega vozila na vodoravni podlagi (sl. 1 in 2), ob naslednjih predpostavkah in omejitvah:

- zanemarjeno je podrsavanje zunanje in notranje gosenice,
- predpostavljena širina sledi gosenice je ena (B = 1),
- zanemarjen je vpliv sredobežne sile,
- predpostavljena teža vozila je ena (G = 1),
- analizirano je obračanje s polmerom obračanja R v območju od obračanja okoli notranje gosenice do obračanja s prostim polmerom obračanja.

Prosti polmer obračanja je tisti, pri katerem je sila na notranji gosenici enaka nič (F_1 = 0). Pri obračanjih, ki so večja od prostega polmera obračanja, na notranji gosenici nastane vlečna sila, pri polmerih obračanja, ki so manjši od prostega polmera obračanja, pa se na notranji gosenici formira zavorna sila ([1] in [2]).

Na sliki 1 so prikazane sile in vrtilni momenti, ki delujejo na gosenično vozilo:

R_2 = odpor pri gibanju naravnost na zunanji gosenici,
R_1 = odpor pri gibanju naravnost na notranji gosenici,
F_2 = vlečna sila na zunanji gosenici,
F_1 = zavorna sila na notranji gosenici,
M_c = moment bočnih odporov obračanja.

Odpora pri gibanju naravnost R_1 in R_2 ter moment bočnega odpora obračanja M_c, se določajo z izrazi ([1] in [2]):

magnitude of the so-called fixed kinematic turning radius R_p. The fixed kinematic turning radius is the turning radius realized with a fixed transmission ratio of a kinematic chain to an inner track and without any sliding of the friction elements in the turning mechanism ([1] and [2]).

This paper analyzes the impact of the fixed kinematic turning radius on the engine power required in a turn and on the load of the friction elements of the turning mechanism by using the concrete example of a tracked vehicle equipped with turning mechanisms that have several fixed kinematic turning radii. The parameters that describe the relative change of the required engine power in a turn, the relative change of the braking power on the friction elements of the turning mechanism, and the change of the efficiency coefficient of the turning mechanism depending on the relative turning radius are defined. On the basis of the performed analysis, recommendations regarding the choice of fixed kinematic turning radii are given.

1 DEFINITION OF PARAMETERS FOR ANALYZING A TURN

The turn of a tracked vehicle on a horizontal surface (Figs. 1 and 2) is analyzed with the following assumptions and constraints:

- sliding of the outer track and the inner track is neglected,
- the distance between the tracks is assumed to be one (B = 1),
- the influence of centrifugal force is neglected,
- the vehicle's weight is assumed to be one (G = 1),
- turns with turning radii R in the interval ranging from a turn around the inner track to a turn with a free turning radius are analyzed.

The free turning radius is characterized by the force on the inner track being zero (F_1 = 0). For turns with radii larger than the free turning radius a tractive force is induced on the inner track, while for turns with radii less than the free turning radius a braking force is induced on the inner track ([1] and [2]).

The forces and torques acting on a tracked vehicle are presented in Figure 1:

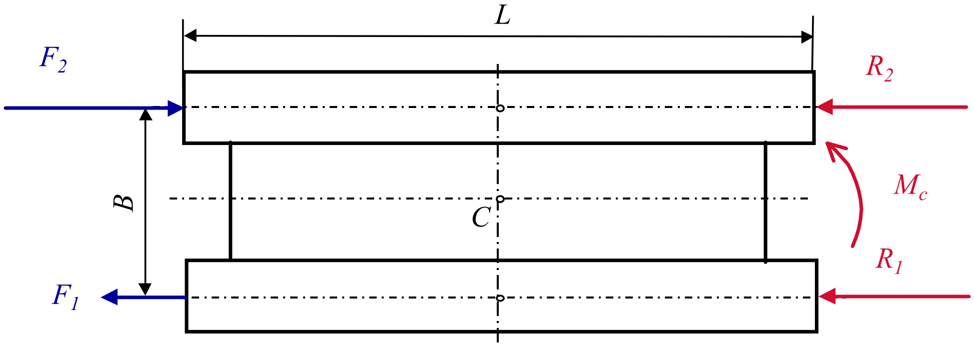
R_2 = resistance to rectilinear motion on the outer track,
R_1 = resistance to rectilinear motion on the inner track,
F_2 = tractive force on the outer track,
F_1 = braking force on the inner track,
M_c = turning resistance torque.

Resistances to rectilinear motion R_1 and R_2, and the turning resistance torque M_c are determined by the following expressions ([1] and [2]):

$$R_1 = 0{,}5\, f\, G \quad (1),$$

$$R_2 = 0{,}5\, f\, G \quad (2),$$

$$M_c = \frac{\mu G L}{4} \quad (3),$$



Sl.1. *Sile in momenti, ki delujejo pri obračanju goseničnega vozila*
Fig. 1. *Forces and torques on a tracked vehicle in a turn*

$$\mu = \frac{\mu_{\text{maks}}}{0,925 + 0,15\rho} \quad (4),$$

kjer so:
f = koeficient odpora pri gibanju naravnost na določeni podlagi,
ρ = relativni polmer obračanja ($\rho = R/B$),
μ = koeficient odpora obračanja na določeni podlagi in za določeni relativni polmer obračanja,
μ_{maks} = koeficient odpora obračanja na določeni podlagi pri ρ = 0,5,
L = dolžina dotikalnega dela gosenice.

Vlečna sila na zunanji gosenici F_2 in zavorna sila na notranji gosenici F_1 lahko določimo z izrazoma ([1] in [2]):

where:
f = the rectilinear motion resistance coefficient for a particular surface,
ρ = the relative turning radius ($\rho = R/B$),
μ = the turning resistance coefficient for a particular surface and a particular relative turning radius,
μ_{max} = the turning resistance coefficient for a particular surface at ρ = 0.5,
L = the length of the leaning part of a track.

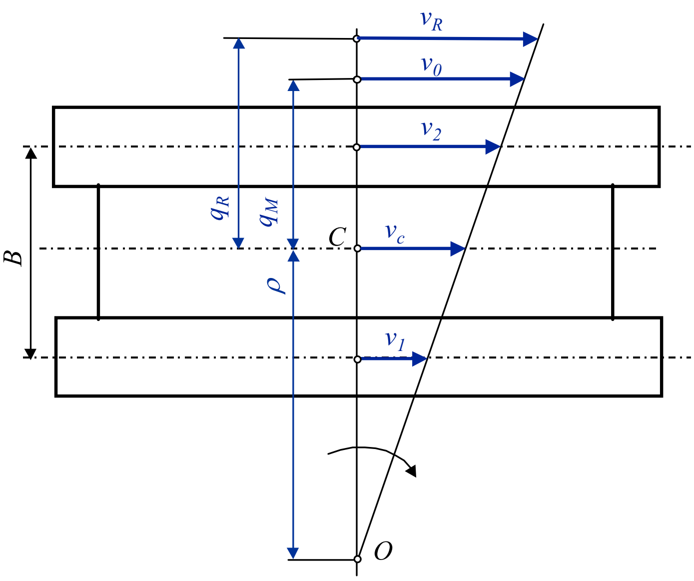
The tractive force on the outer track F_2 and the braking force on the inner track F_1 can be determined by the following expressions ([1] and [2]):

$$F_2 = R_2 + \frac{M_c}{B} \quad (5),$$

$$F_1 = -R_1 + \frac{M_c}{B} \quad (6).$$

Na sliki 2 so prikazane hitrosti vozila pri obračanju in relativni polmeri obračanja goseničnega vozila:
v_2 = hitrost goseničnega vozila na zunanji gosenici,
v_1 = hitrost goseničnega vozila na notranji gosenici,

Figure 2 presents the velocities and relative turning radii of a turning tracked vehicle:
v_2 = the velocity of a tracked vehicle on the outer track,
v_1 = the velocity of a tracked vehicle on the inner track,



Sl.2. *Načrt hitrosti goseničnega vozila pri obračanju*
Fig. 2. *Velocity plan of a turning tracked vehicle*

v_c = hitrost težišča goseničnega vozila,
v_0 = hitrost točke vozila, ki ohranja enako hitrost pri obračanju in pri gibanju naravnost,
q_M = kinematski parameter mehanizma obračanja (relativna koordinata točke vozila, ki ima hitrost v_0).

Uvedimo parameter q_R, ki zadovoljuje naslednji pogoj [3]:

v_c = the velocity of the center of mass of a tracked vehicle,
v_0 = the velocity of a point on the vehicle which retains the same velocity in a turn as in rectilinear motion,
q_M = the kinematic parameter of the turning mechanism (relative coordinate of a point on the vehicle with velocity v_0).

Let us introduce parameter q_R, satisfying the following condition [3]:

$$(R_1 + R_2)\cdot q_R\cdot B = M_c \quad (7).$$

Z uporabo izraza (7) uvajamo povezanost med momentom odpora obračanju M_c in momentom vsote odporov pri gibanju naravnost $(R_1 + R_2)\cdot B$. Po uvrstitvah izrazov (1), (2), in (3) v izraz (7) dobimo:

Expression (7) describes the correlation between the turning resistance torque M_c and the torque of the sum of resistances to rectilinear motion $(R_1 + R_2)\cdot B$. Inserting (1), (2) and (3) into (7) results in the following expression:

$$q_R = \frac{\mu L}{4fB} \quad (8).$$

Uvedemo pojem relativnega računskega polmera obračanja ρ_p:

The relative fixed kinematic turning radius ρ_p is defined as:

$$\rho_p = \frac{R_p}{B} \quad (9).$$

Pri obračanju goseničnega vozila, razen odporov pri gibanju naravnost$(R_1 + R_2)$, obstajajo tudi dodatni bočni odpori, ki oblikujejo moment odpora obračanja M_c. Potrebna moč za obvladovanje skupnih zunanjih odporov obračanja (P_0) je večja od potrebne moči za premagovanje odporov pri gibanju naravnost (P_{pr}) ([3] in [4]):

Besides resistances to rectilinear motion $(R_1 + R_2)$, there are additional lateral resistances, which form the turning resistance torque M_c in the turning movement of a tracked vehicle. The power required for overcoming the total external resistances in a turn (P_0) is larger than the power required for overcoming the resistance in rectilinear motion (P_{pr}) ([3] and [4]):

$$P_{pr} = (R_1 + R_2)\, v_0 \quad (10),$$

$$P_0 = (R_1 + R_2) v_0 \frac{q_R + \rho}{q_M + \rho} \quad (11),$$

$$P_0 = P_{pr} \frac{q_R + \rho}{q_M + \rho} \quad (12).$$

Potrebna moč motorja za izvedbo obračanja goseničnega vozila (P_{mz}) se določi z izrazom ([3] in [4]):

The engine power required for accomplishing the turn of a tracked vehicle (P_{mz}) is determined by the following expressions ([3] and [4]):

$$P_{mz} = (R_1 + R_2) v_0 \frac{q_R + \rho_p}{q_M + \rho_p} \quad (13),$$

$$P_{mz} = P_{pr} \frac{q_R + \rho_p}{q_M + \rho_p} \quad (14).$$

Pri obračanju goseničnega vozila s polmeri obračanja, ki so različni od računskih, se na drsnih elementih mehanizma za obračanje sprošča moč drsenja (P_k), ki se določa z izrazom ([3] in [4]):

The power of sliding (P_k) that is spent on the friction elements of the turning mechanism during the turns of a tracked vehicle at turning radii different from the fixed kinematic turning radius is determined by the following expression ([3] and [4]):

$$P_k = (R_1 + R_2) v_0 \frac{q_R - q_M}{q_M + \rho_p} \frac{\rho - \rho_p}{q_M + \rho} \quad (15),$$

$$P_k = P_{pr} \frac{q_R - q_M}{q_M + \rho_p} \frac{\rho - \rho_p}{q_M + \rho} \quad (16).$$

Uvedimo koeficient relativne potrebne moči motorja pri obračanju (ψ_{mz}), koeficient relativne moči

The coefficient of relative engine power required in a turn (ψ_{mz}), the coefficient of relative drsenja v drsnih elementih mehanizma za obračanje ψ_k in koeficient koristnega delovanja mehanizma obračanja η_{mz}, in sicer ([3] in [4]):

power of sliding in the friction elements of the turning mechanism ψ_k, and the efficiency coefficient of the turning mechanism η_{mz} are defined as ([3] and [4]):

$$\psi_{mz} = \frac{P_{mz}}{P_{pr}} \quad (17),$$

$$\psi_{mz} = \frac{q_R + \rho_p}{q_M + \rho_p} \quad (18),$$

$$\psi_k = \frac{P_k}{P_{pr}} \quad (19),$$

$$\psi_k = \frac{q_R - q_M}{q_M + \rho_p} \frac{\rho - \rho_p}{q_M + \rho} \quad (20),$$

$$\eta_{mz} = \frac{P_0}{P_{mz}} \quad (21),$$

$$\eta_{mz} = \frac{q_R + \rho}{q_M + \rho} \frac{q_M + \rho_p}{q_R + \rho_p} \quad (22).$$

Na podlagi gornjih izrazov lahko povzamemo, da se koeficient relativne potrebne moči motorja pri obračanju ψ_{mz}, koeficient relativne moči podrsavanja v drsnih elementih mehanizma obračanja ψ_k in koeficient koristnega delovanja mehanizma obračanja η_{mz} spreminjajo v odvisnosti od:

– koeficienta odpora gibanja f na tleh, kjer se obrača,
– relativnega polmera obračanja ρ,
– relativnega proračunskega polmera obračanja ρ_p in
– parametra gibanja q_M.

Idealen mehanizem obračanja bi bil tisti, pri katerem bi za vsak relativni polmer obračanja dosegli $\psi_{mz}=1$, $\psi_k = 0$ in $\eta_{mz} = 1$. Vrednosti koeficientov ψ_{mz}, ψ_k in η_{mz} za realni mehanizem obračanja pričajo o stopnji uspešnosti projektnega oblikovanja mehanizma obračanja z vidika smotrne rabe moči motorja, a posredno tudi o njegovem vplivu na porabo pogonskega goriva.

These expressions show that the coefficient of relative engine power required in a turn ψ_{mz}, the coefficient of relative power of sliding in the friction elements of the turning mechanism ψ_k, and the efficiency coefficient of the turning mechanism η_{mz} depend on:

– the rectilinear motion resistance coefficient f for a particular surface,
– the relative turning radius ρ,
– the relative fixed kinematic turning radius ρ_p,
– the kinematic parameter q_M.

An ideal turning mechanism would achieve $\psi_{mz} = 1$, $\psi_k = 0$ and $\eta_{mz} = 1$ for every turning radius. For real turning mechanisms the values of the coefficients ψ_{mz}, ψ_k and η_{mz} indicate the quality of design, regarding rational use of engine power, and indirectly influence fuel consumption.

2 ANALIZA VPLIVA VELIKOSTI RAČUNSKEGA POLMERA OBRAČANJA

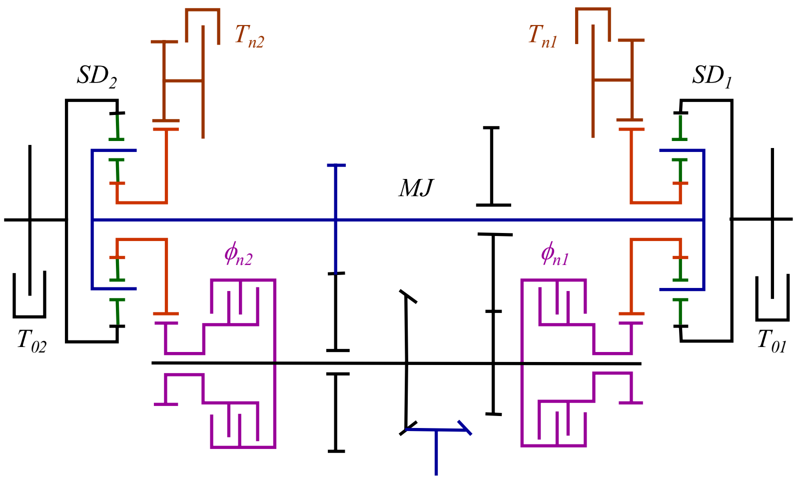
Za izvajanje analize je izbran mehanizem obračanja na goseničnem vozilu BVP - M80, katerega shema gibanja [5] je prikazana na sliki 3. Prikazan mehanizem obračanja sodi v skupino t.i. pogonskih prenosov v bloku (TUB), pri katerih je pogonsko in konstrukcijsko združena funkcija menjanja stopnje prenosa v menjalniku in menjanje hitrosti obračanja pogonskih koles pri obračanju goseničnega vozila. Ta pogonski prenos v bloku je sestavljen iz menjalnika (MJ), zbirnih diferencialov (SD_2 in SD_1), pomožnih drsnih spojk (ϕ_{n2} in ϕ_{n1}), pomožnih drsnih zavor (T_{n2} in T_{n1}) in drsnih zavor za zaustavljanje (T_{02} in T_{01}).

S sprožitvijo drsne zavore T_0 v TUB do notranje gosenice nastane najmanjši relativni računski polmer obračanja $\rho_{p0} = 0,5$. S popolnim proženjem pomožne drsne spojnice ϕ_n v TUB do notranje gosenice nastane še po en relativni računski polmer obračanja v vsaki stopnji prenosa ($\rho_{p1} = 1,2$; $\rho_{p2} = 3,1$; $\rho_{p3} = 4,8$; $\rho_{p4} = 7,5$; $\rho_{p5} = 11,1$). Obračanje s preostalimi polmeri obračanja

2 AN IMPACT ANALYSIS FOR A FIXED KINEMATIC TURNING RADIUS

The analysis is conducted on the turning mechanism of the BVP-M80 tracked vehicle. Its kinematic scheme [5] is presented in Figure 3. This turning mechanism belongs to the category of the so-called block transmissions (BT). In block transmissions the functions of changing gears in a gearbox and of changing the rotation speed of the propulsion wheels during a turn are kinematically and constructionally unified. The presented block transmission consists of a gearbox (MJ), summing differentials (SD_2 and SD_1), auxiliary friction clutches (ϕ_{n2} and ϕ_{n1}), auxiliary friction brakes (T_{n2} and T_{n1}), and halting friction brakes (T_{02} and T_{01}).

By activating a halting friction brake T_0 in the BT to the inner track, the minimum relative fixed kinematic turning radius of $\rho_{p0} = 0.5$ is realized. By fully activating an auxiliary friction clutch ϕ_n in the BT to the inner track, yet another relative fixed kinematic turning radius is realized for each gear ($\rho_{p1} = 1.2$; $\rho_{p2} = 3.1$; $\rho_{p3} = 4.8$; $\rho_{p4} = 7.5$; $\rho_{p5} = 11.1$). Turns



Sl. 3. *Shema gibanja mehanizma obračanja goseničnega vozila BVP M-80*
Fig. 3. *Kinematic scheme of the turning mechanism of the BVP-M80 tracked vehicle*

nastane z drsenjem enega od drsnih elementov v TUB (ϕ_n ali T_n ali T_0).

Za gosenično vozilo BVP M-80 (5) so znane vrednosti [5] q_M = 0,5 in L/B = 1,3. Analiziramo obračanje z vozilom na vodoravni s travo pokriti podlagi z osvojenima koeficientoma ([1] in [2]) f = 0,06 in μ_{max} = 0,8. Grafični prikaz rezultatov računanja koeficientov ψ_{mz}, ψ_k in η_{mz}, za izbrano vozilo je podan na slikah 4, 5 in 6.

Pri analizi dobljenih rezultatov je opazno naslednje:

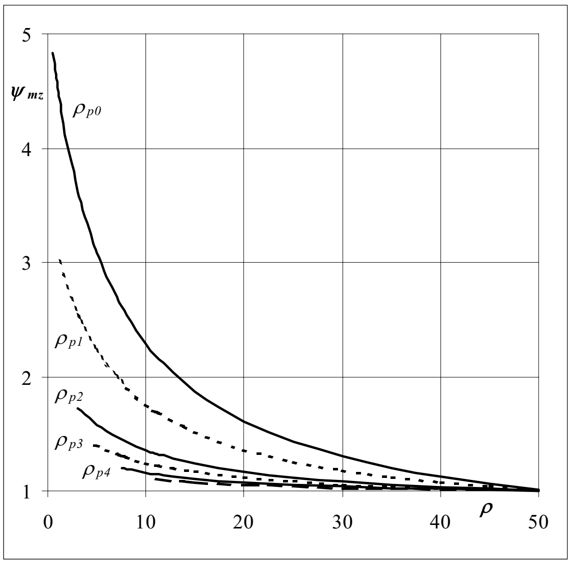
– večanje relativnega računskega polmera obračanja vpliva na zmanjševanje koeficientov relativne potrebne moči motorja pri obračanju ψ_{mz} in koeficienta relativne zavorne moči ψ_k, ob povečanju koeficienta koristnega delovanja mehanizma obračanja η_{mz} za relativne polmere

with other turning radii are realized by sliding one of the friction elements in the BT (ϕ_n or T_n or T_0).

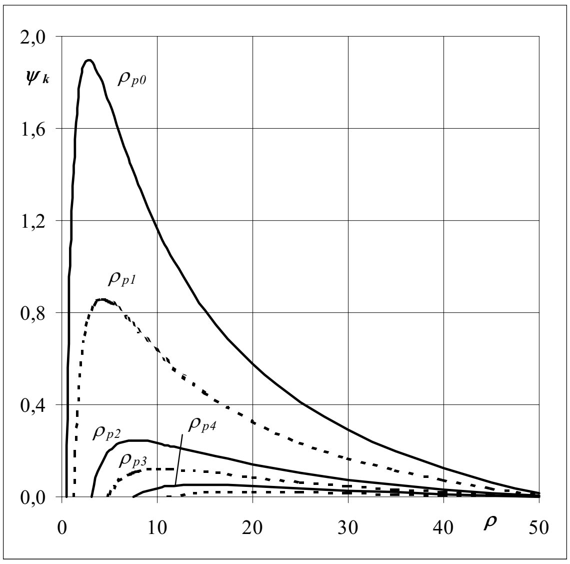
For the BVP M-80 tracked vehicle, the following values are known [5]: q_M = 0.5 and L/B = 1.3. The turn of the vehicle on a horizontal sodded-grass surface is analyzed with the assumed coefficients ([1] and [2]) f = 0.06 and μ_{max} = 0.8. Graphs of the coefficients ψ_{mz}, ψ_k and η_{mz} are calculated for the chosen vehicle and presented in Figures 4, 5 and 6.

Analysis of the results shows that:

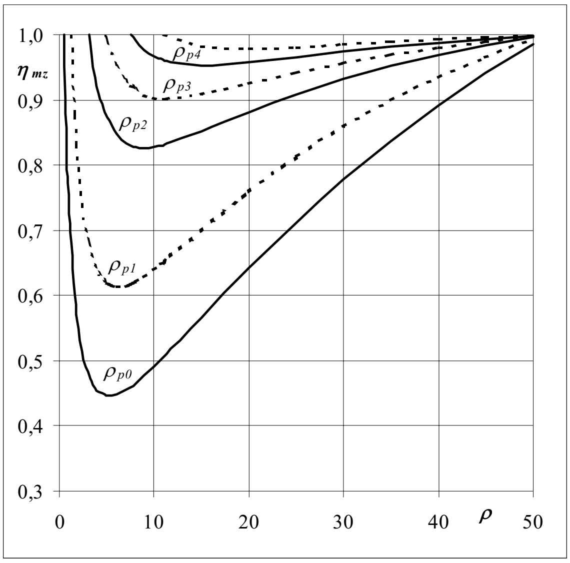
– with the increase of the relative fixed kinematic turning radius, the coefficient of relative engine power required in a turn ψ_{mz} decreases, as does the coefficient of the relative power of sliding in the friction elements of the turning mechanism ψ_k, while the efficiency coefficient of the turning mechanism η_{mz} increases for relative turning radii



Sl. 4. *Koeficient relativne potrebne moči motorja pri obračanju*
Fig. 4. *Coefficient of relative engine power required in a turn*



Sl. 5. *Koeficient relativne moči drsenja v mehanizmu obračanja*
Fig. 5. *Coefficient of relative power of sliding in the turning mechanism*



Sl. 6. *Koeficient koristnega dela mehanizma obračanja*
Fig. 6. *Efficiency coefficient of the turning mechanism*

obračanja ρ, ki so večji od relativnega računskega polmera obračanja za posamezno stopnjo prenosa,

- zmanjševanje koeficientov ψ_{mz} in ψ_k ter povečanje koeficienta η_{mz} je posebno izraženo v območju relativnega računskega polmera $\rho_{pi} \in \{1,0; 5,0\}$,
- za intervale računskih polmerov $\rho_{pi} \in \{5,1; 15,0\}$ je gibanje ugodnih vrednosti koeficientov ψ_{mz}, ψ_k in η_{mz} majhne intenzivnosti,
- obstoj več relativnih računskih polmerov obračanja, ki se medsebojno razlikujejo po velikosti, omogoča prehod obračanja goseničnih vozil z višje ravni (ρ_{pi}) na sosednjo nižjo raven (ρ_{pi-1}) v primeru, ko je treba izvesti obračanje z relativnim polmerom, ki je manjši od ρ_{pi} in večji od ρ_{p0} = 0,5,
- prehod obračanja goseničnega vozila z višje ravni (ρ_{pi}) na sosednjo nižjo raven (ρ_{pi-1}) v primeru, ko je treba izvesti obračanje z relativnim polmerom, manjšim od (ρ_{pi}), a večjim od ρ_{p0} = 0,5, zmanjšuje obremenitev pogonskega motorja in drsnih elementov mehanizma obračanja.

ρ that are larger than the relative fixed kinematic turning radius ρ_{pi} for the particular gear,

- the decrease of ψ_{mz} and ψ_k and the increase of η_{mz} are particularly pronounced in the interval of the relative fixed kinematic turning radii $\rho_{pi} \in \{1.0; 5.0\}$,
- in the interval of relative fixed kinematic turning radii $\rho_{pi} \in \{5.1; 15.0\}$ the favorable trend of values of the coefficients ψ_{mz}, ψ_k and η_{mz} is more moderate,
- the existence of several relative fixed kinematic turning radii that are different in magnitude allows transitioning from a higher (ρ_{pi}) to the nearest lower level (ρ_{pi-1}), for the case when a turn with relative radius less than ρ_{pi} and larger than ρ_{p0} = 0.5 is required,
- transitioning from a higher (ρ_{pi}) to the nearest lower level (ρ_{pi-1}), for the case when a turn with a relative radius less than ρ_{pi} and larger than ρ_{p0} = 0.5 is required, decreases the engine load and the load on the friction elements of the turning mechanism.

3 SKLEP

Pri izvajanju manevra obračanja goseničnega vozila se z zmanjševanjem polmera obračanja pojavljajo povečani odpori obračanja in povečane obremenitve pogonskega motorja in sklopov v prenosnem mehanizmu za gibanje vozila.

Obstoj relativnih računskih polmerov obračanja, ki so večji od ρ_{p0} = 0,5, prispeva k zmanjševanju obremenitev pogonskega motorja in elementov v prenosih v primeru obračanja s polmeri obračanja, ki so enaki ali večji od relativnega računskega polmera obračanja. Koeficienti relativne potrebne moči motorja pri obračanju (ψ_{mz}), relativne zavorne moči (ψ_k) ter koeficient koristnega delovanja mehanizma obračanja (η_{mz}) imajo ugodne vrednosti za to območje obračanja.

3 CONCLUSION

The decrease in turning radius during the turn of a tracked vehicle leads to increased turning resistances, an increased engine load and an increased load on the transmission devices of the vehicle.

The existence of relative fixed kinematic turning radii larger than ρ_{p0} = 0.5 enables a decrease in the engine load and the load on the transmission elements for the cases of turns with turning radii greater than or equal to the relative fixed kinematic turning radius. The coefficient of relative engine power required in a turn (ψ_{mz}), the coefficient of relative braking power (ψ_k), and the efficiency coefficient of the turning mechanism (η_{mz}) have favorable values for those turning radii.

Ugodno gibanje vrednosti koeficientov ψ_{mz}, ψ_k in η_{mz} je posebej izraženo pri relativnih računskih polmerih obračanja v območju $\rho_{pi} \in \{1,0; 5,0\}$. Za intervale relativnih računskih polmerov $\rho_{pi} \in \{5,1; 15,0\}$ je gibanje ugodnih vrednosti koeficientov ψ_{mz}, ψ_k in η_{mz} umirjene intenzivnosti. V področju obračanja, v katerem bi se uporabili relativni računski polmeri obračanja, ki so večji od $\rho_{pi} = 15$, se koeficienti ψ_{mz}, ψ_k in η_{mz} le malo spreminjajo.

Ob projektiranju novih pogonskih prenosov za gosenična vozila je zato priporočljivo uporabiti en računski polmer obračanja $\rho_{p0} = 0,5$ in več relativnih računskih polmerov obračanja v območju $\rho_{pi} \in \{ 1,0; 15,0\}$.

A favorable trend of values of the coefficients ψ_{mz}, ψ_k and η_{mz} is particularly pronounced for relative fixed kinematic turning radii in the interval $\rho_{pi} \in \{1.0; 5.0\}$. In the interval of relative fixed kinematic turning radii $\rho_{pi} \in \{ 5.1; 15.0\}$ the favorable trend of values of ψ_{mz}, ψ_k and η_{mz} is more moderate. In the range of turns with relative fixed kinematic turning radii larger than $\rho_{pi} = 15$, the coefficients ψ_{mz}, ψ_k and η_{mz} do not change significantly.

When designing the transmission of a tracked vehicle it is desirable to realize one fixed kinematic turning radius $\rho_{p0} = 0.5$ and several other fixed kinematic turning radii in the interval $\rho_{pi} \in \{ 1.0; 15.0\}$.

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- To analyse potential scientific and technological processes reflecting energy, water and environment exchange;
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Enote in okrajšave

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

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

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

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

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The paper should be written in the following format:
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- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

The layout of the text

Texts should be written in A4 format, with double spacing and margins of 3 cm to provide editors with space to write in their corrections. Microsoft Word for Windows is the preferred format for submission. One hard copy, including all figures, tables and illustrations and an identical electronic version of the manuscript must be submitted simultaneously.

Please do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering. Graphs, tables and equations in LaTeX may be supplied in good quality hard-copy format, so that they can be copied for inclusion in the Journal.

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

Units and abbreviations

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

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

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Za pripravo diagramov in risb priporočamo CDR format (CorelDraw), saj so slike v njem vektorske in jih lahko pri končni obdelavi preprosto povečujemo ali pomanjšujemo.

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

Vse označbe na slikah morajo biti dvojezične.

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

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

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

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.

[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.

[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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

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

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Good quality black-and-white photographs or scanned images should be supplied for illustrations. In certain circumstances, colour figures may be considered.

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The list of references

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

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.

[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.

[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

Author information

The following information about the authors should be enclosed with the paper: names, complete postal addresses, telephone and fax numbers and E-mail addresses.

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