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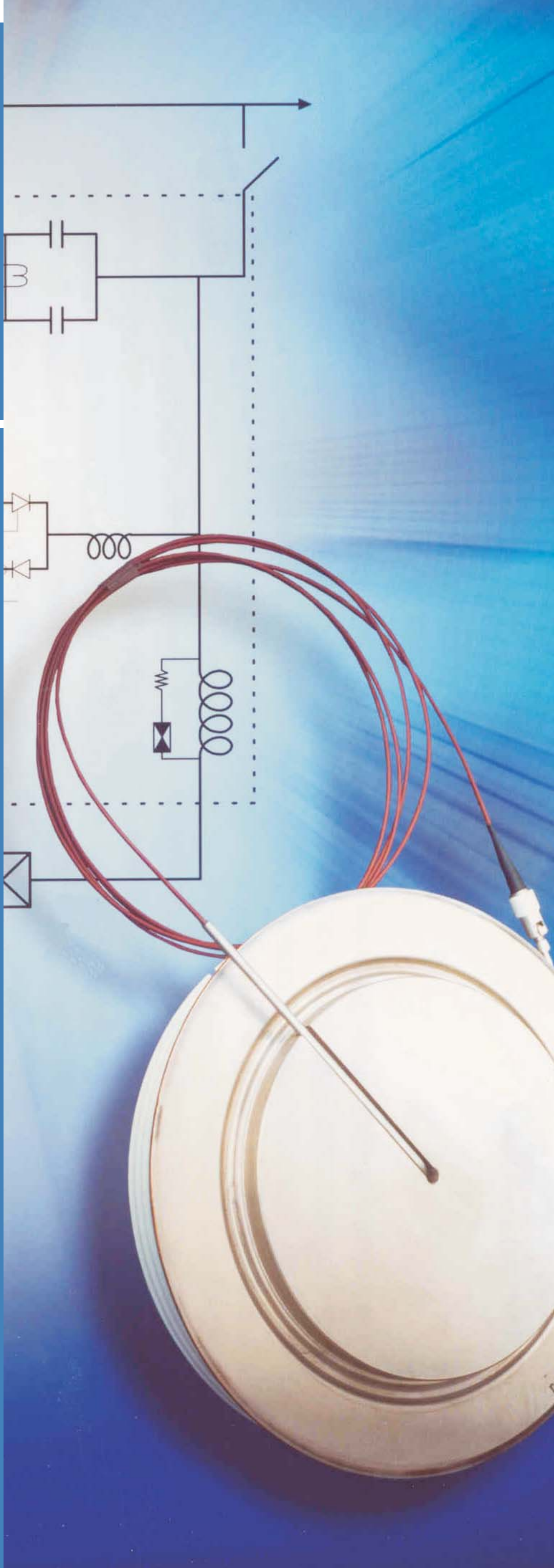

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Možnosti stabilizacije preoblikovalnih lastnosti žice z ravnanjem med valji

Stabilizing the Forming Properties of Wire by Using a Roller-Straightening Process

Miha Nastran - Karl Kuzman

Nestabilne preoblikovalne lastnosti vhodnih materialov predstavljajo v današnjem stanju avtomatizacije proizvodnje še vedno precejšen problem. Zlasti v velikoserijski proizvodnji, pri kateri vse več uporabljamo avtomatizirane montažne linije, je potreba po enakih polizdelkih praktično neizogibna. Dejstvo je, da so raztrosi geometrijskih značilnosti polizdelkov velikokrat posledica neenakomernih mehanskih lastnosti vhodnega materiala, na katerega proizvodni inženirji podjetij, ki se ukvarjajo s kovinsko predelavo, nimajo vpliva. Prispevek prikazuje možnosti stabilizacije preoblikovalnih lastnosti žice z uporabo ravnalnih naprav, ki so sestavni del vsakega proizvodnega procesa predelave žice. V začetku je najprej na kratko prikazana reologija jekel pri izmeničnih obremenitvah. Sledi modeliranje ravnalnega procesa in stabilizacijski algoritem. Na koncu preverimo model na konkretnem industrijskem primeru izdelave reber za mehanizme registratorjev.

(Ključne besede: preoblikovanje žice, ravnanje žice, lastnosti preoblikovalne, stabilizacija lastnosti)

The unstable forming properties of input material cause many problems in automated production processes. This is particularly so in mass production, where automated assembly lines are increasingly common, and product uniformity is a priority. It is a fact that the main reasons for the fluctuations in part geometries are the inconsistent mechanical properties of the input material, and production engineers are often unable to influence this. Here we investigate the possibility of stabilizing the mechanical properties of wire by using a roller straightener, which is used in every wire-processing production process. At the beginning a short outline of the steel's response during cyclic straining is given. This is followed by the modeling of the wire-straightening process and by the stabilization algorithm. Finally, the model is tested on a real industrial process – the production of leverarch mechanisms for ringbinder files.

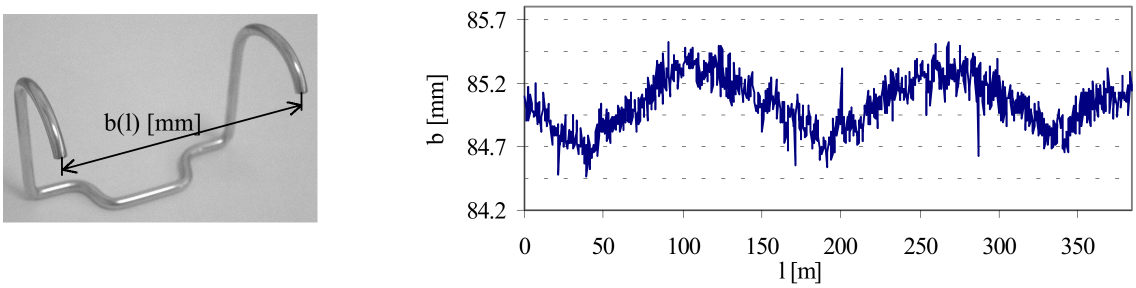
(Keywords: wire forming, wire straightening, forming properties, stability properties)

0 UVOD

Potreba po enakomernih mehansko preoblikovalnih lastnostih vhodnega materiala se zlasti kaže pri velikoserijski proizvodnji, pri kateri je potrebno zagotoviti ozka tolerančna polja geometrijskih značilnosti polizdelkov[1]. Dejstvo je, da dejansko jekla z absolutno enakomernimi mehanskimi lastnostmi ni. Vselej so v njem zaradi krajevno različne mikrostrukture, ki je posledica predhodnih tehnoloških postopkov obdelave jekla, opazne neenakomernosti, ki se preslikajo v geometrijska odstopanja izdelkov. Industrijski primer neenakomerne geometrijske oblike izdelka je prikazan na sliki 1. Širina izdelanega rebra se s časom spreminja, kljub temu, da parametri procesa ostajajo ves čas nespremenjeni.

0 INTRODUCTION

The need for wire with stable mechanical properties is especially important during mass production, where it is necessary to keep the geometrical features of products within narrow tolerance fields [1]. The problem is, however, that it is not possible to obtain steel that has absolutely homogenous mechanical properties. Due to local differences in the microstructure, which is a consequence of previous technological operations, there are always some inhomogenities in mechanical properties, which affect the final geometry. An industrial example of part-geometry fluctuation is presented in Figure 1. The width of the product is time dependent even though the process parameters remain constant.



Sl. 1. *Neenakomernost geometrijske oblike izdelka*
Fig. 1. *Fluctuation of the product geometry*

Vzrok časovnemu spreminjanju geometrijske oblike je potrebno iskati tudi v neenakomernih mehanskih in geometrijskih lastnostih surove žice. Zagotavljanje enakomernih lastnosti jekla že sega na metalurško področje in se z njim v prispevku ne bomo ukvarjali. Bolj kot definiranje vzroka nastanka prikazane neenakomernosti geometrijske oblike izdelka je pomembna rešitev, s katero bi kljub opaznim neenakomernim lastnostim žice stabilizirali krivilni postopek. Reševanje tega problema in smernice za stabilizacijo so tema nadaljnje razprave v prispevku.

1 PREOBLIKOVALNE LASTNOSTI ŽICE

Pri raziskavi je bil najprej narejen preskus, s katerim smo potrdili prevladujoč vpliv preoblikovalnih značilnosti žice na končno geometrijsko obliko izdelka. Prav tako smo iskali odvisnost med spreminjanjem geometrijskih parametrov žice ter končno geometrijsko obliko izdelka.

V ta namen je bila izdelana simulacija ravnalnega postopka z uporabo spremenjenega Pragerjevega modela utrjevanja materiala, ki je bila namenjena inverznemu načinu razpoznavanja meje plastičnosti žice. Hkrati s tem je bilo treba konstruirati tudi preskusno ravnalno napravo, ki omogoča meritve prečnih sil, ki delujejo na ravnalno kolo, ter preprosto nastavljanje položajev ravnalnih valjev. Prav tako je preskusna ravnalna priprava rabila sprotnemu merjenju ovalnosti žice, za katero smo prav tako sumili, da lahko vpliva na geometrijske značilnosti izdelka. Izkazalo se je, da ovalnost žice nima bistvenega vpliva na geometrijsko obliko. Na sliki 2 so prikazane povečane vrednosti meritve premera žice v ravnini *x* in *y* ter povečana vrednost širine izdelanega rebra.

Korelacijski koeficient med meritvijo premera v ravnini *x* ter širino rebra je 0,65, med meritvijo širine v ravnini *y* ter meritvijo geometrijske oblike pa 0,57. Glede na to, da je korelacijski koeficient med geometrijsko obliko in mejo plastičnosti 0,75 (sl. 3), lahko sklepamo na glavni vpliv meje plastičnosti žice na končno geometrijsko obliko izdelka.

Prav tako pokaže teoretičen izračun, da ima spreminjanje prečnega prereza žice v primerjavi s

It is inevitable that the reason for the unstable geometry is to be found in the non-stable mechanical properties of the incoming wire. Keeping the microstructure of the steel homogeneous is the domain of the metallurgist and will not be considered in this paper. The solution of how to stabilize the forming process, in spite of the fluctuation of in the material's properties, is much more important than finding the reason for the fluctuation of the mechanical properties. This paper discusses the solution to the problem and gives directives for stabilising the process.

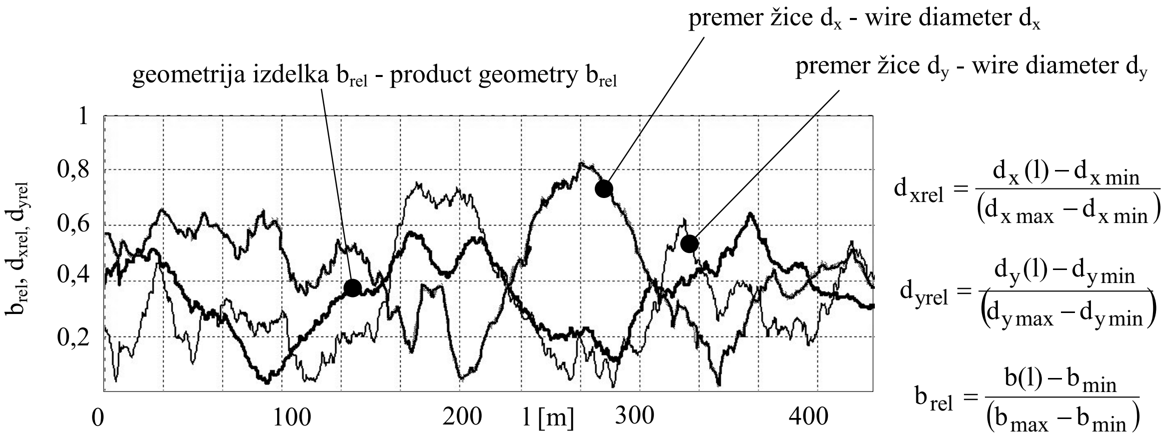
1 FORMING PROPERTIES OF WIRE

First, a test was made to confirm the major influence of the mechanical properties on the geometry of the product. The correlation between the fluctuation in the wire's geometry and the geometry of the finished part were checked as well.

A simulation of the straightening process was made, and a modification of Prager's flow rule was used. It serves for the inverse approach to the identification of the wire's flow stress. Parallel to this an experimental wire straightener was designed in such a way that it was possible to measure the transverse roller forces and to preset the rollers simple way. The experimental straightener also serves for measuring the wire diameter. We also suspected that the wire diameter has an influence on the final product geometry. It was shown that the fluctuation in the wire's diameter has no influence on the final geometry of the part. The scaled value of the measurements of wire's diameter in the xz and yz planes are shown in Figure 2, together with the scaled values of the part's width.

The correlation between the part geometry and the wire diameter in the x direction is 0.65, while between the diameter in the y direction and the part's geometry it is only 0.57. The correlation between the flow stress and the part's geometry is 0.75, which implies a major influence of the flow stress.

A theoretical calculation shows that the influence of the wire's diameter on the transverse roller forces can be neglected. From which it can be



Sl. 2. *Odvisnost med geometrijsko obliko izdelka in premerom žice*
Fig. 2. *Correlation between the product geometry and the wire's diameter*

spremembo meje plastičnosti zanemarljiv vpliv na velikost prečnih sil na ravnalne valje. S tem lahko sklepamo, da je sprememba prečne sile povezana izključno s spremembo meje plastičnosti žice.

Na sliki 3 je prikazana meja plastičnosti žice v odvisnosti od lege žice v kolutu [2], kjer je lepo razvidna soodvisnost med geometrijsko obliko izdelka ter mejo plastičnosti žice. Sklepamo lahko, da imajo preoblikovalne lastnosti žice bistven vpliv na nadaljnji krivilni postopek, vplivajo pa tudi na premer žice. Spreminjanje premera žice nima bistvenega vpliva na krivilni postopek, saj so odstopanja premajhna.

1.1 Osnovna zamisel stabilizacijskega algoritma

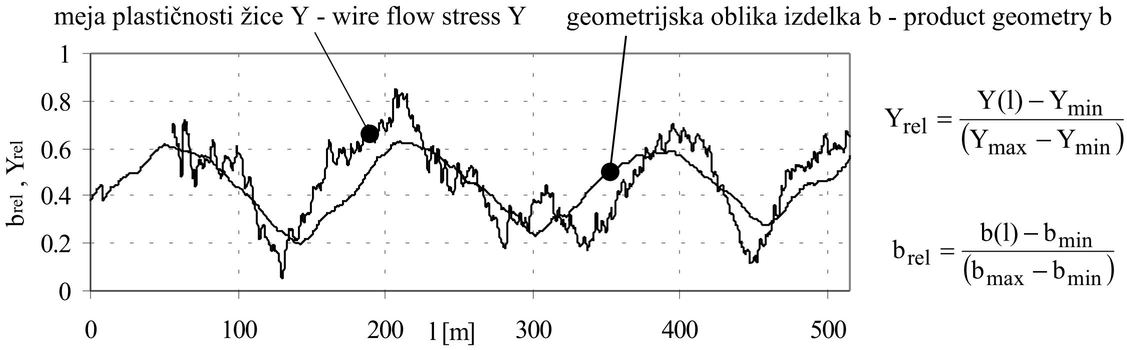
Osnovna zamisel je v tem, da bi z ravnalnim postopkom, pri katerem se material obremenjuje izmenično v nateznem in tlačnem področju, vplivali na mejo plastičnosti na izstopu iz ravnalke. Osnova razmišljanju je eksperimentalno potrjeno dejstvo [2], da je meja plastičnosti žice odvisna od velikosti povečanja plastične deformacije, bodisi v nateznem ali tlačnem področju. Za dosego zastavljenega cilja je najprej treba imeti dober model ravnalnega postopka, zato si bomo najprej ogledali njegovo modeliranje.

concluded that the variation in the transverse roller forces is only a consequence of the fluctuation in the flow stress.

The time dependence of the wire's flow stress [2] is presented in figure 3. The correlation between the wire's flow stress and the product geometry is clear. It can be concluded that the forming properties of wire have a major impact on the subsequent bending process, as wel as having an influence on the wire's diameter. The fluctuation in the wire's diameter has no significant influence on the bending process, since it is too small.

1.1 The main idea of the stabilization algorithm

The main idea is to use the straightening process, where the material is exposed to cyclical deformation in the tensile and compressive regions, to influence the wire's yield stress at the end of the straightening process. The basis for this is an experimentally verified fact [2]: that the yield stress depends on the total amount of cyclical deformation in the tensile or compressive region. To achieve this we have first to have a good model of the straightening process, so the modeling will be presented first.



Sl. 3. *Odvisnost med geometrijsko obliko izdelka in mejo plastičnosti žice*
Fig. 3. *Correlation between the product geometry and wire's yield stress*

2 MODELIRANJE RAVNALNEGA POSTOPKA

Pred nadaljnjo obdelavo žice na žično krivilnem avtomatu je le to treba izravnati v ravnalnih napravah ([3] in [4]). Glede na tip preoblikovalnega postopka, ki sledi, poznamo več vrst ravnalnih naprav, ki jih delimo predvsem po kontinuirnem ali prekinjanem načinu dela. V našem primeru se bomo omejili le na prekinjane ravnalne naprave, ki se uporabljajo pri izdelavi loka spenjanja prikazanega na sliki 1.

Najprej je treba uspešno modelirati ravnalni postopek, ki bo dovolj hiter, da ga bomo kasneje lahko uporabili v algoritmu za stabilizacijo preoblikovalnih lastnosti žice. Prav zaradi tega smo se deloma umaknili iz povsem numeričnega postopka v analitično numerični popis dogajanja, ki omogoča hitrejše računanje.

2.1 Reološki model

Reološki model preoblikovanja materiala, ki ga bomo uporabili v računskem modelu, je bistven za natančno modeliranje. Bistveno pri ravnanju žice je, da material izmenoma obremenjujemo v plastičnem področju, s čimer dosežemo na koncu čim večjo ravnost žice. Obnašanje jekla pri takšni deformaciji je opisano z diagramom napetost - deformacija pri izmenični obremenitvi ([5] do [7]), ki jo je treba definirati s preizkusi. Malooglj ična poprej hladno deformirana jekla, kakršna žica tudi je, izkazujejo pri tovrstni obremenitvi Bauschingerjev pojav [8], ki pomeni nižanje meje plastičnosti pri spremembi smeri obremenjevanja. Natančna simulacija ravnalnega postopka zaradi tega zahteva poznavanje obnašanja jekla pri izmenični obremenitvi. To pomeni poznavanje diagrama $\sigma-\varepsilon$ (sl. 4), ki pa ga je za primer žice z debelino 4 mm eksperimentalno težko definirati.

Ena od možnosti je obrnjen postopek prek modeliranja upogibnega preizkusa, v našem primeru pa smo se odločili za poenostavitev in v Pragerjeve enačbe [9] za popis zveze med napetostjo in

2 MODELING OF THE STRAIGHTENING PROCESS

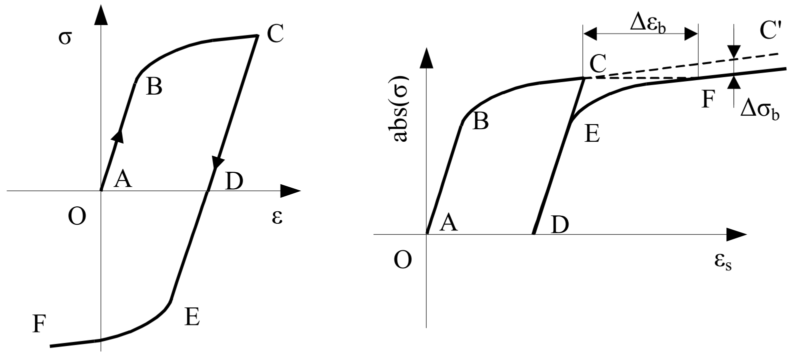
Prior to any further wire processing on the bending machinery it is necessary to straighten the wire in wire straighteners ([3] and [4]). Depending on the type of process that follows the straightening, many different types of straighteners can be applied. They can basically be divided into continuous and non-continuous types. We will confine ourselves to discontinuous wire straighteners, which are used in the production of the arch presented in Figure 1.

First, it is necessary to develop a numerical model of the wire straightener that will be fast enough to calculate the required repositionings of the rollers mounted in the straightener. This was the reason for using an analytical numerical approach rather than a purely numerical simulation of the straightening process.

2.1 Constitutive model

A constitutive model of the material that will be used in the model is essential for accurate modeling. The core of the straightening process is a cyclic, plastic deformation of the wire, which results in the final straightness of the wire. The material response for such deformations is characterized by the $\sigma-\varepsilon$ diagram during cyclic deformation ([5] to [7]), which has to be defined during the experimental testing. Low-carbon cold-drawn steels exhibit the Bauschinger phenomena when they are cyclically deformed into the plastic region. This means lowering the yield stress when the material is deformed in the opposite direction. A reliable simulation of the straightening process, therefore, requires a knowledge of the material's response during cyclical deformation. When presenting this in one dimension it is necessary to know the parameters of the diagram presented in Fig.4. In the case of wire with a diameter of 4 mm it is not a simple task to define this diagram.

One possibility is an inverse approach, by modeling the bending test. In our case we chose a simplification, therefore an extended form of Prager's [9] equation was used to describe the material's



Sl. 4. *Shematski prikaz Bauschingerjevega pojava [8]*
Fig. 4. *Schematic representation of the Bauschinger phenomena*

deformacijo vnesli še dodaten koeficient D_{cyc}, s katerim je dana možnost spreminjanja meje plastičnosti žice iz enega nihaja v drugega.

Diferencialne enačbe Pragerjevega modela so:

behavior during straightening. In order to capture the softening of the material, an additional term D_{cyc} was added to allow for it.

The differential equations of Prager's model are:

$$C = \left[(1+K) \cdot \sigma - E \cdot K \cdot \varepsilon \right] \tag{1}$$

$$d\sigma = E \cdot d\varepsilon \qquad C \geq 0 \tag{2}$$

$$d\sigma = E \cdot \left[1 - \frac{1}{Y^{2n} \cdot (1+K)^{3n}} \cdot \left[(1+K) \cdot \sigma - E \cdot K \cdot \varepsilon \right]^{2n} \right] \cdot d\varepsilon \qquad C \leq 0 \tag{3}$$

$$Y_i = Y_0 \cdot D_{cyc.}^{\,i-1} \tag{4.}$$

Pri tem so:

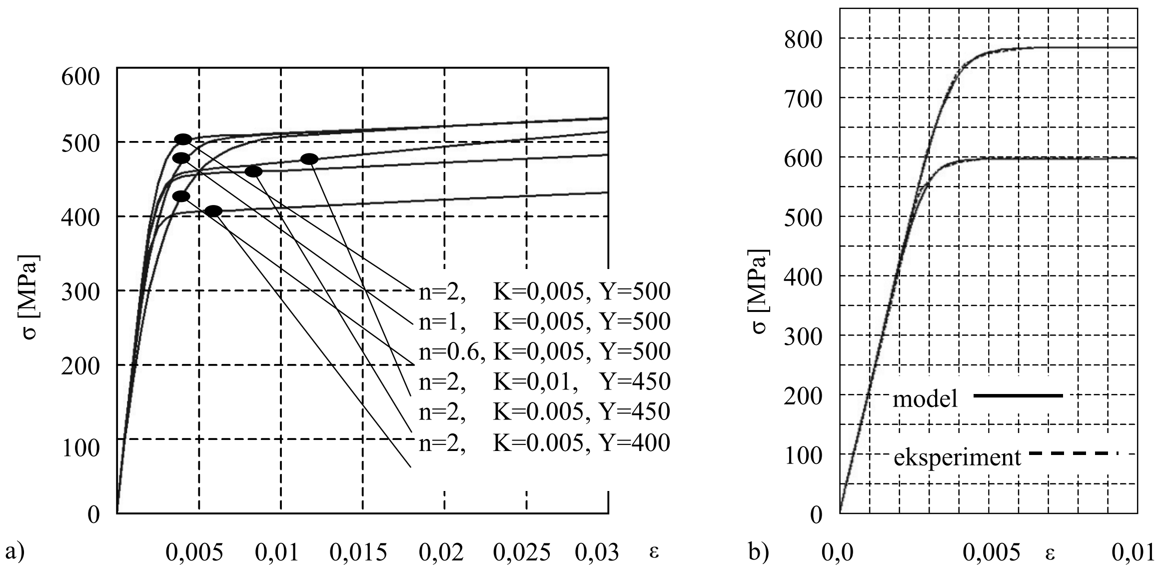
E - modul elastičnosti (MPa)
Y - meja plastičnosti v i-tem ciklu (MPa)
σ - napetost (MPa)
ε - deformacija
n - faktor prehoda
K - limita strmine v plastičnem področju (MPa)

Vzrok, da smo se odločili prav za Pragerjev model zveze med napetostjo in deformacijo žice, je v tem, da ob pravilni izbiri parametrov n in K izredno dobro popiše obnašanje materiala med enoosnim nateznim preizkusom. Glede na to, da je plastična deformacija žice v ravnalni napravi za področje preoblikovanja izredno majhna (< 1%), je za pravilno modeliranje ravnalnega postopka pomemben prav prehod iz elastičnega v plastično področje. Navadno pri obravnavanju postopkov preoblikovanja upoštevamo Hookov zakon v elastičnem področju ter funkcijsko odvisnost meje plastičnosti od primerjalne plastične deformacije v plastičnem področju. Takšen popis pa predstavlja v področju prehoda iz elastičnega v plastično področje lomljeno krivuljo, ki ni primerna za popis zveze med napetostjo in deformacijo pri modeliranju preoblikovalnih postopkov, kakršen je ravnanje žice.

Where:

E - Young's modulus (MPa)
Y - yield stress in the i-th cycle (MPa)
σ - stress (MPa)
ε - deformation
n - transition factor
K - plastic slope limit (MPa)

The reason why Prager's model was used for the description of relationship between the stress and the deformation is that when appropriate values of the parameters n and K are chosen, a tensile-test experiment can be modeled very accurately. Since the material deformation during roller straightening is very low (< 1%), the transition region from the elastic to the plastic stress state is very important for accurate modeling. Normally, when forming processes are modeled we use Hooke's law in the elastic region and a certain functional relationship between the equivalent plastic deformations and the yield stress in the plastic region. Such a description results in a transition field with a non-smooth curve that is not appropriate for modeling the stress-strain relationship for processes such as wire straightening in the roller straighteners.



Sl. 5. *Pragerjev reološki model a) in primerjava s preizkusi b)*
Fig. 5. *Prager's flow rule a) and a comparison with the experiments b)*

Primerjava diagrama $\sigma-\varepsilon$, dobljenega z enoosnim nateznim preizkusom ter modeliranega diagrama s Pragerjevim modelom je prikazana na sliki 5. Prikazan je tudi vpliv parametrov n in K na obliko krivulje prehoda iz elastičnega v plastično področje.

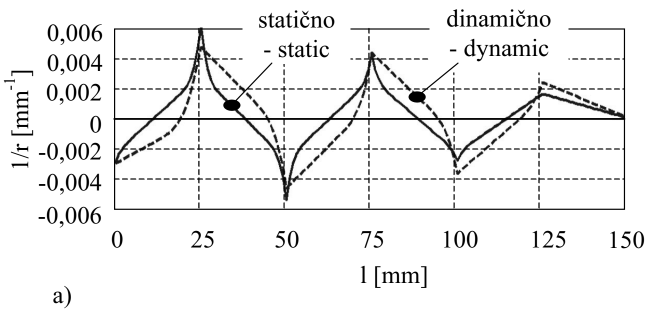
A uniaxial tensile test diagram is compared with the one modeled by Prager's flow ruler in Fig.5. The influence of the parameters n and K on the form of the elastic-plastic transition curve is presented as well.

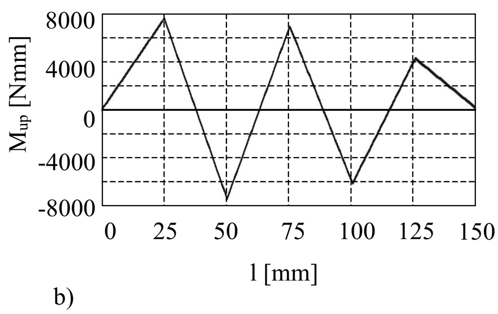
2.2 Upogibni moment - ukrivljenost

2.2 Bending moment – curvature

Naslednji korak pri modeliranju ravnalnega postopka je pravilen popis zveze med ukrivljenostjo žice vzdolž ravnalne naprave ter upogibnim momentom [10], ki deluje na žico. V praksi se lege ravnalnih valjev nastavijo tako, da začetni valji deformirajo žico približno na dvakratno vrednost ukrivljenosti v kolutu, toda v nasprotni smeri. Nato pa se ukrivljenost postopoma zmanjša do teoretične vrednosti nič na izhodu iz ravnalne naprave. Izhajamo torej iz diagrama, ki popisuje vrednosti ukrivljenosti žice na posameznem ravnalnem valju (sl. 6) in je dobljen na podlagi izkušenj.

The next step in the numerical simulation of the wire straightener is the definition of the connection between the wire curvatures and the bending moment acting on the wire along the straightener [10]. Initially the wire straightener is preseted to the know-how values so that the wire is initially deformed to double the initial curvature in the opposite direction. Normally, the curvature fades out towards the end of the straightener. The diagram describing the wire curvature (Fig.6) is therefore the basis for further calculations. It is based on the experiences of the company personnel.





Sl. 6. *Ukrivljenost žice a) ter upogibni moment b) vzdolž ravnalke*
Fig. 6. *Wire curvature a) and bending moment b) along the straightener*

Upogibni moment, s katerim je treba delovati na delček žice, če hočemo, da bo njegova ukrivljenost enaka k_i, je definiran z integralom zmnožka med napetostjo in ročico po prerezu žice (en. 5):

In order to obtain curvature k_i a certain bending moment has to be applied in the cross-section of the wire. It is defined by the numerical integration of the normal stress multiplied by the distance from the neutral plane over the cross-section of the wire (Eq.5).

$$M_i = 4\cdot \int_0^{d_0/2} \sigma\left(k_i y\right)\sqrt{d_0^2/4-y^2}\, y\, dy \qquad (5),$$

kjer je k_i ukrivljenost žice v legi, ko se le ta dotika i-tega ravnalnega valja, $\sigma(k_i, y)$ pa je dobljena z uporabo diferencialnih enačb Pragerjevega modela. Upogibni moment na prvem ravnalnem valju je enak nič, saj se na njem deformacija žice še ne pojavi. Dejstvo je, da ravnalni valji delujejo na žico le v določenih singularnih točkah, zato je porazdelitev upogibnega momenta vzdolž ravnalne naprave lahko samo linearna. Izračunamo jo s pomočjo definiranih točk (en.5) na način:

where k_i represents the wire curvature when interacting with the i-th roller, $\sigma(k_i, y)$ represents the material data obtained by Prager's flow rule. The bending moment on the first roller is zero, since no deformation occurs there. Since the rollers are acting on the wire only at singular points the distribution of the bending moment from one roller to another is linear. This means that it is possible to calculate the bending moment distribution on the wire traveling through the roller straightener (Eq.5):

$$M\left(x\right) = M\left(x_i\right) + \frac{M\left(x_{i+1}\right) - M\left(x_i\right)}{x - x_i} \qquad x_i \le x \le x_i + 1 \qquad (6).$$

Kljub temu, da je porazdelitev upogibnega momenta vzdolž ravnalne naprave linearna, pa porazdelitev ukrivljenosti ni odsekoma linearna

As the moment is linearly distributed over the length of the roller straightener the wire curvature is not. Wire is locally subjected to a small amount of funkcija, čemur botruje dejstvo, da je žica deformirana v plastično področje. Ukrivljenost je določena z enačbo (7), le da ne iščemo upogibnega momenta, temveč ukrivljenost, katere rezultat je želen upogibni moment.

plastic deformation, which causes a nonlinear distribution in the curvature along the wire straightener. It is defined by Eq.7, where the curvature at which the desired bending moments occur is looked for.

$$M(x) = 4\int_0^{d_0/2} \sigma\left(k(x)y\right)\sqrt{d_0^2/4 - y^2}\, y\, dy \quad k(x) = U\left(M(x)\right) \qquad (7).$$

Poleg zveze med napetostjo in deformacijo je ukrivljenost žice odvisna še od tega, ali le ta v ravnalki miruje ali pa se giblje. Ker je ravnalni postopek dinamičen, bomo obravnavali le primer, pri katerem se žica vzdolž ravnalne naprave giblje. Primer upogibnega momenta in ukrivljenosti žice je za žico z debelino 4 mm podan na sliki 6. Številčne vrednosti ukrivljenosti in upogibnega momenta pa so prikazane v preglednici 1.

Apart from the stress–strain relationship, the wire curvature depends on whether it is traveling through the straightener or it is stopped within the straightener. Since the straightening process is dynamic, it will be focused only on the case where the wire is moving through the straightener. An example of the bending moment and the curvature for a wire with 4-mm diameter is represented in Fig.6. The values are listed in Table 1.

Preglednica 1. *Številčne vrednosti momenta in ukrivljenosti*
Table 1. *Bending moment and wire curvature*

valj / roller	1	2	3	4	5	6	7
ukrivljenost v mm^{-1} curvature [mm^{-1}]	-0,0025	0,0048	-0,0045	0,0034	-0,0031	0,0030	0,00
upogibni moment v Nmm bending moment [Nmm]	0	8397	-7950	7679	-6837	6311	0

Izračunane vrednosti upogibnega momenta in ukrivljenosti uporabljamo za izračun položaja ravnalnih valjev in s tem poti žice skozi ravnalno napravo ter velikosti prečnih sil, ki delujejo na žico v ravnalki. Definicija lege žice v ravnalki temelji na numerični integraciji izraza za ukrivljenost vzdolž ravnalne naprave, definicija prečnih sil pa izhaja iz porazdelitev upogibnega momenta.

Based on the calculated values for the bending moment and the wire curvature, it is possible to define the roller position of the wire straightener and the roller force acting on each roller. The definition of the position is based on the numerical integration of the wire curvature term along the straightener axis. Roller forces are based on the bending moment distribution.

2.3 Numerična integracija ukrivljenosti

2.3 Numerical integration of the curvature

Ukrivljenost žice je dobljena z enačbami (5) do (7) in je osnova za nadaljnji preračun. Ker je odvisnost ukrivljenosti le odsekoma gladka krivulja, analitičen postopek integracije praktično ni mogoč. Zato je potrebno uporabiti numerično intergacijo izraza za ukrivljenost žice vzdolž ravnalne naprave.

V splošnem je matematični izraz za ukrivljenost definiran z enačbo:

The presented equations (5-7) describe the technique for obtaining wire curvature, which is the basis for the calculation of the roller positions within the wire straightener. The function describing the wire's curvature is smooth only in the interval between two adjacent rollers. This is the reason why it is not possible to integrate the wire's curvature analytically. Thus it is necessary to use numerical integration of the curvature term along the straightener.

In general the curvature of a mathematical function is expressed by the following term:

$$k(x) = \frac{\dfrac{\partial^2 y}{\partial x^2}}{\sqrt{\left[1+\left(\dfrac{\partial y}{\partial x}\right)^2\right]^3}} = \frac{1}{r(x)} \qquad (8),$$

kjer sta:
$k(x)$ - ukrivljenost žice
$r(x)$ - polmer ukrivljenosti

Izraz (8) je nelinerana diferencialna enačba drugega reda, ki jo je mogoče na podlagi dejanskih

where:
$k(x)$ - wire curvature
$r(x)$ - bending radius

This is a second-order nonlinear differential equation, which can be simplified based on special geometrijskih značilnosti še nekoliko poenostaviti. Ker je prvi odvod funkcije (poti žice skozi ravnalko) praktično enak nič, ga lahko zanemarimo, s čimer se izraz za ukrivljenost poenostavi v:

geometrical characteristics. Since the first derivative of the function is small, it can be neglected, which means that the mathematical curvature term can be simplified:

$$k(x)=\frac{\partial^2 y}{\partial x^2} \quad (9).$$

Napaka, ki jo naredimo pri neupoštevanju prvega odvoda funkcije, je za primer izravnavanja žice z debelino 4 mm manjša od 1 odstotka, kar je zanemarljivo in torej lahko za nadaljnji preračun uporabimo kar enačbo (9). Dvojna integracija vzdolž ravnalke da iskano lego, ob tem pa moramo upoštevati dve konstanti, ki se pojavita ob vsakokratnem integriranju in določata lego žice na prvem in zadnjem ravnalnem valju.

Dejansko se v praksi nastavlja lega ravnalnih valjev in ne ukrivljenost. Ta je le posledica lege, poleg tega pa so ravnalke navadno nastavljene tako, da so valji, nameščeni na eni strani, pritrjeni, na drugi pa jih je mogoče premikati. Pravilna rešitev integracije je torej tista, ki da pot žice takšno, da se le ta dotika ravnalnih koles. Zato je na tem mestu potreben iterativen postopek točnega določanja začetne ukrivljenosti žice na posameznih ravnalnih valjih. Nekaj možnosti poti žice skozi ravnalko je prikazanih na sliki 7.

A numerical error that originates from the neglecting of first derivative is calculated for the wire of 4 mm, and represents less than 1%, which can be neglected. For the further calculation, Eq.9 can be used instead. Double integration along the straightener axis gives the results, but it is necessary to consider both constants from the integration. They define the position of the wire on the first and last roller.

In pratice the position of the rollers is changed. The wire's curvature change is only a consequence of changing the roller positions. Apart from this, the position of the four upper rollers normally stays constant, but it is possible to change the positions of the rollers on the opposite side. A correct solution of the numerical integration is the one where the wire exactly touches the rollers. Therefore, an iterative approach is necessary to define accurate initial curvatures of the wire on each roller. Some possibilities are presented in Fig.7.

2.4 Prečne sile na ravnalne valje

Prečne sile na ravnalne valje uporabljamo za inverzen izračun trenutne meje plastičnosti žice, kar je temelj za stabilizacijski algoritem. Njihov izračun sloni na momentnem ravnotežju sil, ki delujejo v sistemu žica - ravnalni valji. Postopek izračuna je shematično prikazana na sliki.8.

2.4 Transverse roller forces

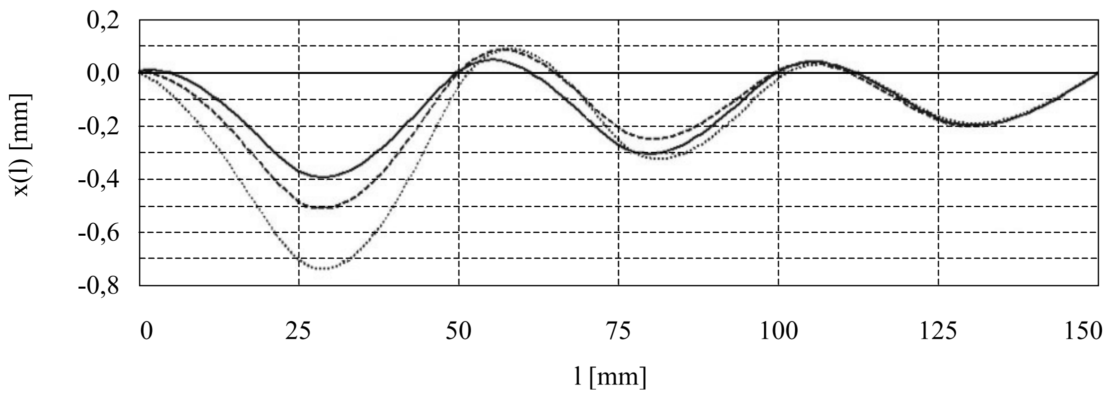
The transverse roller forces are needed for the inverse calculation of the current yield stress of the wire, which is the basis for the stabilization algorithm. The calculation is based on the moment equilibrium in the system of wire and straightening rollers. The procedure is schematically represented in Fig.8.

2.5 Eksperimentalno testiranje simulacije

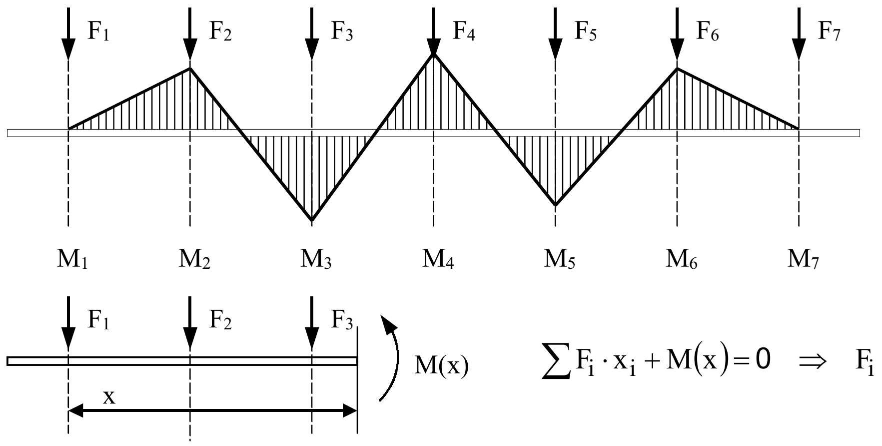
Predstavljen numerični model ravnalnega postopka je bil testiran na žici, na kateri smo poznali napetost tečenja. Izmerjene in izračunane vrednosti

2.5 Experimental testing of the simulation

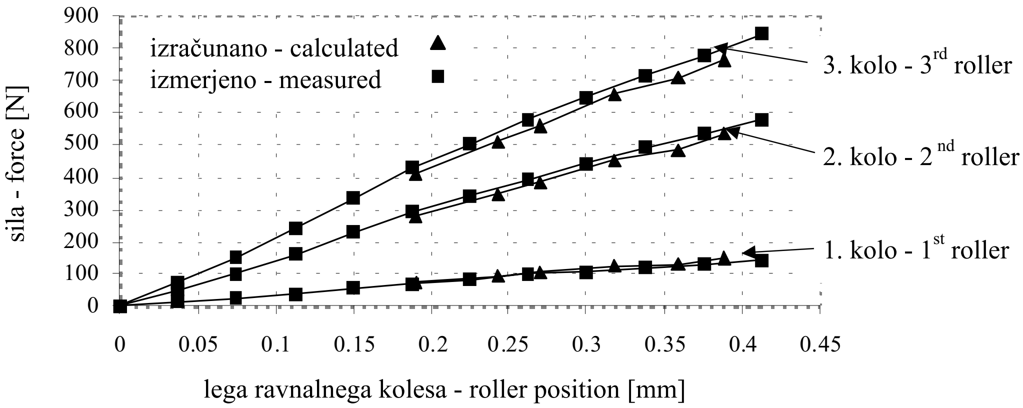
The numerical model of the wire straightener was tested on a wire with known yield stress. The measured and calculated values for the roller forces were practically the same (Fig.9). This means that the



Sl. 7. *Različne izračunane poti žice skozi ravnalko*
Fig. 8. *Different calculated wire paths through the straightener*



Sl. 8. *Izračun prečnih sil na ravnalne valje*
Fig. 8. *Calculation of the transverse roller forces*



Sl. 9. *Eksperimentalno testiranje simulacije ravnanja [11]*
Fig. 9. *Experimental verification of the straightening simulation [11]*

Preglednica 2. *Simulacija ravnalnega postopka*
Table 2. *Simulation of the straightening process*

številka ravnalnega valja / roller no.	1	2	3	4	5	6	7
položaj / roller setting [mm]	0	-0,69	-0,05	-0,25	-0,02	-0,17	0
prečna sila na valj / transverse roller force [N]	325	940	1230	1200	1130	805	255

sil, ki delujejo na ravnalno kolo so bile praktično enake (sl. 9). To pomeni, da je model dovolj natančen in da ga lahko uporabimo v obrnjeni metodi določanja trenutne meje plastičnosti žice.

Rezultati simulacije so lege ravnalnih koles ter prečne sile na ravnalne valje in so za primer žice s premerom 4 mm prikazani v preglednici 2.

3 STABILIZACIJSKI ALGORITEM

Prikazan numerični model ravnalnega postopka je jedro algoritma za stabilizacijo meje plastičnosti žice. Poleg tega pa je pred samo vpeljavo sistema treba izpolniti še nekatere robne pogoje.

Obnašanje žice pri izmenični deformaciji je najbolj pomemben parameter, ki dejansko pove, ali je z ravnalnim postopkom mogoče stabilizirati mejo

developed numerical model is accurate enough and can therefore be used as an inverse method for the characterization of the flow properties of the wire passing through the roller straightener.

The result of the simulation is the roller position and the roller forces. For the wire with a diameter of 4 mm they are presented in Table 2.

3 STABILIZATION ALGORITHM

The above-presented numerical model of the wire-straightening process serves as the basis for the stabilization of the yield stress of the wire. Certainly, there are some preconditions, which have to be fulfilled in order that the flow stress stabilization can be carried out.

The wire's behavior under cyclic deformation is the most important parameter, which tells whether it will be possible to stabilize the yield stress or not.

plastičnosti ali ne. Obnašanje dveh različnih vrst žice je prikazano na sliki 9. Diagram prikazuje mejo plastičnosti žice po ravnanju v odvisnosti od celotne plastične deformacije [11], ki smo jo za potrebe stabilizacijskega algoritma definirali z izrazom:

The behavior for two different wire types is presented in Fig.10. It presents the yield stress of the wire after being straightened with respect to the total amount of wire curvature [11], which has been for the purpose of the stabilization algorithm defined as:

$$k^{TOT} = \sum_{i=2}^{n-1} |k_i| \quad (10).$$

Izraz pomeni vsoto absolutnih vrednosti ukrivljenosti žice na posameznem ravnalnem valju in je mera za velikost izmenične plastične deformacije.

Maloogljična jekla navadno izkazujejo izmenično mehčanje (krivulja B na sl. 10). To pa je odvisno od velikosti prirasta plastične deformacije. Če je le ta večji, se material lahko zopet utrjuje (krivulja A na sl.10). Sprememba meje plastičnosti je torej odvisna od materiala in prirasta plastične deformacije. Za primer jekla B na sl.10 je mogoče z nadzorom velikosti prirasta plastične deformacije (nastavitve ravnalnih koles) uspešno izvesti stabilizacijo meje plastičnosti.

Glavna zamisel stabilizacije je v tem, da z numeričnim modelom ravnanja, predstavljenega v prejšnjem razdelku, definiramo mejo plastičnosti žice, ki je trenutno v ravnalki. Na podlagi eksperimentalnih podatkov s slike 10 se nato izračunajo potrebne popravke nastavitev ravnalnih koles. Posledica tega je izpostavitev žice drugačnim izmeničnim deformacijam, kar povzroči tudi drugačno vrednost meje plastičnosti po ravnanju. Dejstvo je, da se meja plastičnosti žice ne spreminja v dolžini, manjši od dolžine ravnalne naprave. Z meritvami je bilo ugotovljeno, da je frekvenca spreminjanja meje plastičnosti približno 8 do 10 min, kar pomeni približno 180 m žice (sl. 11).

It represents the sum of the absolute values of the wire's curvature on a single straightener roller and it is a measure of the total cyclic plastic deformation.

Low-carbon cold-drawn wire materials normally exhibit cyclic softening (curve B in Figure 10). This depends on the plastic increment. If the plastic increment is higher, it is possible that the material will harden again (curve A in Figure 10). The change of the flow stress depends on the material and on the increment of the plastic deformation. In the case of material B from Fig.9 it is possible that the mechanical properties of the wire are stabilised by controlling the plastic increment, which comes from controlling the positions of the straightening rollers in the roller straightener.

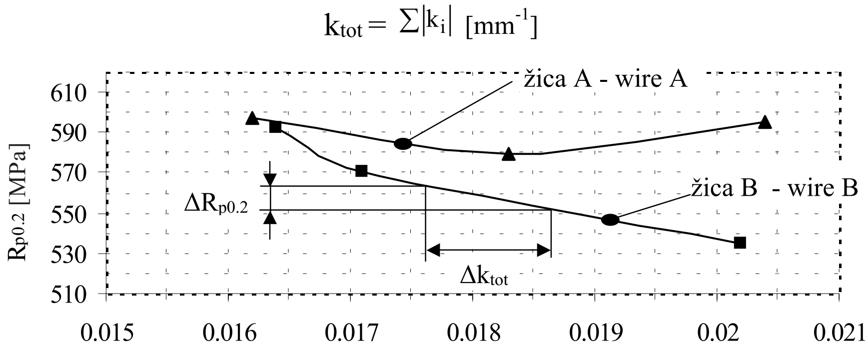
The basic idea of the stabilization is that by using a numerical model of the wire straightener, described in the previous paragraph, the wire's yield stress passing the roller straightener is calculated. By combining the data from Figure 10, the necessary adjustments of the wire's curvature are calculated afterwards. This means that the wire is exposed to different amounts of cyclic deformation, which means a different yield stress of the wire after straightening. The yield stress of wire does not fluctuate over short time periods. It was confirmed from measurements that the cycle time of the flow-stress fluctuation is 8–10 min, which means approximately 180 m, as shown in Fig. 11.

3.1 Postopek stabilizacije

Ravnalna naprava stalno meri sile na ravnalna kolesa. Z numerično simulacijo smo sile na ravnalna kolesa izrazili kot neko funkcijo, ki je odvisna od več parametrov postopka (meja plastičnosti, premer žice, lege koles itn.). Ob predpostavki, da se spreminja samo meja plastičnosti, lahko zapišemo:

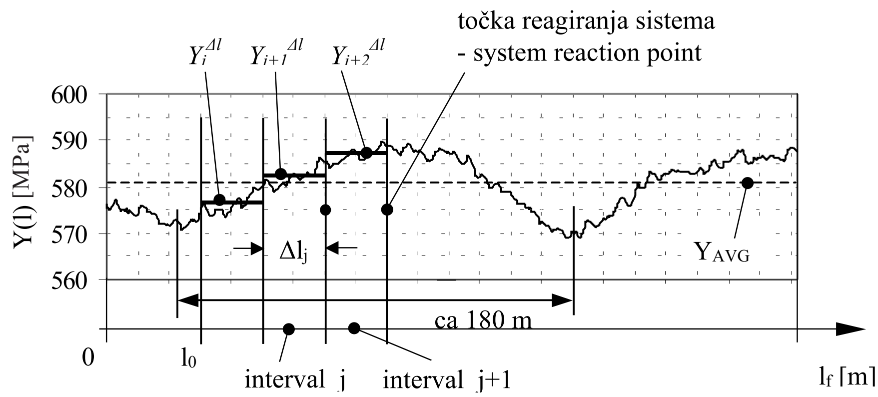
3.1 Stabilization procedure

The roller forces are constantly measured by the roller straightener. Using a numerical simulation the roller forces were expressed as a function that is dependent on material and process parameters (yield stress, wire diameter, roller positions, etc.). If only the yield stress fluctuates, the equation can be expressed as:



Sl. 10. *Meja plastičnosti za žici dveh različnih proizvajalcev v odvisnosti od* k^{TOT}

Fig. 10. *Yield stress of the wire, from two different suppliers, depending on* k^{TOT}



Sl. 11. *Spreminjanje meje plastičnosti ter prikaz točk, kjer ukrepamo [11]*
Fig. 11. *Fluctuation of the flow stress of the wire and the reaction points [11]*

$$F_i = f(Y(l)) \tag{11}$$

Enačba inverznega postopka pa je na podlagi en. (11) naslednja:

Based on Eq.11, the inverse is:

$$Y(l) = f^{-1}(F_i(l)) \tag{12}$$

Razlika med trenutno mejo plastičnosti in povprečno vrednostjo v določeni količini žice se izračuna kot:

The difference between the current yield stress and the average yield stress of the wire is calculated as:

$$\Delta Y_j = Y_j^{\Delta l} - Y_{AVG} = \frac{1}{\Delta l_j}\int_{\Delta l_j} Y(l)dl - \frac{1}{l_f}\int_0^{l_f} Y(l)dl \tag{13}$$

pri čemer sta:
Δl_j - opazovani korak (sl.11)
l_f - celotna dolžina žice od začetka merjenja

Potrebno popravo parametra k^{TOT} za bolj enakomerno mejo plastičnosti žice po ravnanju dobimo z uporabo diagrama na sliki 10. Potrebna poprava izhaja iz velikosti odstopanja trenutne vrednosti meje plastičnosti ΔY_j od povprečne vrednost Y_{AVG}.V obliki funkcije:

where:
Δl_j - measured interval (Fig.11)
l_f - cumulative length of the wire

In order to stabilize the yield stress in the next step, j+1, it is necessary to correct the value k^{TOT} according to the findings presented in Fig.10. The necessary correction is defined by the difference between the current value of the yield stress, ΔY_j, and the average value of the yield stress Y_{AVG}. The function is:

$$k_{j+1}^{TOT} = u^{-1}(Y_{AVG} - \Delta Y_j) \tag{14}$$

$$\Delta k^{TOT} = k_{j+1}^{TOT} - k_j^{TOT} \tag{15}$$

Novo izračunano vrednost k^{TOT} je nato treba enakomerno porazdeliti na vse ravnalne valje hkrati, in sicer tako, da izpolnimo robne pogoje (žica se mora dotikati ravnalnih valjev, pri tem pa lahko spreminjamo le lege drugega, četrtega in šestega ravnalnega valja). Prav tako ni mogoče spreminjati ukrivljenosti na vseh ravnalnih kolesih. Prvo je namreč določeno z ukrivljenostjo žice v kolutu, zadnje pa je odvisno od ravnosti žice na izstopu. Prav tako je ukrivljenost na predzadnjem ravnalnem valju odvisna od ravnosti žice na izstopu. Torej je v ravnalni napravi s sedmimi ravnalnimi kolesi (n=7) v eni ravnini mogoče poljubno spreminjati ukrivljenost na štirih ravnalnih valjih.

The new calculated value of k^{TOT} is necessary to distribute uniformly on every roller in such a way as to fulfill all the boundary conditions (the wire should touch the roller, but only the second, fourth and sixth rollers can be changed). Furthermore, it is not possible to change the curvature on all rollers. The first one, k_1, is defined by the coil curvature, and the last one should be zero. The one before the last is defined by the zero condition on the last roller as well. A seven-roller wire straightener (n=7) allows for curvature adjustments on four of the rollers. The correlations between the adjacent curvatures

Razmerja med posameznimi nastavitvami morajo ostati enaka. Referenčno vrednost predstavlja drugo ravnalno kolo, ukrivljenosti na preostalih treh pa izrazimo kot:

should remain constant. The second roller is taken for reference and the curvature on the others is expressed as:

$$k_{ij} = k_{2j} \cdot q_{2i} \qquad i = 3..(n-2) \qquad \text{j-ti korak / j-th step} \tag{16}$$

$$k_{ij+1} = k_{2j+1} \cdot q_{2i} \qquad i = 3..(n-2) \qquad \text{j+1-korak / j+1-step} \tag{17}.$$

Koeficienti q_{2i} so v ravnalnem postopku nespremenjeni in pomenijo razmerja med nastavitvijo na drugem ravnalnem kolesu in preostalimi (tremi - v primeru ravnalke s sedmimi ravnalnimi kolesi). En. (15) lahko sedaj izrazimo kot:

The coefficients q_{2i} are constants in a certain roller-straightening process and represent the ratios between the curvature on the second roller and the other three (in the case of the seven-roller straightener). Eq.15 can be expressed as:

$$\Delta k^{TOT} = k_{2j+1} \cdot \left(1 + \sum_{i=3}^{n-2} q_{2i}\right) - k_{2j} \cdot \left(1 + \sum_{i=3}^{n-2} q_{2i}\right) \tag{18}.$$

Nova ukrivljenost na drugem ravnalnem kolesu je:

The new, wire curvature on the second roller is:

$$k_{2j+1} = k_{2j} + \frac{\Delta k^{TOT}}{\left(1 + \sum_{i=3}^{n-2} q_{2i}\right)} \tag{19}.$$

Preostale tri ukrivljenosti k_{3j+1}, k_{4j+1} in k_{5j+1} določimo z enačbo (17). Nove lege ravnalnih koles so določene s postopkom, opisanim v prejšnjem poglavju o numerični simulaciji ravnalnega postopka. Odvisnost lege od ukrivljenosti lahko zapišemo z uporabo odvisnosti:

Curvatures k_{3j+1}, k_{4j+1} and k_{5j+1} are defined by Eq.17. The new positions of the straightening rollers are calculated using the numerical model of the straightener presented in the previous section. The position of the rollers can be expressed by the function:

$$x_{ij+1} = V(k_{ij+1}) \tag{20}.$$

Zveza med lego ravnalnega kolesa in skupno ukrivljenostjo žice k^{TOT} ni linearna in je za primer jekla B s slike 10 prikazana na sliki 12. Stabilizacijski algoritem za to jeklo pa lahko zaradi nižanja meje plastičnosti pri izmenični obremenitvi opišemo preprosto z naslednjimi enačbami:

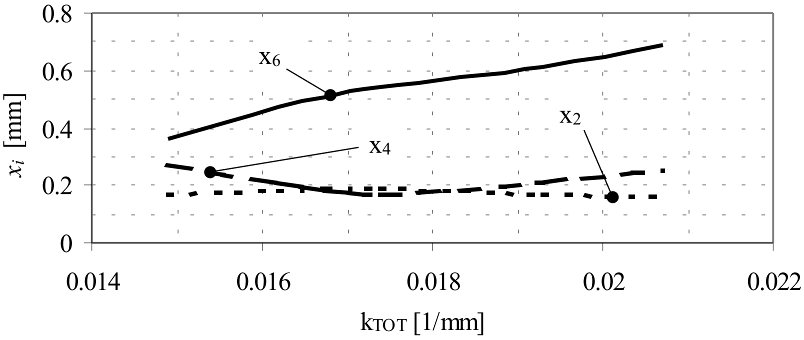
The connection between the roller position and total wire curvature, k^{TOT}, is not linear and is presented in Fig.12 (steel B from Fig.10) The stabilization algorithm for the steel B can be, due to the softening of the material during the total cyclic deformation, schematically presented by the equations:

$$\text{če/if} \quad Y_{j+1}^{\Delta l} \geq Y_j^{\Delta l} \Rightarrow k_{j+1}^{TOT} \geq k_j^{TOT} \tag{21}$$

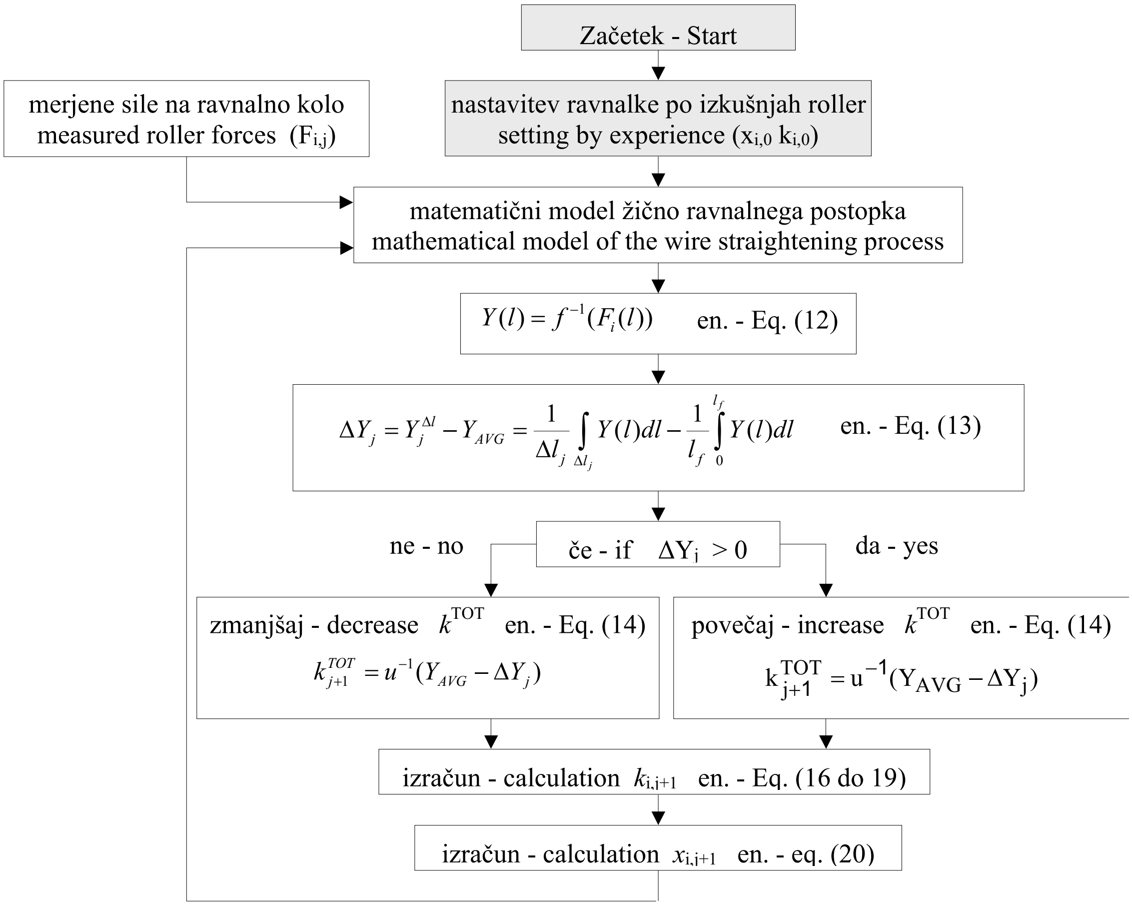
$$\text{če/if} \quad Y_{j+1}^{\Delta l} \leq Y_j^{\Delta l} \Rightarrow k_{j+1}^{TOT} \leq k_j^{TOT} \tag{22}.$$

Če je meja plastičnosti v ciklu j+1 večja kakor v ciklu j, potem je treba vrednost k^{TOT} povečati, če hočemo, da bomo dosegli nižjo mejo plastičnosti materiala.

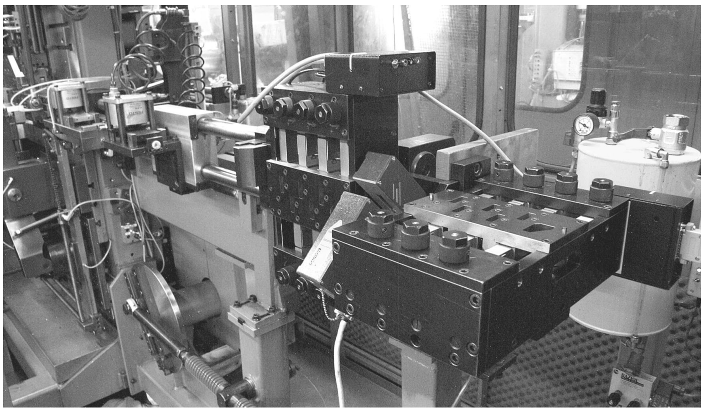
If the yield stress in the cycle j+1 is higher than in cycle j, then the value k^{TOT} should be increased to soften the material.



Sl. 12. *Zveza med lego ravnalnih koles in celotno ukrivljenostjo k^{TOT}*
Fig. 12. *The connection between the roller settings and the total curvature, k^{TOT}*



Sl. 13. *Shematičen prikaz stabilizacijskega algoritma [11]*
Fig. 13. *Schematic representation of the stabilisation procedure [11]*



Sl. 14. *Preizkusna ravnalna naprava*
Fig. 14. *Experimental wire straightener*

Celoten postopek stabilizacije je shematsko prikazan na sl.13.

3.2 Testiranje stabilizacijskega algoritma

Prikazan stabilizacijski algoritem je bil eksperimentalno preverjen na industrijskem primeru izdelave reber, sestavnih delov mehanizmov za registratorje in mape v podjetju NIKO Železniki. V skladu s predstavljenim algoritmom smo spremenili

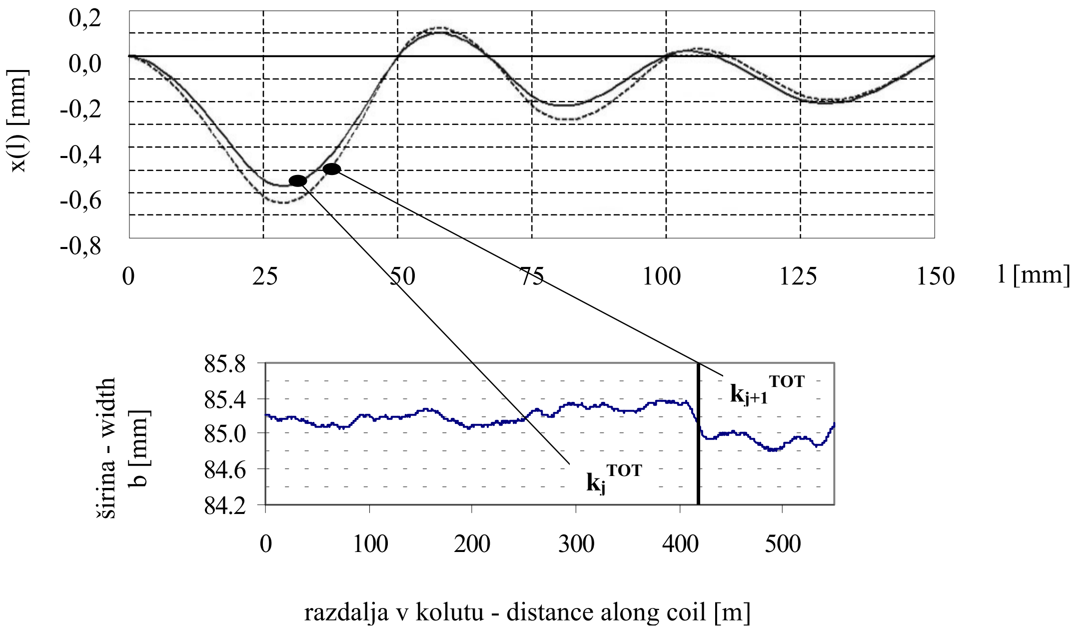
The whole stabilization procedure is schematically presented in Fig.13.

3.2 Testing of the stabilization algorithm

The presented numerical model of the stabilization algorithm was finally evaluated in the production of arches for leverarch mechanisms at a company called NIKO Železniki. According to the presented algorithm the roller positions were changed to

Preglednica 3. *Nastavitve ravnalnih koles*
Table 3. *Roller presetting*

valj št. i roller no. i	$x_{i,1}$ k_{TOT} = 0,0174 mm^{-1}	$x_{i,2}$ k_{TOT} = 0,0193 mm^{-1}	Δx_i
1,3,5,7	0 mm	0 mm	0 mm
2	0,19 mm	0,17 mm	-0,02 mm
4	0,17 mm	0,22 mm	0,05 mm
6	0,53 mm	0,61 mm	0,08 mm



Sl. 15. *Preizkusno vrednotenje predlaganega modela: a) pot žice, b) širina izdelka (slika1) pred spremembo (nastavitev j) in po (nastavitev j+1) spremembi lege ravnalnih koles*
Fig. 15. *Experimental verification of the proposed model: a) wire path, b) product width (Figure 1) before (setting j) and after (setting j+1) presettings of the rollers*

lego ravnalnih valjev za izračunane vrednosti. Posledica tega je bila spremenjena pot žice skozi ravnalko in s tem tudi spremenjena meja plastičnosti žice. V končni fazi se je spremenila geometrijska oblika rebra, kot posledica spremembe meje plastičnosti žice. Na sliki14 je prikazana preizkusna merilna oprema, nameščena na žično krivilni avtomat.

S spremembo poti žice skozi ravnalko, ob čemer je bila žica še vedno ravna, se je spremenila širina izdelka, kot glavni geometrijski parameter izdelka (sl. 15b). Spremembe lege ravnalnih koles so prikazane v preglednici 3, pot žice skozi ravnalko pred spremembmo in po njej lege valjev pa na sliki 15a).

the calculated values. This means that the wire path through the straightener was changed as well, which means a certain difference in the flow stress of the wire that is coming out of the wire straightener. Because of this difference there is a clear change in the geometrical parameters of the finished arch. The experimental set-up mounted onto the bending machine is presented in Fig.14.

By changing the wire path through the straightener (wire remains straight), the width ,as the major geometrical parameter, changed as well (Fig.14.b). Table 3 presents the corrections performed on the straightening rollers. Figure 15 a) presents the wire path through the straightener before and after the roller presetting.

4 SKLEP

V prispevku je bil najprej prikazan numerični model ravnanja žice v ravnalni napravi, ki v nadaljevanju rabi kot jedro stabilizacijskega algoritma. Zamisel je bila preizkusno ovrednotena, s čimer smo potrdili, da je takšen način stabilizacije geometrijskih parametrov izdelkov iz žice mogoč, kljub temu, da so

4 CONCLUSION

A numerical model of the wire-straightening process has been presented, which serves as the core for the stabilization algorithm. The idea was experimentally verified, which confirmed that the stabilization of the geometrical parameters of the product made out of wire is possible, even though v njej prisotne spreminjajoče se materialne lastnosti. Pri tem nas ne zanimajo vzroki za te neenakomerne lastnosti materiala, temveč se osredotočimo na samo stabilizacijo.

Nadaljnje možnosti uporabe se odpirajo predvsem v smeri izdelave pločevinastih izdelkov. Kakršenkoli drug način poprave geometrijske oblike je zaradi večje zapletenosti izdelkov otežen. Postopek s stabilizacijo meje plastičnosti jekla pa ponuja tudi v tem primeru odlične možnosti.

the input material had an inhomogeneous yield stress. The reasons for the material inhomogenities are not a part of the discussion. We have only focused on the stabilization principle.

Further applications are also possible in the field of sheet-metal forming. Any other way of correcting the geometry of sheet-metal parts is more difficult because of the complex geometry. The material's yield-stress stabilization algorithm also promises good results in this field of production.

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Naslov avtorjev: dr. Miha Nastran
prof.dr. Karl Kuzman
Fakulteta za strojništvo
Univerza v Ljubljani
Aškerčeva 6
1000 Ljubljana
miha.nastran@domel.com
karl.kuzma@fs.uni-lj.si

Authors' Address: Dr. Miha Nastran
Prof.Dr. Karl Kuzman
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia
miha.nastran@domel.com
karl.kuzma@fs.uni-lj.si

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Raven hrupa v delovnem okolju ob upoštevanju različnih poprav

Considering Various Corrections of Noise Level in the Workplace Environment

Vlado Fras - Andrej Polajnar - Borut Buchmeister

Podani so rezultati raziskave, s katero smo naredili primerjavo med ravnmi hrupa v delovnem okolju ob upoštevanju različnih poprav (impulzne, kakor to določa nova slovenska zakonodaja, in tonske, kakor je podana v standardu ISO 9612) in tudi brez njih. Meritve smo opravili v treh podjetjih kovinskopredelovalne industrije.

Analiza je bila opravljena z namenom, da bi videli, kakšen je dejanski vpliv posamezne poprave na dnevno izpostavljenost delavca hrupu (predvsem tonske poprave, ki je nova zakonodaja ne predvideva).

Rezultati so pokazali, da gre za statistično pomembno razliko z veliko stopnjo zaupanja med posameznimi popravami.

(Ključne besede: ravni hrupa, poprave tonske, poprave impulzne, analize frekvenčne)

In this paper research results are presented that compare the noise levels in the workplace and consider different corrections (impulse as envisaged by the new Slovenian legislation and tone correction as given in the ISO 9612 standard) or the absence of corrections. The measurements were taken in three metalworking companies.

The analyses were performed to determine the influence of a single correction on a worker's daily exposure to noise (especially tone correction, which is not mentioned by the new legislation).

The results show a statistically important difference, with a high level of reliability between the single corrections.

(Keywords: noise level, tone corrections, impulse corrections, frequency analysis)

0 UVOD

Izpostavljenost dovolj visokim ravnem hrupa ima lahko za posledico, med drugim, okvaro sluha. Dodatni negativni vpliv pa imata še impulzivni značaj hrupa in navzočnost izrazitih tonov ([1] do [3] in [5]).

Za impulziven hrup je značilna visoka vrednost, ki traja kratek čas. Človeško uho ni zmožno slediti spremembam hrupa, ki so krajše od 100 ms. Zaradi počasnejšega odziva ušesa pa vpliv na poškodbe sluha ni zmanjšan.

Poudarjeni toni so nevarni predvsem zato, ker stalno delujejo na točno določeno frekvenčno področje v ušesu.

Pri meritvah lahko upoštevamo impulzivnost in poudarjene tone v obliki dodatnih popravnih faktorjev.

Po stari slovenski zakonodaji [8] se je hrup s poudarjenimi toni ali izrazitimi impulzi ocenjeval za 5 dB strožje, pri čemer pa ni bilo izrecno definirano, kaj

0 INTRODUCTION

Exposure to relatively high levels of noise can, amongst other things, result in hearing defects. The nature of the impulsive noise and the presence of pronounced tones represent additional negative influences ([1] to [3] and [5]).

Impulsive noise is characterised by a high value over a short period of time. The human ear cannot follow noise changes that occur over less than 100 ms; however, this slow response of the ear does not result in a lowering of the hearing impairment.

Pronounced tones are dangerous because they are constantly acting over a certain frequency range in the human ear.

In these measurements the impulsiveness and pronounced tones in the form of additional corrective factors can be taken into consideration.

According to the previous Slovenian legislation [8], noise with pronounced tones or explicit impulses was classified as being for 5 dB higher; however, poudarjeni toni ali impulzi so, torej stvar posamezne presoje (v praksi zanemarjeno).

Nova slovenska zakonodaja [6] se je naslonila na standard ISO 9612 [5]. Ta podaja kot možen način upoštevanja impulzivnosti hrupa t.i. *impulzno popravo* K_I, kar je prevzela tudi naša zakonodaja, ni pa prevzela upoštevanja prisotnosti izrazitih tonov (t. i. *tonska poprava* K_T), kar prav tako navaja omenjeni standard.

V pričujoči raziskavi smo zato izvedli primerjavo med vrednostmi hrupa, ki jih dobimo z upoštevanjem posameznih poprav in brez njih. Zanimal nas je vpliv upoštevanja poprav na skupno (dnevno) izpostavljenost delavca hrupu in ne le pri posameznem opravilu. To se zdi primerno, ker je osnovni kriterij pri zaščiti delavca pred hrupom ([5], [6] in [9]) dnevna izpostavljenost hrupu $L_{EX,8h}$.

1 MATERIALI IN METODE

1.1 Opis merilnih mest

Pri izvajanju meritev smo se omejili na kovinsko predelovalno industrijo. Meritve smo izvedli v treh slovenskih podjetjih.

- PODJETJE A

Poglavitna dejavnost podjetja je izdelava namenskih orodij. V proizvodnji se v glavnem uporabljajo obdelovalni stroji (struženje, frezanje, razrez ipd.)

Dodatna dejavnost podjetja je kovanje polizdelkov in energijska oskrba drugih industrijskih obratov (kotlarna, kompresorska postaja)

- PODJETJE B

Glavna dejavnost podjetja je izdelava večje opreme s področja toplotne tehnike. V proizvodnji se v glavnem uporabljajo metode razreza in spajanja kovin

- PODJETJE C

Glavna dejavnost podjetja je izdelava namenskih nadgradenj na vozilih. V proizvodnji se v glavnem uporabljajo kleparski in ključavničarski postopki.

1.2 Opis postopka merjenja

Uporabili smo merilni instrument podjetja Bruel&Kjaer, s serijsko številko 2201657 in območjem merjenja 50 do 120 dB, ki izpolnjuje določila tehničnih specifikacij po IEC 225, IEC 651 in IEC 804.

- **Določitev ravni hrupa**

Meritve smo izvedli v skladu s standardom SIST ISO 9612.

Merilni mikrofon postavimo na delavčevo mesto in v višini njegovega ušesa 0,2 m od njega. Mikrofon mora biti obrnjen proti viru ropota. Med mikrofonom in virom ropota ne sme biti ovir.

there was no explicit definition of what the pronounced tones or impulses were, this was a matter of subjective estimation and was often neglected in practise.

The new Slovenian legislation [6] is based on the ISO 9612 standard [5]. This standard states the possibility of considering noise impulsiveness e.g. *impulse correction* K_I, which has been incorporated into our new legislation but has not taken over the consideration of any pronounced tones' presence (e.g. *tonality correction* K_T), which is, however, stated in the above-mentioned standard.

Our research compares the noise values obtained when considering single corrections with those that do not consider them. We were also interested in the influence of cumulative (daily) noise exposure when considering the correction. This seems reasonable since the workers' daily noise exposure, $L_{EX,8h,}$ is the basic criterion when protecting the worker from noise ([5], [6] and [9]).

1 MATERIALS AND METHODS

1.1 Description of the places were the measurements were taken

The measurements were restricted to the metalworking industry. These measurements were performed in three Slovenian companies.

- COMPANY A

The company produces tools. The production involves the use of machines (milling, turning, cutting, etc.)

Other processes include the forging of semimanufactured products and the supply of energy to other areas (boiler house, compressor unit/station).

- COMPANY B

The company produces large equipment for power techniques/technology. The production involves cutting and joining metod parts.

- COMPANY C

The company produces special purpose upgrading on vehicles. The production involves plumbing and locksmithing processes.

1.2 Description of the measuring procedure

A Bruel&Kjaer measuring instrument, with the serial no. 2201657 and range 50 to 120 dB which meets the IEC 225, IEC 651 and IEC 804 technical specification regulations, was used.

- **Determination of the noise level**

The measurements were performed in accordance with the SIST ISO 9612 standard.

The measuring microphone was set up in the workplace at ear level, 0.2 m from the ear. The microphone had to face the noise source. There must be no hindrance between the microphone and the noise source.

Čas merjenja mora biti dovolj dolg, da odčitek ustrezne ravni hrupa niha za manj ko 0,5 dB. Čas merjenja ne sme biti krajši od 15 s. Pri izrazitem periodičnem hrupu je potrebno zajeti vsaj eno periodo.

Kadar delavec spreminja lokacijo delovnega mesta med delavnikom, meritve izvajamo na vseh značilnih lokacijah, pri čemer upoštevamo čas, ki ga porabi na enem delovnem mestu.

V primerih, ko se raven hrupa v delovnem prostoru spreminja povsem naključno, npr. kleparska delavnica, izvajamo meritve naključno in v dovolj velikih časovnih obdobjih, tako da so rezultati med seboj neodvisni. Običajno vzamemo najmanj pet meritev in na podlagi tega določimo ocenjeno raven hrupa (enačba 4).

• Frekvenčna analiza

Na delovnih mestih smo izvedli dodatno še terčno frekvenčno analizo hrupa z namenom, da bi ocenili navzočnost poudarjenih tonov.

Frekvenčne analize smo izvedli v skladu s standardom SIST ISO 9612. Rezultat analize je na zaslonu instrumenta izrisan kot palični diagram.

1.3 Vrednotenje rezultatov meritev

• Določitev ravni hrupa z impulzno popravo

Impulzno popravo upoštevamo v skladu z novo slovensko zakonodajo, torej tako da izmerjeni ustrezni ravni hrupa prištejemo razliko med ravnijo, merjeno z dinamiko I (Impulse), in ravnijo, merjeno z dinamiko F (Fast). Če je razlika manjša od 2 dB, se zanemari, če pa je večja od 6 dB, se prišteje le 6 dB.

Na delovnih mestih smo ocenjevali hrup med celotnim delavnikom. Ostali smo pri sistemu označevanja (določevanja) ustrezne ravni L_{Aeq}, namesto dnevne izpostavljenosti hrupa $L_{EX,8h}$ (nova zakonodaja), ker dejansko dobimo enake rezultate, če zajamemo vse ravni hrupa v dnevu (tudi obdobja relativne tišine) in iz njih izračunamo ustrezno raven L_{Aeq}, kakor če računamo $L_{EX,8h}$ ob upoštevanju časa, ko prevladuje relativna tišina.

Iz navedenih razlogov smo tudi hrup z impulzno popravo označevali z L_{AIeq}, namesto z $L_{Ar,Te}$, kakor je v novi zakonodaji, torej [6]:

The measuring time had to be sufficient to ensure that the equivalent noise level reading varied by less than 0,5 dB. The measuring time must not be shorter than 15 s. In the case of a pronounced periodic noise, at least one whole period has to be measured.

In cases where the worker changes his working place in the course of his working day, measurements are performed in all typical locations by considering the time spent in each workplace.

In cases where the noise level in the workplace changes periodically, e.g. in a plumbing workshop, measurements were performed randomly in time intervals large enough to ensure independent, relevant results. Usually, five measurements were taken to define the estimated noise level (Equation 4).

• Frequency analysis

An additional third-octave band-frequency noise-level analysis was performed in the workplaces with the aim of evaluating the presence of pronounced tones.

The frequency analyses were performed in accordance with the SIST ISO 9612 standard. On the instrument's monitor, the analysis result is shown as a bar chart.

1.3 Evaluation of the results

• Determination of the noise level by means of impulse correction

Impulse correction is taken into account in accordance with the new Slovenian legislation, which means that the difference between the level measured by the dynamic I (Impulse) and the level measured by the dynamic F (Fast) is added to the measured equivalent noise level. If the difference is less than 2 dB it is ignored. In cases where the difference is more than 6 dB, only 6 dB are added.

In the workplaces the noise was evaluated throughout the working day. We used the marking system for equivalent level, $L_{AEq,}$ instead of the daily noise exposure, $L_{EX,8h}$ (new legislation), because we actually obtain the same results when we consider all the noise levels over the whole day (even the periods of relative silence) and calculate the equivalent level, L_{Aeq}, or when we calculate $L_{EX,8h}$ considering the period of relative silence.

For the reasons given the noise using impulse correction is marked as L_{AIeq} instead of $L_{ar,Te}$ as, stated in the new legislation [6]:

$$L_{AIeq} = 10\log\left(\frac{1}{T_e}\sum_{i=1}^{n} T_i 10^{0.1\left(L_{Aeq,T_i}+K_{Ii}\right)}\right) \quad (1),$$

kjer so:

$L_{Aeq,Ti}$ - ustrezna zvezna A-vrednotena raven hrupa med časovnim obdobjem T_i,
K_{Ii} - impulzna poprava med časovnim obdobjem T_i,
T_e - trajanje izpostavljenosti hrupu.

where:

$L_{Aeq,Ti}$ represents the equivalent A evaluated noise level during the time interval T_i
K_{Ii} represents the impulsive correction during time interval T_i
T_e represents the duration of the noise exposure.

• Določitev ravni hrupa z impulzno in tonsko popravo

Če pri terčni frekvenčni analizi ugotovimo, da raven pri določeni frekvenci za več ko 5dB presega ravni najbližjih sosednjih frekvenc (levo in desno), potem govorimo o poudarjenih tonih. V tem primeru predlaga standard ISO 9612 dodatni koeficient K_T. Vrednost $K_T = 5$. Raven hrupa z impulzno in tonsko popravo - L_{AITeq} izračunamo [5]:

• Determination of the noise level by means of impulse and tone correction

In this case the third-octave band-frequency analysis shows that the level at a certain frequency exceeds the closest neighbouring frequencies (to the left and to the right) by more than 5 dB, a case of pronounced tones is encountered. In such a case the ISO 9612 standard suggests an additional coefficient K_T. The value of $K_T = 5$. The noise level with the impulse and tone correction, L_{AITeq}, is calculated as [5]:

$$L_{AITeq} = 10\log\left(\frac{1}{T_e}\sum_{i=1}^{n} T_i 10^{0.1\left(L_{Aeq,T_i}+K_{Ii}+K_{Ti}\right)}\right) \qquad (2),$$

kjer je:
K_{Ti} - tonska poprava med časovnim obdobjem T_i.

where:
K_{Ti} represents the tone correction during the time interval T_i

• Določitev ravni hrupa brez poprav [5]

• Determination of the noise level without correction [5]

$$L_{Aeq} = 10\log\left(\frac{1}{T_e}\sum_{i=1}^{n} T_i 10^{0.1 L_{Aeq,T_i}}\right) \qquad (3).$$

• Določitev ravni hrupa, ki se naključno spreminja

V primerih, ko se raven hrupa v delovnem prostoru spreminja povsem naključno – npr. kleparska delavnica, standard ISO 9612 predlaga za določitev ocenjene ravni hrupa naslednji postopek.

Meritve, da bi določili zanesljivosti, si morajo slediti v dovolj velikih časovnih obdobjih, da so rezultati med seboj neodvisni.

Pri n-kratnem številu neodvisnih vzorcev L_i določimo ocenjeno raven z naslednjo zvezo [5]:

• Determination of the periodically changing noise level

In cases when the noise level changes periodically, e.g. in a plumbing workshop, the ISO 9612 standard suggests the following procedure for determining the estimated noise level.

To ensure independent results, measurements aiming at reliability determination have to follow in large enough time intervals.

In n-time the number of independent samples, L_i, the estimated level is determined as follows [5]:

$$L_{Aeq} = \overline{L} + 0{,}115 s^2 \qquad (4),$$

kjer je:

where:

$$\overline{L} = \frac{1}{n}\sum_{i=1}^{n} L_i$$

aritmetično povprečje izmerjenih ravni v decibelih in

is the arithmetic mean of the measured levels in decibels and

$$s = \sqrt{\frac{\sum_{i=1}^{n}(L_i - \overline{L})^2}{n-1}}$$

standardni odmik v decibelih.

is the standard deviation in decibels.

1.4 Obdelava rezultatov - testiranje razlike med dvema aritmetičnima povprečjema

Ker smo opazovali iste vzorce v dveh različnih okoliščinah, je šlo za odvisne vzorce. Pri vsakem od opazovanih enot imamo dvojico podatkov, tako da izvedemo *preskus dvojic*, s katerim preskušamo razliko med aritmetičnima povprečjema.

Iz vzorčnih podatkov najprej izračunamo za vsako enoto razliko d_i, iz njih pa oceno aritmetičnega povprečja razlike:

1.4 Result processing – testing the difference between two arithmetic means

Since the same samples under two different circumstances were observed we dealt with dependent samples. In each of the observed units we have two lots of data; a *couple test* is performed in which the difference between the arithmetic means is tested.

From the sample data the d_i for each unit is calculated followed by the arithmetic mean estimation:

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i$$

in oceno variance razlik [11]:

and the variant difference estimation [11]:

$$s_d^{\,2} = \frac{1}{n-1}\left[\sum d_i^{\,2} - \frac{1}{n}\left(\sum_{i=1}^{n} d_i\right)^2\right]$$

n - velikost vzorca.

Standardna napaka aritmetičnega povprečja:

n - sample size.

Standard arithmetic mean error:

$$se\left(\bar{d}\right) = \frac{s_d}{\sqrt{n}}$$

Določitev faktorja t:

t-factor determination:

$$t = \frac{\bar{d}}{se\left(\bar{d}\right)} \tag{5}$$

Tako izračunano vrednost Studentovega faktorja t primerjamo s tabeliranim. Za velikost vzorca n = 40 (število različnih delovnih mest, ki smo jih analizirali) sledijo pri (n –1) prostostnih stopnjah m = 39 naslednje vrednosti t-faktorja glede na različne stopnje zaupanja α (preglednica 1):

Thus the calculated Student t-factor value is compared to the tabulated one. For a sample size of n = 40 (number of different analysed workplaces) the t-factor values regarding the different reliability level α follow in (n –1) degrees of freedom m = 39 (Table 1).

Preglednica 1. *Vrednosti faktorja t*
Table 1. *t-factor values*

α	0,1	0,05	0,025	0,01	0,005	0,001	0,0005	0,0001
t	1,3031	1,6839	2,0211	2,4233	2,7045	3,3069	3,5510	4,0942

2 REZULTATI IZMERJENIH VREDNOSTI

Pri določitvi dnevne izpostavljenosti delavca hrupu na posameznem delovnem mestu smo njegov delavnik (7,5 ure) razdelili na tipična opravila. Merili smo raven hrupa pri posameznem opravilu in čas trajanja opravila. Po enačbah (1), (2) in (3) smo izračunali dnevno izpostavljenost.

Na delovnih mestih, kjer se hrup spreminja naključno, smo za ocenitev ravni hrupa uporabili še enačbo (4).

Malico (0,5 ure) smo zanemarili, ker ima relativna tišina zanemarljiv vpliv na osnovno ustrezno raven.

Končni rezultati ravni hrupa po posameznih delovnih mestih v podjetjih A, B in C so prikazani v preglednici 2.

Kot primer izračuna ravni hrupa je prikazano delovno mesto št. 4 – delo na računalniško krmiljenem frezalnem stroju ILR WALDRIC. Rezultati meritev po posameznih opravilih in določitev popravnih faktorjev so podani v preglednici 3.

Končni rezultati – ustrezne ravni hrupa v enem delavniku:

2 RESULTS OF THE MEASURED VALUES

When determining the worker's daily noise exposure in a particular workplace the working day (7,5 h) was divided according to the typical work operations. The noise level of the individual operation and the operation-time duration were measured. The daily exposure was calculated, based on Eqs. (1), (2) and (3).

In workplaces where the noise changes periodically, Equation (4) was additionally implemented to estimate the noise level.

The coffee break (0,5 h) was ignored because the relative silence had a negligible effect on the basic equivalent level.

The final results of noise levels in the individual workplaces in companies A, B and C are shown in Table 2.

An example of a noise-level calculation is shown for workplace No. 4 – work performed on the CNC ILR WALDRIC milling machine. The measurement results of single operations and the correction-factor determination are shown in Table 3.

Final results – equivalent noise level over the whole working day:

$$\boldsymbol{L_{AIeq} = 82{,}4 \ \ \mathrm{dB}}$$
$$\boldsymbol{L_{AITeq} = 87{,}4 \ \ \mathrm{dB}}$$
$$\boldsymbol{L_{Aeq} = 80{,}5 \ \ \mathrm{dB}}$$

Preglednica 2. *Končni rezultati ravni hrupa*
Table 2. *Final results of noise level*

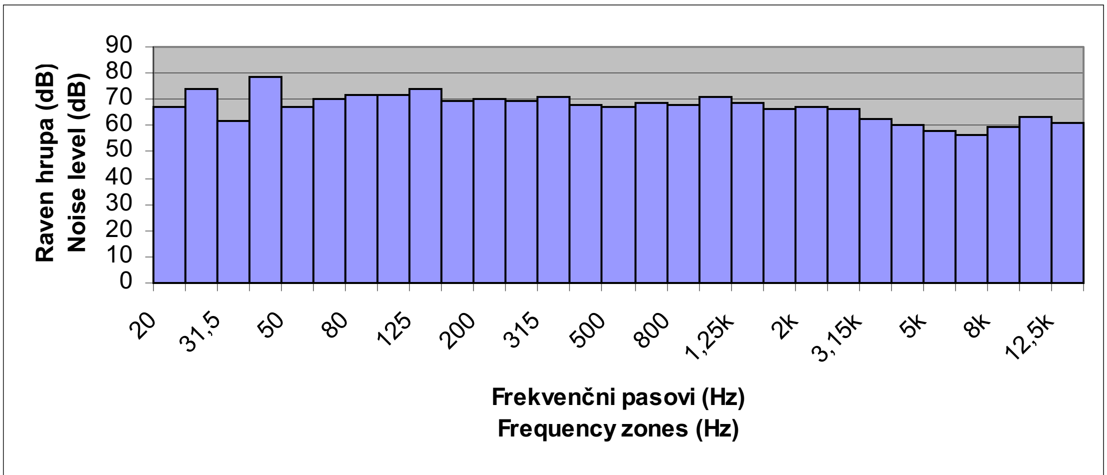
Št. Nr.	delovno mesto work place	L_{AITeq} dB	L_{AIeq} dB	L_{Aeq} dB
PODJETJE A COMPANY A				
1	struženje turning	84,3	84,3	84,3
2	frezanje miliing	86,0	86,0	84,2
3	RK/CNC Bohle	75,4	75,4	75,4
4	RK/CNC ILR Waldric	87,4	82,4	80,5
5	avtogeno rezanje oxyacetylene cutting	93,6	92,3	92,3
6	krožna žaga Ø 1000 circular saw Ø 1000	87,6	83,0	83,0
7	stiskalnica 400 t press 400 t	105,6	100,6	94,7
8	montažna dela assembly	90,7	87,0	83,0
9	varjenje welding	95,4	92,1	87,8
10	koordinatni vrtalni stroj co-ord. drilling machine	88,7	83,9	83,8
11	brušenje grinding	88,2	85,0	83,9
12	nadzor checking	69,6	69,6	67,1
13	delovodja foreman	71,2	71,2	71,2
14	konstrukcija design	48,6	48,6	48,6
15	kovaško kladivo – 20 t sledge-hammer – 20 t	112,6	107,6	101,6
16	kovaško kladivo – 3 t sledge-hammer – 3 t	108,9	103,9	97,9
17	delovodja foreman	97,2	92,3	86,9
18	kompresorist compressor-man	88,5	88,5	88,5
19	kotlarna boiler house	86,3	83,4	83,4
20	tehnik technician	73,7	68,8	68,8
PODJETJE B COMPANY B				
21	razrez pločevine sheet cutting	99,2	94,4	88,8
22	varilec - elektro obločno welder – arc welding	100,0	95,6	92,3
23	varilec - CO_2 welder – CO_2	101,6	97,1	94,9
24	viličarist fork-lift trucker	89,1	85,2	84,3
25	ličar lacquerer	84,7	84,7	84,7
26	rezalec pločevine s plazmo – I plasma sheet cutter – I	90,9	90,9	90,9
27	rezalec pločevine s plazmo – II plasma sheet cutter – II	86,3	86,3	86,2
28	prebijalni stroj punching machine	92,0	87,1	82,3
29	zahtevnejša montaža complicated assembly	73,3	73,3	71,6
30	vodja proizvodnje production manager	83,4	83,4	79,0
31	konstrukcija design	58,1	58,1	52,1
PODJETJE C COMPANY C				
32	montažno – kleparska dela z Al assembly-plumbing work with Al	105,4	98,6	95,9
33	razrez pločevine sheet cutting	99,2	94,3	88,8
34	klepar plumber	105,3	99,6	96,5
35	ključavničar locksmith	102,6	98,7	96,8
36	priprava za ličenje preparation for lacquering	88,5	83,8	83,8
37	ličar – komora lacquerer - chamber	82,4	82,4	82,4
38	strojna obdelava machining	83,7	81,1	79,9
39	obratovodja works manager	81,6	76,6	71,2
40	konstrukcija design	51,9	51,9	51,9

Preglednica 3. *Rezultati meritev na del. mestu št. 4 (frezanje)*
Table 3. *Measurement results for workplace No. 4 (milling)*

	Rezultati meritev Measurement results		
	grobo frezanje coarse milling	fino frezanje fine milling	priprava, preostalo preparation, other
$L_{AIeq,Ti}$ (dB)	84,5	82,4	74,3
$L_{Aeq,Ti}$ (dB)	79,7	81,6	73,1
T_i (min)	150	240	60
K_{Ii} (dB)	4,8	0	0
K_{Ti} (dB)	5	5	0
$L_{Aeq,Ti}+K_{Ii}+K_{Ti}$ (dB)	89,5	86,6	73,1
$L_{Aeq,Ti}+K_{Ii}$ (dB)	84,5	81,6	73,1

Slika 1 prikazuje rezultat frekvenčne analize pri opravilu 1 – grobo frezanje. Izrazita tona sta dva (25 Hz, 40 Hz), K_{Ti} = 5 dB. Prisoten je impulzni značaj: K_{Ii} = 4,8 dB (razvidno iz rezultatov meritev).

Figure 1 shows the frequency-analysis result for operation 1 – coarse milling. There are two pronounced tones (25 Hz, 40 Hz), K_{Ti} = 5 dB. The impulse character: K_{Ii} = 4,8 dB measurement results) is present.



Sl. 1. *DM 4, opravilo 1 (grobo frezanje)*
Fig. 1. *WP 4, operation 1 (coarse milling)*

2.1 Primerjava izmerjenih ravni hrupa

Razlike med izmerjenimi ravnmi hrupa L_{AITeq}, L_{AIeq} in L_{Aeq} zaradi različnih poprav (po posameznih delovnih mestih) so prikazane na sliki 2.

- **Primerjava L_{AITeq} in L_{Aeq}**

Izračunana vrednost faktorja *t* znaša ***t* = 7,93**.
Sklep: z veliko stopnjo zaupanja (α=0,0001) lahko trdimo, da so ravni hrupa, ki jih dobimo z upoštevanjem impulzne in tonske poprave - L_{AITeq}, statistično pomembno višje glede na ravni hrupa, ki jih dobimo brez upoštevanja poprav - L_{Aeq}.

- **Primerjava L_{AIeq} in L_{Aeq}**

Izračunana vrednost faktorja *t* znaša ***t* = 6,09**.
Sklep: z veliko stopnjo zaupanja (α=0,0001) lahko trdimo, da so ravni hrupa, ki jih dobimo z upoštevanjem impulzne poprave - L_{AIeq}, statistično pomembno višje glede na ravni hrupa, ki jih dobimo brez upoštevanja poprav - L_{Aeq}.

- **Primerjava L_{AITeq} in L_{AIeq}**

Izračunana vrednost faktorja *t* znaša ***t* = 7,48**.

2.1 Comparison of the measured noise levels

The difference between the measured noise levels L_{AITeq}, L_{AIeq} and L_{Aeq} because of different corrections (in individual places) are shown in Figure 2.

- **Comparison of L_{AITeq} and $L_{A\,eq}$**

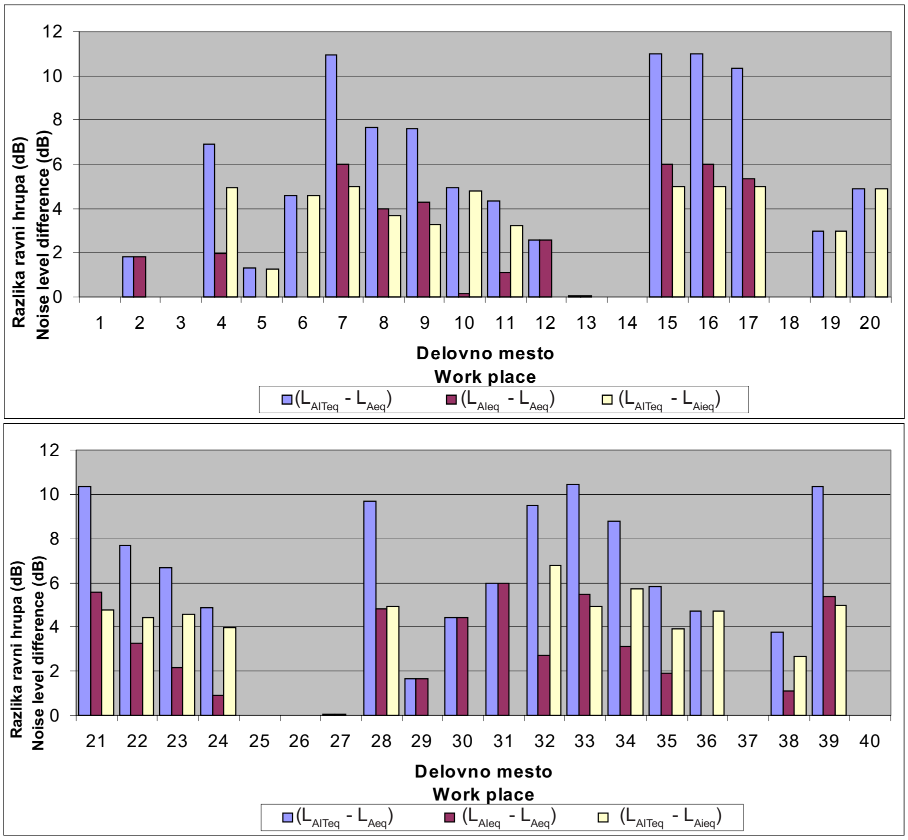
The calculated t-factor value is *t* = 7,93
Conclusion: with a high level of reliability (α=0.0001) we can state that the noise levels obtained by considering the impulse and tone correction, L_{AITeq}, are statistically considerably higher in comparison to the noise levels obtained without the correction, L_{Aeq}, consideration.

- **Comparison of L_{AIeq} and $L_{A\,eq}$**

The calculated t-factor value is *t* = 6,09
Conclusion: with a high level of reliability (α=0.0001) we can state that the noise levels obtained by considering the impulse and tone correction, L_{Aieq}, are statistically considerably higher in comparison to the noise levels obtained without the correction, L_{Aeq}, consideration.

- **Comparison of L_{AITeq} and L_{AIeq}**

The calculated t-factor value is *t* = 7,48



Sl. 2. *Razlika* L_{AITeq} - L_{Aeq} , L_{AIeq} - L_{Aeq} *in* L_{AITeq} - L_{AIeq}

Fig. 2. *Difference* L_{AITeq} - L_{Aeq} , L_{AIeq} - L_{Aeq} and L_{AITeq} - L_{AIeq}

Sklep: z veliko stopnjo zaupanja (α=0,0001) lahko trdimo, da so ravni hrupa, ki jih dobimo z upoštevanjem impulzne in tonske poprave - L_{AITeq}, statistično pomembno višje glede na ravni hrupa, ki jih dobimo z upoštevanjem le impulzne poprave L_{AIeq}.

3 SKLEP

Na podlagi slike 2 lahko ugotovimo, na katerih delovnih mestih se je upoštevanje poprav izkazalo kot najočitnejše:

- **izrazit impulzni značaj:**
  - dela s stroji, ki povzročajo izrazite impulze: strojne škarje, stiskalnica, kovaško kladivo, prebijalni stroj, nekatere serije varenja, grobi postopki odrezovanja ipd. (delovna mesta: 21, 7, 15, 16, 28, 9, 33 - sl. 2);
  - postopki, kakor so: uporaba ročnega orodja (kladivo ipd.), trki, padci ipd. (delovna mesta: 34, 9, 22, 33 - sl. 2);
- **opaznost izrazitih tonov:**
  - dela s stroji, ki povzročajo izrazite tone:
    hitrorotacijski stroji: črpalke, brusilka, brusilni stroj, polirni stroj, poravnalni stroj, vrtanje, krožna žaga ipd. (delovna mesta: 10, 22, 23, 32, 6 - sl. 2),
    stroji z impulznim značajem: prebijalni stroj, stiskalnica, kovaško kladivo, strojne škarje ipd. (delovna mesta: 28, 7, 15, 16, 21 - sl. 2),

Conclusion: with a high level of reliability (α= 0.0001) we can state that the noise levels obtained by considering the impulse and tone correction, L_{AITeq}, are statistically considerably higher in comparison to the noise levels obtained without the correction, L_{AIeq}, consideration.

3 CONCLUSION

Based on Figure 2 we can conclude in which workplaces the correction consideration proved to be the most obvious:

- **pronounced impulse character:**
  - work on machines causing pronounced impulses: machine scissors, press, sledge-hammer, punching machine, some welding series, coarse milling procedures and the like (work places: 21, 7, 15, 16, 28, 9, 33 - Fig. 2);
  - procedures like the use of hand tools (hammer and the like), shocks, falls and the like (workplaces: 34, 9, 22, 33 - Fig. 2);
- **presence of pronounced tones:**
  - work on machines causing pronounced tones:
    high-speed rotating machines: pumps, turning machine, polishing machine, levelling/evening machine, drilling, circular saw and the like (workplaces: 10, 22, 23, 32, 6 - Fig. 2),
    impulse character machines: punching machine, press, sledge-hammer, machine-scissors and the like (work places: 28, 7, 15, 16, 21 - Fig. 2),

drugi stroji: krožna žaga, grobo frezanje, viličar idr. (delovna mesta: 6, 4, 24 - sl. 2);
- postopki, povezani z uporabo kladiva ipd.

Vpliv impulzne in/ali tonske poprave je zanemarljiv na delovnih mestih, kjer:
- postopki ne povzročajo impulzov in tonov (struženje, frezanje, kompresorska postaja, razrez s plazmo, ličarstvo ipd.);
- prevladuje relativna tišina (miselna dela).

Iz rezultatov analize lahko ugotovimo, da so ravni hrupa ob upoštevanju poprav statistično pomembno višje kakor ravni brez poprav. Še posebej to velja za upoštevanje tonske poprave. Tako hrup ob upoštevanju tonske in impulzne poprave hkrati večkrat za 10 dB presega ravni, ki jih dobimo brez upoštevanja poprav. To so pa že vrednosti, zaradi katerih se lahko upravičeno vprašamo o smiselnosti uporabe takšnih poprav ali pa po drugi strani o nujnosti njihovega upoštevanja.

Hrup v delovnem okolju predstavlja enega bistvenih, predvsem pa enega najpogostejših obremenilnih faktorjev. Kot dodatno zaščito pred hrupom lahko uporabimo ergonomski koeficient K_{er}, ki služi kot poprava v smislu dodatnega časa, potrebnega za okrevanje organizma [10].

other machines: circular saw, coarse milling, fork-lift truck and the like (workplaces: 6, 4, 24 - Fig. 2);
- procedures bound to use a hammer and the like

The influence of impulse and/or tone correction is negligible in workplaces:
- where the procedures do not cause impulses or tones (turning, milling, power station, plasma cutting, lacquering and the like);
- with relative silence (mental work).

From the results of the analysis we can conclude that the noise levels when considering the corrections, are statistically higher than those without corrections. This is especially valid when considering the tone correction. In this way, noise, when considering the tone and impulse correction at the same time, often exceeds the levels obtained without correction consideration by more than 10 dB. These are the values that make us think about the suitability of using such corrections, or on the other hand, about the necessity of considering them.

Noise in the working environment is one of the major and certainly most frequent stressors at work. The ergonomic coefficient K_{er} can be used as an additional protection against the effects of noise on workers because it offers extra time for human organism to recover [10].

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Naslov avtorjev: mag. Vlado Fras
Varnost Maribor d.d.
Kraljeviča Marka 5
2000 Maribor

prof. dr. Andrej Polajnar
doc. dr. Borut Buchmeister
Univerza v Mariboru
Fakulteta za strojništvo
Smetanova 17
2000 Maribor

Authors' Address: Mag. Vlado Fras
Varnost Maribor d.d.
Kraljeviča Marka 5
2000 Maribor, Slovenia

Prof. Dr. Andrej Polajnar
Doc. Dr. Borut Buchmeister
University of Maribor
Faculty of Mechanical eng.
Smetanova 17
2000 Maribor, Slovenia

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Termohidravlična analiza obratovanja uparjalnika za ukapljeni naftni plin

A Thermohydraulic Analysis of a Liquefied-Petroleum-Gas Revaporizer

Sanib Bašič - Leopold Škerget - Matjaž Hriberšek

Prispevek obravnava analizo obratovanja električnega uparjalnika za ukapljeni naftni plin. Na začetku je podan opis naprave in delovanje v ustaljenih obratovalnih razmerah. Nato je definiran cilj analize in vpeljan navidez osnosimetrični prerez uparjalnika. Podane so vodilne enačbe toka newtonske tekočine v območju sekundarne kapljevine za prenos toplote in toka skozi porozni grelnik. Definirani so robni pogoji na mejah računskega območja. Ločeno so podane osnovne kriterialne enačbe za vrednotenje prenosnih pojavov v posameznih delih uparjalnika. Poseben poudarek je namenjen razmeram konvektivnega uparjanja binarne zmesi v cevni vijačni spirali. Opisan je iterativni računski postopek, s katerim je doseženo končno obratovalno stanje naprave. Na koncu so predstavljeni dobljeni rezultati s komentarjem in sklepi. Za izbrane parametre je obratovalna točka uparjalnika znotraj predpisanih temperaturnih mej.

(Ključne besede: prenos toplote, uparjalniki, analize termohidravlične, plini naftni ukapljeni)

This paper deals with the thermohydraulic characteristics of an electrical liquefied-petroleum-gas (LPG) revaporizer. To begin with both the revaporizer's description and its working performances are presented. The main goals of the analysis are defined and the quasi-axisymmetrical revaporizer section is introduced. The governing equations for Newtonian fluid flow in the region of the secondary liquid and for flow through a porous heater are presented. The boundary conditions on the computational region boundaries are prescribed. Further, basic empirical corelations for the evaluation of the transport phenomena within the individual revaporizer zones are presented. Special attention is devoted to the convective boiling process of the binary mixture in helically coiled tubes. The iterative calculating procedure with which we finally reached the working state of the device is explained. At the end the achieved results are discussed with comments and conclusions included. The operating point of the revaporizer was to lie inside the prescribed temperature range for the selected combination of process parameters.

(Keywords: heat transfer, vaporizers, thermohydraulic analysis, liquified petroleum gas)

0 UVOD

Ukapljeni naftni plin (UNP) se uporablja kot natančnejše ime za nekaj vrst ogljikovodikov, kakor so propan (C_3H_8), butan (C_4H_{10}) in zmesi propana in butana v različnih sestavinskih razmerjih. UNP je na temperaturi okolice in pri atmosferskem tlaku v plinastem agregatnem stanju in se v tej obliki uporablja kot vir energije oz. gorivo. Že pri manjših nadtlakih ob nespremenjeni temperaturi (nekaj barov – odvisno od deleža sestavnih komponent) UNP preide v kapljevito agregatno stanje in se v tej obliki preprosto prevaža in skladišči.

Odvisno od potreb po UNP-u se ta porabnikom v večini primerov dostavlja v prenosnih jeklenkah, hramih ali cisternah. V vseh hranilnikih je največji del polnitve v kapljevitem agregatnem stanju, le manjši del nad gladino zaseda plinasta faza. Pri polnjenju hranilnikov je takšno prostorninsko

0 INTRODUCTION

Liquefied petroleum gas (LPG) is the name used for several kinds of hydrocarbons, such as propane (C_3H_8), butane (C_4H_{10}) and various propane-butane mixtures. At atmospheric pressure and room temperature LPG has a liquid aggregate state, and in this state it is used as an energy source. At lower gauge pressures (a few bar – depending on the component contents) and temperatures LPG can be easily converted into a liquid aggregate state. This is an important characteristic of LPG, and is used for its economic transport.

With regards to requirements, LPG is normally delivered to consumers in gas bottles, containers and cisterns. In all types of storage most of the volume is occupied by the liquid phase, and only a small part above the liquid surface is filled by the gas phas. The appropriate volume ratio between the phases during razmerje med fazama odvisno od visoke vrednosti prostorninskega temperaturnega raztezka kapljevite faze UNP-a [15].

Odvzem plinaste faze neposredno iz shrambnega prostora, ki ga pogosto imenujemo *naravno uparjanje* UNP-a je povezan s celo vrsto pomanjkljivosti (majhni masni pretoki, uparjanje po frakcijah, usedanje težjih primesi, nevarnost podhladitve UNP-a pri večjih odvzemih). Tem pomanjkljivostim se lahko izognemo z uvedbo *prisilnega oz. pospešenega uparjanja*, ki temelji na odvzemu kapljevite faze UNP-a iz skladiščnih prostorov. Sprememba agregatnega stanja UNP-a v tem primeru poteka zunaj plinskih hranilnikov, v zato posebej skonstruiranih uparjalnikih, ki jih kot dodatne komponente uvajamo v plinska omrežja.

Uparjalniki UNP-a so posebno skonstruirani dvofazni prenosniki toplote, ki izrabljajo toplotno energijo določenih zunanjih virov za pospešeno uparjanje UNP-a. Najbolj uveljavljena razdelitev uparjalnikov za UNP je glede na vir toplote, ki ga ti uporabljajo za pospešeno uparjanje UNP-a. Tako poznamo električne uparjalnike, uparjalnike z vodno paro, toplovodne uparjalnike ter uparjalnike, ki izkoriščajo vrele ostanke zgorevanja UNP-a [17]. V središču pozornosti pričujočega prispevka je električni uparjalnik za UNP s posredno kapljevino za prenos toplote.

1 OPIS IN DELOVANJE UPARJALNIKA

Uparjalnik (slika 1) ima obliko pokončne valjaste posode [18], [19], ki jo sestavljajo valjni plašč (1) ter pokrov (2) in dno plašča (3). Na pokrovu posode sta dovodni (4) (sl. 2) in odvodni cevovod (5) ter spremljajoča krmilna in varnostna oprema. Znotraj posode uparjalnika je navpično nameščen cevni snop, ki se prilega obliki plašča in je na svojih koncih povezan z vstopnim (6) oz. izstopnim (7) priključkom na pokrovu uparjalnika. Cevni snop sestoji iz dveh sosrednih in simetričnih vijačnih cevnih spiral, zunanje (8) in notranje (9). Cevni snop dodatno sestavljajo še trije navpično nameščeni pomožni cevni vodniki (10, 11 in 12).

Skozi ustrezno odprtino je v notranjost plašča v smeri njegove navpične osi vstavljen električni grelnik (13) nespremenljive moči in je pritrjen za dno posode. Uporovni električni grelnik sestavljajo grelna telesa U, obdana z zaščitnim plaščem, ki so pritrjena na skupno krožno nosilo grelnika (14). Na pokrovu uparjalnika so po njegovem obodu pritrjeni trije tovarniško zapečateni kapilarni termostati (15a, 15b in 15c) s pasivnimi stikali, industrijski živosrebrni termometer (16) in mehanski merilnik ravni sekundarne kapljevine za prenos toplote (17). V središču pokrova je nameščen še avtomatski merilnik ravni (električno ravensko stikalo) sekundarne kapljevine v plašču uparjalnika (18). Vsi omenjeni instrumenti s svojimi

reservoir loading is a consequence of the high-temperature dilatation coefficient of the LPG's liquid phase [15].

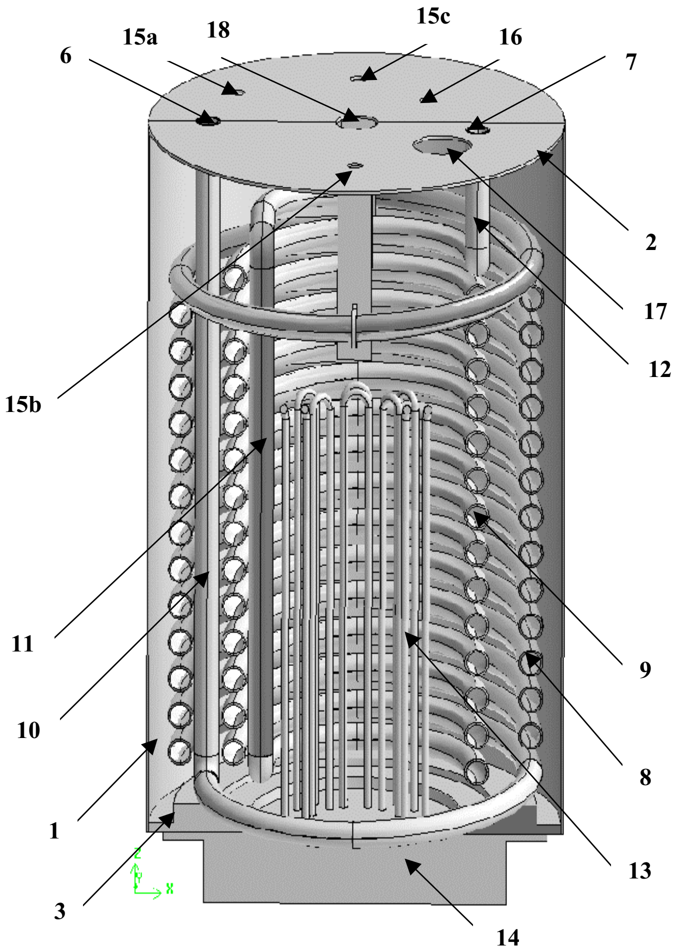
Gas-phase discharging directly from a gasholder, which is often referred to as *natural LPG revaporization*, is accompanied by some imperfections (low mass-flow rate, fractional vaporisation, heavy fractions sedimentation, a risk of bottle subcooling at high discharging rates). To avoid these problems *forced or promoted vaporisation* is frequently used. In this case the LPG's liquid phase is taken out directly from the gas reservoir and the phase transition occurs outside gasholder in specially designed evaporators, which are introduced into the gas network as additional system components.

LPG revaporizers are two-phase heat exchangers that use heat energy from some external sources to promote the evaporation of LPG. The best known classification of LPG revaporizers is in terms of the heat source to be used for the forced revaporization of the LPG. There are electrical revaporizers, revaporizers with hot water or water steam as the heat source, and revaporizers that use the hot combustion products of LPG [17]. This article deals with an electrical LPG revaporizer with a secondary liquid for the heat transfer.

1 DESCRIPTION OF THE REVAPORIZER AND ITS WORKING CHARACTERISTICS

The revaporizer (Figure 1), which is designed as a vertical cylindrical vessel, consists of a cylindrical shell (1), a cover (2) and a vessel bottom (3). On the cover there are supply (4) (Figure 2) and discharging (5) pipelines and auxiliary control and safety equipment. Within the vessel there is a vertically placed tube bundle. At its terminations the tube bundle is connected with inlet (6) and outlet (7) connections on the revaporizer cover. The tube bundle consists of two concentric and symmetric helically coiled tubes, outer (8) and inner (9). The tube bundle also includes three vertically placed auxiliary connecting tubes (10, 11 and 12).

Through a suitable opening in the vessel bottom in the direction of the vertical axis a constant-power electrical heater is inserted (13). The electrical resistance heater consists of heating U-elements covered with copper sheaths and linked together with a circular heater holder (14). On the revaporizer cover three capillary thermostats (15a, 15b and 15c) with passive contactors, an industrial mercury thermometer (16) and a mechanical secondary-liquid-level gauge (17) are mounted. In addition, in the centre of the revaporizer cover, an automatic secondary-liquid-level gauge (18) is installed. The sensors of all this equipment are immersed in the



Sl.1. *Prikaz notranjosti uparjalnika z osnosimetričnim prerezom cevnega snopa in grelnika*
Fig. 1. *Revaporizer interior and axisymmetric sections of the tube bundle and heater*

tipali segajo v notranjost posode (sl. 9) in so do določene globine potopljeni v sekundarno kapljevino za prenos toplote.

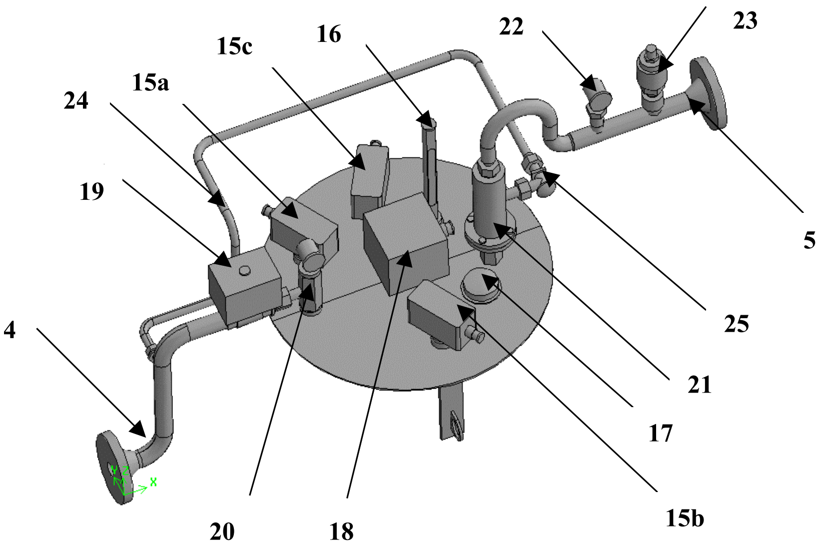
Pred vstopnim priključkom sta na dovodni cevovod (4) pritrjena elektromagnetni ventil (19) in manometer vstopne strani (20). Za izstopnim priključkom so na odvodnem cevovodu (5) nameščeni glavni zaporni ventil (21), manometer izstopne strani (22) ter tlačni varnostni ventil (23). Dovodni (4) in odvodni cevovod (5) uparjalnika sta povezana z zunanjo povratno cevjo (24), ki ima na mestu prehoda v glavni zaporni ventil (21) pritrjen dodatni zaporni ventil za plinske napeljave (25). Zunanja povratna cev (24) in zaporni ventil (25) sta namenjena odpravljanju posledic poplavljanja cevnega snopa (nezgodne razmere [18] in [19]). V posodo je do določene višine nad cevnim snopom nalita sekundarna kapljevina za prenos toplote (transformatorsko olje ali raztopina monoetilenglikola in vode).

Dovodni cevovod uparjalnika je priklopljen na hranilnik UNP-a. Hranilniki za UNP so običajno izdelani iz jeklene pločevine brez toplotne izolacije in je UNP, ki je v njih, v termodinamičnem ravnotežju z okolico [15]. Odvodni cevovod uparjalnika je povezan s porabnikom plina oz. gorilnikom, pred katerim je krmilnik tlaka oz. krmilnik pretoka [16].

secondary liquid for heat transfer in the revaporizer vessel.

In front of the inlet connection, an electromagnetic valve (19) and an inlet side manometer (20) are mounted on the supply pipeline (4). Behind the outlet connection, the main block valve (21), the outlet side manometer (22), and the pressure safety valve (23) are assembled on the discharging pipeline (5). The supply (4) and discharging (5) pipelines are additionally connected together by the external recurrent tube (24). On recurrent tube at the joint situ with main block valve (21), additional block gas valve is mounted (25). External recurrent tube (24) and block valve (25) serve as auxiliary system for elimination of tube bundle flooding consequences (incident circumstances [18] and [19]). Up to the prescribed level over the tube bundle, revaporizer vessel is filled up with secondary liquid for heat transfer (mineral oil or solution of mono-ethylene-glycol and water).

The supply pipeline of the revaporizer is connected to the LPG reservoir. They are usually manufactured from steel plate without heat insulation, and the LPG within the reservoir is in thermodynamic equilibrium with the surroundings [15]. On the opposite side, the discharging pipeline of the revaporizer is connected with the gas consumer. Normally, it is a burner. In front of the burner a pressure or mass-flow rate regulator is placed [16].



Sl.2. *Pokrov uparjalnika s krmilno in varnostno opremo*
Fig. 2. *Revaporizer cover with control and safety equipment*

Parna faza, ki je nad prosto gladino v shrambni posodi za UNP, potiska kapljevito fazo po navpični sifonski cevi skozi izstopni ventil hranilnika v dovodni cevovod (4) električnega uparjalnika. Po vklopu električnega grelnika (13), zaradi naravne konvekcije v sekundarni kapljevini in predvsem zaradi slabega odvoda toplote (ni pretoka UNP-a skozi cevni snop, ker je elektromagnetni ventil (19) na začetku zaprt), slednja akumulira sproščeno toplotno energijo grelnika in se hitro segreva. Ko temperatura kapljevine v točki namestitve tipala termostata, ki krmili delovanje elektromagnetnega ventila (15a), doseže temperaturo 65 °C se elektromagnetni ventil (19) odpre in v cevni snop priteče kapljevita faza UNP-a. Ker kapljevita faza, ki priteka iz hranilnika, ustreza točki na vrelni krivulji UNP-a ob podanem sistemskem tlaku, se uparjanje začne takoj po vstopu kapljevite faze v uparjalnik.

V primeru, da temperatura sekundarne kapljevine v točki namestitve tipala termostata, ki krmili delovanje električnega grelnika (15c), doseže temperaturo 80 °C, se grelnik (13) avtomatsko izklopi. Na pokrovu uparjalnika je nameščen tretji termostat (15b), ki je namenjen za krmiljenje električnega grelnika, in sicer v primeru, da iz določenih razlogov prvi termostat (15a) odpove, njegov električni stik pa je sklenjen pod 85 °C. Med temperaturama merilnih točk 65 °C in 80(85) °C je delovno območje uparjalnika. V tem temperaturnem območju uparjalnik deluje ustaljeno, morebitna sprememba parametrov postopka (poglavje 2) pa lahko povzroči premik delovne točke iz ene v drugo lego.

2 DEFINICIJA PROBLEMA

Prispevek sega na področje konstruiranja dvofaznih prenosnikov toplote. Izvirna konstrukcijska

Due to the pressure head the gas phase in the LPG gasholder pushes the liquid phase out through a vertical siphon tube and the outlet valve to the supply pipeline (4) of the electrical revaporizer. After the electrical heater (13) start-up, the free convection and the low-heat transfer rate (LPG does not flow through the tube bundle because at the start the electromagnetic valve (19) is closed) cause the secondary liquid to accumulate the heat energy of the heater and warm up very fast. When liquid temperature at the point where the thermostat sensor for the electromagnetic valve control is placed reaches 65 °C the valve is opened and the liquid phase of the LPG starts to flow into the tube bundle. Due to fact that the state of the liquid phase entering the tube bundle corresponds to the dew point of LPG for the defined system pressure the evaporation starts immediately after liquid phase enters the revaporizer.

In the case when the secondary liquid temperature at the point where the thermostat sensor for the electric heater working control is placed reaches 80 °C, the electric heaters (13) are automatically turned off. On the revaporizer cover the third thermostat (15b) is placed. It also serves for electrical heater control in case the first thermostat breaks down. It is switched on at 85 °C. As a result the operating region of the revaporizer has to be found between the temperatures measured by the two control thermostat sensors. These temperatures are 65 and 80(85) °C. In this temperature region the revaporizer operates normally and steady-state conditions are usually achieved. Changes to the process parameters governing the revaporizer's thermohydraulic behaviour (Chapter 2) may cause the operating point to be moved to another position.

2 PROBLEM DEFINITION

This paper deals with heat excanger that have a two-phase-flow design. The original construction izvedba električnega uparjalnika je razvita v podjetju Nafta Lendava d.o.o. (*konstruiranje na novo*), na kar so sledile postopne izkustvene spremembe sedanjih izvedb (*optimizacija*). Po več ko dveh desetletjih so razvili izvedbo, za katero smo z namenom nadaljnjih izboljšav izvedli numerično analizo obratovanja, ki jo podajamo v pričujočem prispevku. Sedanji električni uparjalnik za UNP je namenjen obratovanju v širokem območju parametrov postopka. Temperatura okolice (T_{sur}), sestava plinske zmesi ($\xi_{C_3H_8}$), zračni tokovi okrog uparjalnika (v_w), vrsta sekundarnega sredstva in višina, do katere ta sega s svojo prosto gladino (H_{sl}) (sl. 3b), ter masni pretok UNP-a ($\dot{m}_{UNP}$), so veličine postopka, ki definirajo obratovalne značilnosti uparjalnika. Večina prenosnikov toplote je namenjena delovanju pri točno določeni kombinaciji parametrov postopka, pri čemer so dovoljena le manjša odstopanja od predpisane delovne točke. V tukaj podanem primeru se parametri postopka lahko močno spreminjajo, uparjalnik pa mora nemoteno delovati v čim širšem območju spreminjajočih se vplivnih veličin (*delovanje v novih razmerah*). Mogoče je torej veliko število obratovalnih točk, ki skupaj dajejo obratovalni diagram uparjalnika. Izdelava obratovalnega diagrama uparjalnika za UNP je končni cilj raziskave. Glede na dejstvo, da obstaja zelo veliko število kombinacij parametrov postopka, ki določajo delovno točko uparjalnika, smo se v prispevku omejili na eno samo delovno točko oz. na eno izbrano kombinacijo parametrov postopka (preglednica 1). Razviti algoritem je mogoče uporabiti za določitev celotnega delovnega območja obravnavanega uparjalnika.

Namen je ugotoviti, ali uparjalnik ob izbrani kombinaciji parametrov postopka deluje in koliko daleč je tako definirana delovna točka od meje neobratovanja. Če so temperature sekundarne kapljevine v točkah namestitve tipal krmilnih termostatov v predpisanem območju (60 do 85 °C), potem uparjalnik nemoteno deluje. Namen smo dosegli tako, da smo s postopnim spreminjanjem robnih pogojev na mejah računskega območja izpolnili delne (uparjanje, pregretje in izgube v okolico) in s tem celotno toplotno bilanco uparjalnika. Preverili smo velikost grelne površine sedanjega cevnega snopa za dosego predpisanih izhodnih veličin pregrete parne faze UNP-a. Parametri postopka, ki

of the electrical LPG revaporizer was developed by Nafta Lendava d.o.o. (*new design*). Some empirical modifications to the existing construction followed (*optimization*). After more than two decades a new construction has been developed for which, with the aim of additional improvements, we performed a numerical analysis of the working conditions presented in this contribution. The existing LPG revaporizer is designed to work within a wide region of process parameters. The surrounding temperature (T_{sur}), the gas-mixture composition ($\xi_{C_3H_8}$), the air flow around the revaporizer (v_w), the secondary liquid type and its filling level in the revaporizer vessel (H_{sl}), and the mass-flow rate of the LPG ($\dot{m}_{UNP}$) are the process parameters that define the operating conditions of the revaporizer. The vast majority of heat exchangers are designed to work for an exactly defined combination of process parameters. Usually, only small deviations from the defined working point are allowed. In the case analysed here the process parameters change significantly and the revaporizer must operate without interruption in as wide as possible region of the affecting parameters (*working under the conditions of the new process parameters*). A large number of operating points defines the revaporizer's operational diagram. The development of an LPG revaporizer operational diagram is the final goal of this analysis. Due to the fact that there are many combinations of process parameters defining the revaporizer's operational points, we limited ourselves to one selected combination of process parameters (Table 1.) The developed algorithm may then be used to determine the entire working region of the revaporizer.

The main goal of our research was to find out whether the revaporizer works for a chosen combination of process parameters, and how far away from the limits of the working region is the defined working point. If the temperatures of the secondary liquid at the control thermostat sensor points are in the prescribed range (60-85 °C), the revaporizer works without interruption. The goal can be reached with a numerical analysis by changing the boundary conditions on the boundary of computational domain and by satisfying the partial (evaporation, superheating and heat loses to surroundings) and the global heat balances of the revaporizer. The size of the tube bundle's surface available for heat transfer was controlled at the

Preglednica 1. *Parametri postopka delovnega stanja, za katero je izveden nadzor obratovanja uparjalnika*
Table 1. The p*rocess parameters defining the working state of the revaporizer for which the numerical analysis is performed*

parametri postopka process parameters					
$T_{sur}\left[{}^oC\right]$	$\xi_{C_3H_8}\left[\%\right]$	$\dot{m}_{LPG}\left[kg/h\right]$	$v_w\left[m/s\right]$	sekundarna kapljevina secondary liquid	$H_{sl}\left[m\right]$
+ 20,0	0,6	$1,0\cdot\dot{m}_{LPG,opt}$	10,0	transformatorsko olje mineral oil	$H_{sl,max}$

definirajo izbrano delovno točko, so podani v preglednici 1.

V uparjalniku potekajo postopki odvisnega prenosa toplote: (a) naravna konvekcija sekundarne kapljevine v posodi uparjalnika, (b) dvofazni (konvektivno uparjanje) in enofazni (pregretje parne faze) diabatni tok UNP-a skozi vijačni cevni snop ter (c) prenos toplote v okolico (toplotne izgube). Zapletena geometrijska oblika cevnega snopa ter notranja zanka naravne konvekcije v plašču uparjalnika ne omogočata izrabe uveljavljenih metod in izkustvenih izrazov za termohidravlični preračun preprostejših izvedb uparjalnikov [24]. Uporaba metod računalniške dinamike tekočin omogoča zanesljivo vrednotenje poteka naravne konvekcije v plašču ([5] in [7]). Po drugi strani te metode za zdaj še ne dajejo zadovoljivih rezultatov na področju numerične simulacije konvektivnega uparjanja pri gospodarskih industrijskih napravah ([5] in [10]). Na pokrovu uparjalnika so krmilni instrumenti, katerih merilne veličine je mogoče uporabiti za spremljanje integralnih kazalnikov obratovanja uparjalnika. Kombinacija uveljavljenih izkustvenih zvez, računalniška dinamika tekočin in fizikalne meritve (krmilni instrumenti na pokrovu uparjalnika) zagotavljajo želene rezultate.

3 NUMERIČNI MODEL

Poskusi s 3D numeričnim modelom uparjalnika so pokazali, da je ta način prezahteven, tako z vidika velikosti problema kakor tudi zaradi svoje zapletenosti in potrebe po velikem številu poenostavitev. Računalniški program FIDAP 8.5, s katerim smo izvedli izračune, ne omogoča modeliranja pojavov, ki nastopajo pri spremembi agregatnega stanja v sistemu kapljevina – para [7]. Popolno uparjanje zmesi propana in butana, ki poteka od vrednosti masnega deleža parne faze 0 do vrednosti 1, prehaja skozi vse načine dvofaznega toka ([3] in [20]) (od mehurčastega prek obročastega do disperzno-kapljičastega) in je izredno zahtevno za numerično modeliranje. Zato smo vpeljali *navidez osnosimetrični* prerez uparjalnika (sl. 3). V nadaljevanju utemeljujemo vpeljavo te poenostavitve:

(a) Problem naravne konvekcije v posodi uparjalnika s sredinsko nameščenim grelnikom je osnosimetričen, torej so učinki obodnega deleža toka zanemarljivi.
(b) Vpliv »plazečih tokov«, ki se pojavljajo vzdolž vijačnih lokov cevnega snopa, je zaradi lokalnega pomena slednjih in njihove nizke intenzitete zanemarljiv.
(c) Odseki pomožnih povezovalnih cevi so zelo kratki v primerjavi z razvito dolžino cevnega snopa in bistveno ne vplivajo na termohidravlično dogajanje v plašču uparjalnika (kolena in podobni odmiki od enoličnosti pretočne poti – sl. 1 – poz.

prescribed outlet temperature of the superheated LPG gas phase. The process parameters defining the selected working point are presented in Table 1.

Within the revaporizer, conjugate heat-transfer processes occur: (a) natural convection of the secondary liquid in the revaporizer vessel, (b) two-phase (convective boiling) and single-phase (superheating of the gas phase) non-adiabatic LPG flow through the helically formed tube bundle and (c) heat transfer to the surroundings (heat loses). The complex geometry of the tube bundle and the internal loop of natural convection in the revaporizer vessel do not allow the use of well-established methods and empirical correlations for the thermohydraulic analysis for a simple design of the evaporators. The methods of computational fluid dynamics enable a reliable evaluation of the natural covection in the shell ([5] and [7]). However, these methods have so far not given satisfactory results in the area of the numerical simulation of convective boiling processes in industrial vaporisers ([5] and [10]). On the revaporizer cover there are control instruments that may be used to give us values of the integral working parameters. Therefore, the combination of known empirical corelations, computational fluid dynamics and measurements (control instrument on the revaporizer cover) is used to obtain the desired results.

3 NUMERICAL MODEL

The modelling work on the construction of a 3D numerical model of the revaporizer showed the complexity of the 3D approach and the need for many simplifications in order to obtain results. The FIDAP 8.5 program package was used to solve the governing equations of fluid flow. Physical phenomena occurring during the phase transformation in the liquid–gas system could not be modelled by the program capabilities [7]. The total evaporation of the propane–butane mixtures, ranging from vapour quality 0 to 1, passes through all the regimes of the two-phase flow ([3] and [20]) (from bubbly, through annular, to the dispersed-flow regime) and is very complex for the numerical modelling. These reasons led us to the introduction of a quasi-axisymmetric section of the revaporizer (Figure 3). Explanations for these simplifications are given below:

(a) The natural convection phenomenon in the revaporizer vessel with the heater in its central part may be considered as an axisymmetrical one as the effects of the tangential velocity component can be neglected.
(b) The creeping flows occurring along the tube bends are only important on a local scale because of its low intensity. Therefore, we can also neglect its influence on the flow field.
(c) The length of the auxiliary connecting tubes is very short compared with the total length of the tube bundle, and its effect on the thermohydraulic conditions of the revaporizer is not important (bends and similar curved flow paths (Figure 1 –

10, 11 in 12) imajo lahko pomemben vpliv na režim dvofaznega toka v področju uparjanja [6]).

(d) Pojavi mehurčastega vrenja in konvektivnega izparevanja, ki potekajo v dvojni vijačni cevni spirali, so zaradi majhnih vrednosti sistemskih parametrov $(p, \dot{q}, G)$ in nizke intenzitete sredobežnih sil razširjeni vzdolž večjega dela cevnega snopa. Zato je mogoče dvofazni tokovni režim v področju uparjanja, ki poteka vzdolž posameznega cevnega loka, preslikati v en sam pripadajoči mu krožni prerez v osnosimetrijski ravnini. Enaka analogija velja v področju pregretja parne faze UNP-a.

(e) Nagib cevnih lokov je zelo majhen in ga z vpeljavo osnosimetričnega modela zanemarimo. S tem so spiralni cevni loki nadomeščeni z dvema vrstama sosrednjih zvitkov.

(f) Zračni prostor nad gladino pomeni dodaten upor toplotnim izgubam v okolico. Vpliv naravne konvekcije v tem delu posode smo v tej fazi dela zanemarili. Ta poenostavitev ni imela bistvenega vpliva na rezultat izračuna.

(g) Električni grelnik je stisnjene izvedbe (velika površina za prenos toplote na enoto prostornine) in ga je mogoče numerično modelirati s porozno snovjo z ustrezno predpisanimi snovnimi lastnostmi (poroznost in prepustnost).

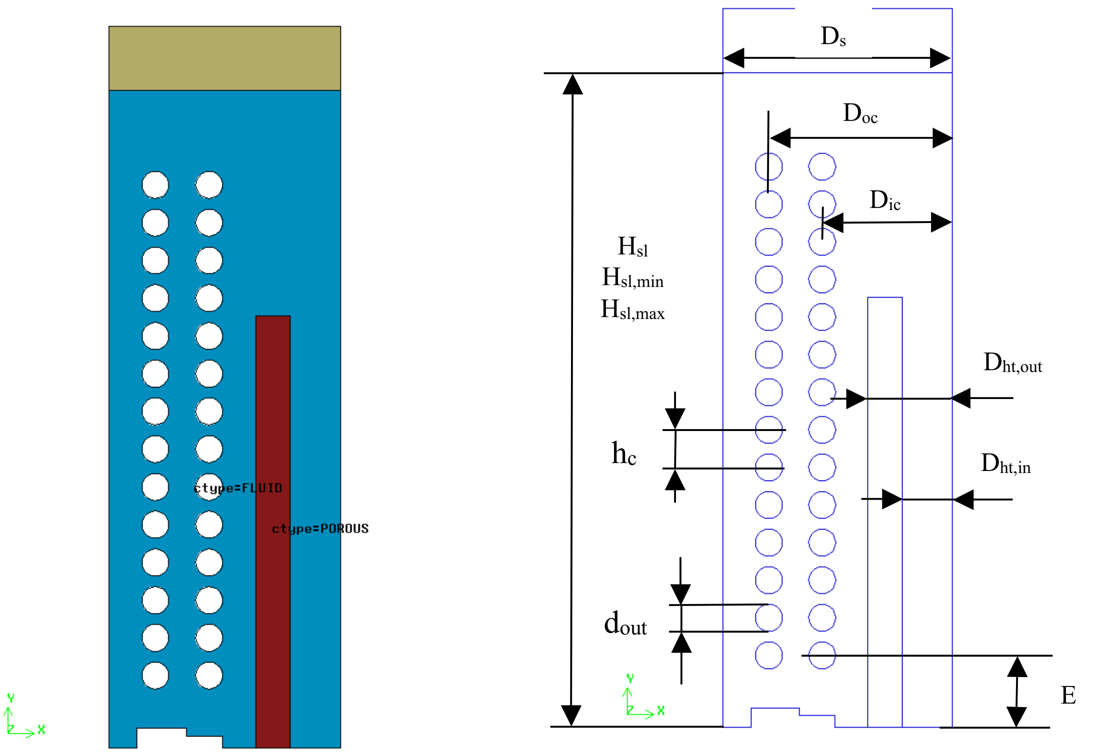
pos. 10, 11 and 12) but may play an important role in the two-phase flow regime when convective boiling occurs [6]).

(d) Because of the low values of the system parameters $(p, \dot{q}, G)$ and low centrifugal forces, the processes of bubbly boiling flow and convective evaporation are spread over a large part of the tube bundle. Because of this, the two-phase flow regime that occurs within one tube turn could be represented by a corresponding circular section in the axisymmetric plane. The same analogy is valid in the region of superheating of the LPG gas phase.

(e) The slope of the tube turn has a very low value and can be neglected when the axisymmetrical section is introduced. Thus, helically coiled turns in the 3D presentation are substituted by two rows of concentric rings.

(f) The air space above the free surface represents an additional thermal factor. Natural convection in this part of the vessel was neglected as its impact on heat loses was assumed to be negligible.

(g) The electrical heater has a compact form (large heat-transfer surface per unit volume) and can be numerically modelled as a heated porous region with suitably selected physical and transport properties (porosity and permeability).



(a) **(b)**

Sl.3. *Navidez osnosimetrični prerez uparjalnika: (a) področji reševanja vodilnih enačb toka, (b) geometrijske veličine prereza*

Fig. 3. *Quasi-axisymmetrical section of revaporizer: (a) regions where governing equations are solved, (b) geometrical dimensions*

4 VODILNE ENAČBE

Numerična simulacija tokovnih in toplotnih razmer je izvedena za področje naravne konvekcije sekundarne kapljevine v uparjalniku. Naravno konvekcijo v zračnem prostoru nad prosto gladino smo zanemarili. Področje sekundarne kapljevine je razdeljeno na področje naravne konvekcije in področje toka skozi porozni grelnik. V nadaljevanju so podane vodilne enačbe za področje toka v sekundarni kapljevini in poroznem grelniku [7].

4 GOVERNING EQUATION

The numerical calculation of the velocity and temperature fields is performed in the region of natural convection of the secondary liquid in the revaporizer shell and in the region of the porous heater. The natural convection within the air space over the free surface was neglected. The governing equations describing the physics of the problem can be written separately for natural convection in a pure fluid and for flow in a porous region [7].

4.1 Naravna konvekcija v plašču uparjalnika

Splošna oblika zakona ohranitve mase se glasi:

4.1 Natural convection in the revaporizer vessel

The general form of the continuity equation is written as:

$$\frac{\partial \rho}{\partial t} + \left(\rho u_i\right)_{,i} = 0 \qquad (1),$$

kjer sta ρ gostota, u_i pa vektor hitrosti. Ohranitev gibalne količine, pri kateri je upoštevan Boussinesqueov približek temperaturne spremenljivosti gostote le pri masnih silah, je podana z enačbo:

where ρ is the fluid density and u_i is the velocity vector. The momentum equation with Boussinesq's approximation, where the temperature's influence on the fluid mass density is considered only within the body force term, is written as:

$$\rho_0\left(\frac{\partial u_i}{\partial t} + u_j u_{i,j}\right) = -p_{,i} + \left[\mu\left(u_{i,j} + u_{j,i}\right)\right]_{,j} + \left(\rho - \rho_0\right) g_i \qquad (2).$$

V enačbi (2) so ρ_0 gostota pri primerljivi temperaturi T_0, p termodinamični tlak, μ dinamična viskoznost in g_i težnostni pospešek. Ob tem velja povezava $\left(\rho-\rho_0\right)/\rho_0 = -\beta_T\left(T - T_0\right)$, ki pomeni normalizirano funkcijsko odvisnost gostote od temperature. Z β_T je označen prostorninski temperaturni raztezek. Energijska enačba za temperaturo kot neodvisno spremenljivko se glasi:

In equation (2), ρ_0 represents the fluid density at the reference temperature T_0, p is the thermodynamic pressure, μ is the dynamic viscosity and g_i is the gravity vector. The term $\left(\rho-\rho_0\right)/\rho_0 = -\beta_T\left(T - T_0\right)$ represents a normalized density temperature variation function, where β_T is the thermal volume expansion coefficient. The energy equation with temperature as an independent variable is written as:

$$\rho c_p\left(\frac{\partial T}{\partial t} + u_i T_{,i}\right) = \left(\lambda T_{,i}\right)_{,i} + I \qquad (3),$$

kjer so c_p specifična izobarna toplota, T temperatura, λ toplotna prevodnost in I intenziteta toplotnega vira oz. ponora.

where c_p is sthe pecific isobaric heat, T stands for the temperature, λ is the heat conductivity and I is the heat source.

4.2 Tok sekundarne kapljevine skozi porozni grelnik

Zakon ohranitve mase je podan z enačbo (1). Zakon ohranitve gibalne količine se glasi [7]:

4.2 Secondary liquid flow through the porous region

The continuity equation is presented with expression (1). The momentum equation for the porous region can be written as [7]:

$$\frac{\rho}{\phi}\frac{\partial u_i}{\partial t} + \left(\frac{\rho\varpi}{\sqrt{\kappa_i}}\left\|u_i\right\| + \frac{\mu}{\kappa_i}\right)u_i = -p_{,i} + \left[\bar{\mu}(u_{i,j} + u_{j,i})\right]_{,j} + \rho g_i \qquad (4),$$

kjer so ϕ poroznost, ϖ koeficient vztrajnosti, κ_i prepustnost porozne snovi, $\|u\|$ absolutna vrednost hitrostnega vektorja in $\bar{\mu}$ dejanska dinamična viskoznost. Energijsko enačbo zapišemo v obliki:

where ϕ is the porosity, ϖ is the inertia coefficient, κ_i is the permeability of the porous matter, $\|u\|$ is the magnitude of the velocity and $\bar{\mu}$ is an effective dynamics viscosity. The energy equation is written as:

$$\left(\rho c_p\right)_e \frac{\partial T}{\partial t} + \rho c_p u_j T_{,j} = \left(\lambda_e T_{,j}\right)_{,j} + I \qquad (5),$$

kjer indeks e velja za primerjalne lastnosti, ki

where subscript e indicates an effective property whose povezujejo posamezne lastnosti tekočine in trdne faze, in so predpisane z naslednjimi izrazi: $(\rho c_p)_e = \phi\rho c_p + (1-\phi)(\rho c_p)_s$ in $\lambda_e = \phi\lambda + (1-\phi)\lambda_s$. V teh izrazih se indeks *s* nanaša na lastnosti trdnine, lastnosti brez indeksa pa veljajo za kapljevino. Zgoraj podani sistem enačb predstavlja znani Forchheimer-Brinkmanov model porozne snovi.

value needs to be prescribed on the basis of the average properties of the liquid and solid phases. These properties are defined by the next expressions: $(\rho c_p)_e = \phi\rho c_p + (1-\phi)(\rho c_p)_s$ and $\lambda_e = \phi\lambda + (1-\phi)\lambda_s$. Here, the subscript *s* refers to solid matrix properties, and the properties without subscripts are those of the liquid phase. The equation system presented above is sometimes referred to as the Forchheimer-Brinkman model.

5 ROBNI POGOJI

5 BOUNDARY CONDITIONS

V nadaljevanju so podani robni pogoji na mejah računskega območja Ω navidezno osnosimetričnega prereza uparjalnika. Predpisani so hitrostni in toplotni robni pogoji. Hitrostni robni pogoj podamo v naslednji splošni obliki

The boundary conditions on the boundaries of the computational domain Ω of the quasi-axisymmetrical revaporizer section are presented. The velocity and hea-transfer boundary conditions are prescribed. The velocity boundary conditions are written as:

$$u_i = u_i(l,t) \quad (6),$$

kjer je *l* koordinatna razdalja vzdolž ustreznega roba. Vzdolž vseh robov so vrednosti hitrostnega vektorja nič. Na simetrijski osi je normalna komponenta hitrosti nič, medtem ko je vzdolž simetrijske osi predpisan pogoj »proste« vrednosti vzdolžne komponente hitrosti [7]. Mešani (Cauchyjev) toplotni robni pogoj se glasi:

where *l* is the coordinate distance along the appropriate boundary. The zero-velocity boundary condition is prescribed along all the solid boundaries. On the symmetry axis of the revaporizer the free-slip boundary condition is set. The momentum flux has to be zero in the direction normal to the symmetry axis [7]. The general form of the mixed boundary condition is given by the expression:

$$\dot{q} = \alpha(T - T_{ref}) \quad (7),$$

kjer so $\dot{q}$ gostota toplotnega toka, α toplotna prestopnost in T_{ref} temperatura okolice. Mešani robni pogoji so predpisani vzdolž dna, plašča in pokrova uparjalnika ter v področju konvektivnega uparjanja in pregretja parne faze UNP-a (cevni loki). Za vsak izmed teh robov določimo vrednost toplotne prestopnosti in vrednost primerljive temperature. Neumannov robni pogoj (gostota toplotnega toka) se glasi:

where $\dot{q}$ is the heat flux, α is the convective heat-transfer coefficient and T_{ref} is a reference temperature (surroundings temperature). The mixed (Cauchy) boundary conditions for heat transfer are prescribed along all the boundaries of the computational domain. These boundaries are the bottom, the shell, the revaporizer cover and the circular sections of the helical tube where the convective boiling and superheating of the LPG take place. The Neumann boundary condition (constant heat flux):

$$\dot{q} = konst \quad (8),$$

in je predpisan vzdolž robov poroznega grelnika.

is prescribed along the boundaries of the porous heater.

5.1 Toplotni robni pogoji

5.1 Temperature boundary conditions

Na robovih računskega območja predpišemo prilagojeno toplotno prestopnost, s katero upoštevamo tudi prevod toplote skozi trdne stene. Pri vijačnih spiralnih ceveh je opazna določena trajna deformacija prečnega prereza, ki je posledica postopka izdelave. Neenakomernost debeline cevne stene zato vpliva na značilnosti prevoda toplote skozi steno cevi. Jensen [9] je podal analitično rešitev tega problema. V našem primeru smo ta vpliv zanemarili in upoštevali dejansko debelino cevne stene pred izdelavo (imenska debelina). Prilagojeno toplotno prestopnost določimo s splošno veljavnim izrazom,

On the boundaries of the computational domain a modified heat-transfer coefficient way prescribed. In this way the heat conduction through the solid walls of the computational region was also taken into consideration. As result of the manufacturing process the helically coiled tubes have some permanent deformation of the transverse section. Accordingly, the non-uniformity of tube-wall thickness affects the heat transfer through the tube walls. Jensen [9] presented an analytical solution of this problem. Here, we have neglected this effect and taken the actual tube-wall thickness before the manufacturing process. Thus, the next expression ki se glasi:

$$\alpha^* = 1/(R + 1/\alpha) \quad (9),$$

kjer je R upor prevoda toplote. Vrednost upora prevoda toplote je določena z izrazom $R = \delta/\lambda$ za ravno steno (dno in pokrov plašča) in z izrazom $R = 1/(2\pi\lambda)\cdot\ln(d_{out}/d_{in})$ za krožno steno (plašč, cev cevnega snopa). Z δ je označena debelina prevodne stene, z d_{out} zunanji in z d_{in} notranji premer krožne stene. Za vsako izmed področij določimo vrednost toplotne prestopnosti, izrazi, ki veljajo za vsako izmed teh področij pa so podani v nadaljnjih oddelkih. Temperaturni robni pogoj v območju obtekanja posode zapišemo z enakostjo:

$$T_{ref} = T_{sur} \quad (10),$$

kjer je T_{sur} temperatura okolice (preglednica 1). V primeru uparjanja dvokomponentne zmesi UNP-a obstaja temperaturno območje uparjanja. Domnevamo, da se temperatura zvišuje linearno v področju uparjanja. Zaradi osnosimetrične ponazoritve uparjalnika je treba podati ločene vrednosti temperature za vsak izmed cevnih lokov. Temperaturni robni pogoj se tako v področju uparjanja glasi:

$$T_{ref} = T_{bub} + (n_{cb} - 1)\Delta T_{cb} \quad (11),$$

kjer so: T_{bub}temperatura vrelišča binarne zmesi propana in butana, n_{cb} – število cevnih lokov, znotraj katerih poteka konvektivno uparjanje UNP-a, ΔT_{cb} pa je temperaturno območje med dvema sosednjima lokoma v področju uparjanja in je podano z izrazom:

$$\Delta T_{cb} = (T_{dew} - T_{bub})/n_{cb} \quad (12).$$

T_{dew} je temperatura rosišča binarne zmesi propana in butana. Tudi v področju pregrevanja parne faze UNP-a domnevamo linearno naraščanje temperaturnega poteka. Primerljiva temperatura je podana z izrazom:

$$T_{ref} = T_{dew} + (n_{sup} - 1)\Delta T_{sup} \quad (13),$$

kjer sta n_{sup} število cevnih lokov znotraj katerih poteka pregrevanje parne faze UNP-a, ΔT_{sup} pa temperaturna razlika med sosednjima lokoma v področju pregrevanja in je podana z enačbo:

$$\Delta T_{sup} = (T_{out} - T_{dew})/n_{sup} \quad (14).$$

S T_{out} je označena temperatura pregrete parne faze UNP-a na izstopu iz uparjalnika.

for the modified heat-transfer coefficient is obtained:

where R represents the heat conduction resistance. The heat conduction resistance is defined by the expression $R = \delta/\lambda$ for the plain wall (bottom and revaporizer cover) and by the expression $R = 1/(2\pi\lambda)\cdot\ln(d_{out}/d_{in})$ for the circular wall (revaporizer shell, tubes of tube bundle). The δ stands for the thickness of the conducting walls, d_{out} is the outer and d_{in} the inner diameter of the circular wall. The temperature boundary condition in the region of the air flow around the revaporizer shell is written as

where T_{sur} is the temperature of the surroundings (Table 1). In the case of an LPG binary mixture a temperature range of evaporation exists. We have supposed that the temperature in this region increases linearly. Due to the axisymmetrical approximation an individual value for the temperature has to be prescribed separately for each of the tube turns. The temperature boundary conditions in the region of the convective boiling of the binary mixture of propane and butane are written as:

where T_{bub} is the bubble-point temperature of the propane–butane mixture, n_{cb} is the number of tube turns in the region of convective boiling and ΔT_{cb} is the temperature difference between adjacent turns of the helically coiled tube in the region of convective boiling, defined by the expression

T_{dew} is the dew-point temperature of the butane–propane mixture. In the superheating region the reference temperature is defined by the expression

where n_{sup} represents the number of tube turns in the region of the superheating of the propane–butane mixture, ΔT_{sup} is the temperature difference between adjacent tube turns in the superheating region defined by the expression:

where T_{out} is the outlet temperature of the propan–-butane vapour phase.

5.2 Enofazni tok v vijačni cevni spirali

Zaradi vijačne oblike pretočne poti so delci tekočine med pretokom izpostavljeni delovanju sredobežnih sil, kot posledica delovanja teh sil pa je prostorska struktura toka bistveno drugačna od tiste, ki jo poznamo pri ravnih ceveh. Tekočinski delci v bližini aksialne osi cevi se gibljejo z največjimi hitrostmi in so izpostavljeni večjim sredobežnim silam od počasneje se gibajočih delcev v neposredni bližini cevne stene. Posledica tega je struktura toka, v kateri se tekočina v središčnem področju cevi premika stran od krivinskega središča vijačnice, tekočina ob cevni steni pa prav nasprotno v smeri simetrijske osi vijačnice. Pojav je znan kot *sekundarno gibanje* v ukrivljenih vodih, ki se superponira na glavno vzdolžno smer toka. Tok se tako sestoji iz para spiralnih vijačnih vrtincev [26]. Odstopanja hidrodinamičnih in toplotnih karakteristik vijačnih cevi v primerjavi z ravnimi cevmi je mogoče pripisati prav pojavu sekundarnega gibanja. V splošnem je, v primerjavi z ravnimi cevmi ob enakih pogojih toka, prenos toplote izboljšan, tlačne izgube pa so nekoliko večje.

Za prehod iz laminarnega v turbulentni režim toka v vijačnih cevnih spiralah velja Schmidtova odvisnost [22], ki podaja kritično vrednost *Re* števila in se glasi:

5.2 Single-phase flow in helically coiled tubes

Because of the helical flow path the fluid particles are subjected to centrifugal forces. Because of this, the spatial flow structure is significantly different from the one which occurs in straight tubes. Fluid particles flowing close to the tube's longitudinal axis have the maximum velocity values and they are subjected to the maximum centrifugal forces in contrast to slowly moving particles in the vicinity of the tube walls. Liquid in the central part of the tube section moves away from the symmetry axis of helical tube. In contrast, liquid in the vicinity of the tube walls moves towards the helical tube symmetry axis. This phenomenon is known as *secondary flow* in curved pipes and it is superimposed on the main axial flow direction. Thus the flow consists of a pair of helical spiral vortices [26]. The hydrodynamic and heat-transfer characteristics are different in comparison with straight tubes and they can be attributed exclusively to the occurence of secondary flow. Normally, heat transfer and pressure losses in comparison with straight tubes under the same flow conditions are increased in helically coiled tubes.

For the laminar-to-turbulent flow transition in helically coiled tubes the Schmidt correlation [22] is used, which represents the critical value of the *Re* number as

$$\mathrm{Re}_{cr} = 2300\left[1+8,6\left(\frac{d_{in}}{D_{mc}}\right)^{0,45}\right] \qquad (15).$$

Reynoldsovo število je defirano kot $\mathrm{Re} = v \cdot d_{in}/\nu$, z d_{in} pa je označen notranji premer cevi vijačne cevne spirale. D_{mc} označuje prilagojeni premer vijačnice, ki upošteva vzpon vijačnice glede na vodoravno ravnino [25] in je podan z izrazom:

The Reynolds number is defined as $\mathrm{Re} = v \cdot d_{in}/\nu$, where d_{in} is the inner tube diameter of the helically coiled tube. D_{mc} represents the diameter of the modified coil, including the slope of the helical tube with respect to the horizontal plane [25], and is written as:

$$D_{mc} = D_c\left[1+\left(\frac{h_c}{\pi D_c}\right)^2\right] \qquad (16).$$

Z D_c je označen premer vijačnice, s h_c pa korak vzpona vijačnice. Schmidt [22] je ugotovil, da med laminarnim in popolnoma razvitim turbulentnim območjem obstaja prehodno območje toka, za katero velja $Re_{cr} < Re < 2.2x10^4$. Za določitev toplotne prestopnosti v področju turbulentnega toka podajamo odvisnost Gnielinskega [8], ki se glasi:

The helical coil diameter is D_c and h_c is the helical tube pitch. Schmidt [22] found that between the laminar and the turbulent flow region a transition region exists, where $Re_{cr} < Re < 2.2x10^4$. An estimation of the heat-transfer coefficient in the turbulent region can be made by means of the Gnielinski correlation [8], written as:

$$Nu = \frac{\xi/8 \cdot \mathrm{Re} \cdot \mathrm{Pr}}{1+12,7\sqrt{\xi/8}\,\left(\mathrm{Pr}^{2/3}-1\right)} \qquad (17),$$

kjer je ξ količnik trenja in je podan z izrazom:

where ξ is the friction factor defined as

$$\xi = \left[\frac{0.3164}{\mathrm{Re}^{0.25}}+0,03\left(\frac{d_{in}}{D_{mc}}\right)^{0,5}\right] \qquad (18).$$

Pr je Prandtlovo število, ki je definirano s $\mathrm{Pr} = \mu \cdot c_p/\lambda$. Nusseltovo število je definirano z izrazom $Nu = \alpha \cdot d_{in}/\lambda$. Območje veljavnosti podanega izraza za določitev *Nu* števila ter tekočine, na katere se izraz nanaša, so podani v

Pr is the Prandtl number defined as $\mathrm{Pr} = \mu \cdot c_p/\lambda$ and the Nusselt number is defined as $Nu = \alpha \cdot d_{in}/\lambda$. The ranges within which the presented expression for the Nu number can be used and the fluids for which this correlation was derived are presented in [9] and [22].

[9] in [22]. Domnevamo, da ekstrapolacija tega izraza na območje parametrov postopkov, ki veljajo v našem primeru, ne povzroča večje napake izračuna.

We suppose that the extrapolation of the presented expression over the range of process parameters encountered in our computations will not significantly affect the results of the numerical analysis.

5.3 Konvektivno uparjanje v vijačni cevni spirali

5.3 Convective boiling in helically coiled tubes

Sistematično obdelanih podatkov o konvektivnem uparjanju zmesi propana in butana ni v dostopni literaturi. Enako velja za raziskave konvektivnega uparjanja binarnih zmesi v vijačnih cevnih spiralah ([3], [12] do [14] in [25]) . Zato smo omejeni na uporabo izrazov, ki veljajo za uparjanje najpogosteje raziskovanih binarnih zmesi (hladiva) v ravnih ceveh. Pri konvektivnem uparjanju binarnih zmesi je *konvektivno izparevanje* prevladujoč mehanizem spremembe agregatnega stanja. Področje *mehurčastega vrenja* je premaknjeno proti večjim vrednostim pregretja cevne stene ali pa se sploh ne pojavlja. Prispevek mehurčastega vrenja je pri konvektivnem uparjanju binarnih zmesi zadušen z učinki difuzije na medfaznih površinah rastočih mehurčkov.

Glede na intenzivnost zadušitve mehurčastega vrenja je Kandlikar [14] podal tri področja, za katera je predpisal različne izraze za določitev toplotne prestopnosti. Področja so definirana na podlagi vrednosti hlapljivosti V_1 in vrelnega števila *Bo*. Hlapljivost je definirana z izrazom:

Systematically assembled data on the convective flow boiling of prop–ne-butane mixtures cannot be found in the open literature. The same statement holds for convective flow boiling investigations of binary mixtures in helically coiled tubes ([3], [12] to [14] and [25]). Because of this we are restricted to using correlations derived for the boiling of frequently explored binary mixtures (refrigerants) in straight tubes. For binary mixtures boiling *convective evaporation* is the dominant mechanism of phase transformation. The *nucleate boiling* mechanism occurs at higher values of tube-wall superheating or it is not present at all. The contribution of nucleate boiling during the convective boiling of binary mixtures is suppressed by diffusion effects at the interfaces of growing bubbles.

With regard to the intensity of the suppression of the nucleation boiling process, Kandlikar [14] defined three regions where different expressions for the heat-transfer coefficient estimation can be used. The regions have been defined on the basis of volatility, V_1, and boiling number values, *Bo*. The volatility is written as

$$V_1 = \left(\frac{c_{p,l}}{h_{lv}}\right)\left(\frac{a}{D_{12}}\right)^{0.5}\frac{\mathrm{d}T}{\mathrm{d}x_1}\left(x_1 - y_1\right) \qquad (19),$$

kjer so: $c_{p,l}$ specifična toplota kapljevite faze, h_{lv} specifična uparjalna entalpija UNP-a, a toplotna difuzivnost, D_{12} snovska difuzivnost, x_1 molski delež komponente 1 v kapljeviti fazi in y_1 molski delež komponente 1 v parni fazi. Odvod $\mathrm{d}T/\mathrm{d}x_1$ določa strmino vrelne krivulje v diagramu T-x_1 ob določeni sestavi. Vrelno število *Bo* je definirano z izrazom:

where $c_{p,l}$ is the specific isobaric heat of the liquid phase, h_{lv} is the specific vaporisation enthalpy of LPG, a the heat diffusivity, D_{12} the molecular diffusivity, x_1 the mole fraction of component 1 in the liquid phase and y_1 the mole fraction of component 1 in the vapour phase. The derivative dT/dx_1 defines the slope of the bubble curve on the T-x_1 diagram for the selected mixture composition. The boiling number is defined as:

$$Bo = \frac{\dot{q}}{G \cdot h_{lv}} \qquad (20),$$

kjer je *G* gostota masnega toka. Snovske lastnosti zmesi propana in butana v primeru kapljevitega in plinastega agregatnega stanja so določene na podlagi izrazov iz [21] in [25].

Za izbrane parametre uparjanje poteka v področju zmerne zadušitve mehurčastega vrenja, povzročene z učinki difuzije (0,03 < V_1 < 0,2 in Bo > 1E-4). Področje prevladujočega mehurčastega vrenja ni več opazno. Konvektivno izparevanje je osnovni mehanizem prenosa toplote. Z difuzijo povzročena zadušitev je zmerna, vendar ne vpliva na člen mehurčastega vrenja v področju prevladujočega konvektivnega izparevanja. Dvofazna toplotna prestopnost v tem področju je podana z izrazom:

where *G* stands for the mass flux. The physical properties of the propane–butane mixtures in the liquid and gas states are calculated on the basis of expressions from references [21] and [25].

For selected process parameters the boiling occurs in the region of moderate suppression of nucleate boiling caused by diffusion (0.03 < V_1 < 0.2 in Bo > 1E-4). The region where nucleate boiling is the dominant mechanism does not exist. The governing heat-transfer mechanism is convective evaporation. Suppression caused by diffusion still exists, but its moderate contribution does not affect the nucleate boiling term in the region where convective evaporation dominates. The two-phase heat-transfer coefficient in this region is written as

$$\alpha_{TP,CBD} = \alpha_{lo}\left(1-x\right)^{0.8}\left[1{,}136 \cdot Co^{-0.9} \cdot f_2\left(Fr_{lo}\right) + 667{,}2 \cdot Bo^{0.7} \cdot F_{fl,m}\right] \quad (21).$$

V enačbi (21) so: α_{lo} enofazna toplotna prestopnost, za primer, da celoten tok zaseda kapljevita faza, x masni delež parne faze, Co konvektivno število, $f_2(Fr_{lo})$ množitelj Froudovega števila in $F_{fl,m}$ parameter, ki je odvisen od lastnosti tekočine in površine cevne stene. Konvektivno število je definirano z izrazom:

In expression (21), α_{lo} is the single-phase all-liquid heat-transfer coefficient, x is the mass fraction of the vapour phase or the quality, Co is the convection number, Fr_{lo} is the Froude number with all flow as liquid and $f_2(Fr_{lo})$ is the Froude number multiplier. $F_{fl,m}$ is a fluid–surface parameter that depends on the fluid and the heater surface characteristics. The convective number is defined as:

$$Co = \left(\frac{\rho_v}{\rho_l}\right)^{0,5}\left[\frac{\left(1-x\right)}{x}\right]^{0,8} \quad (22),$$

kjer sta ρ_v gostota parne faze in ρ_l gostota kapljevite faze. Množitelj Froudovega števila ima vrednost 1 za pokončne in vodoravne cevi z vrednostjo $Fr_{lo} > 0{,}4$. Za $Fr_{lo} \leq 0{,}4$ pri vodoravnih ceveh je vrednost $f_2(Fr_{lo})$ definirana z izrazom $(25Fr_{lo})^{0,3}$. Froudovo število za primer, da celoten tok zaseda kapljevita faza, je definirano z izrazom:

where ρ_v and ρ_l are the density of the vapour and the liquid phases, respectively. The Froude number multiplier is 1 for vertical tubes and for horizontal tubes with $Fr_{lo} > 0.4$. For $Fr_{lo} \leq 0.4$ at horizontal tubes the value of $f_2(Fr_{lo})$ is $(25Fr_{lo})^{0.3}$. The Fr number with all flow as the liquid is defined as

$$Fr_{lo} = \frac{G^2}{\rho_l^2 \cdot g \cdot d_{in}} \quad (23).$$

Parameter učinkov stične površine [14] je določen z vzvodnim pravilom in se glasi:

Fluid–surface parameters [14] are defined by the mixing rule as

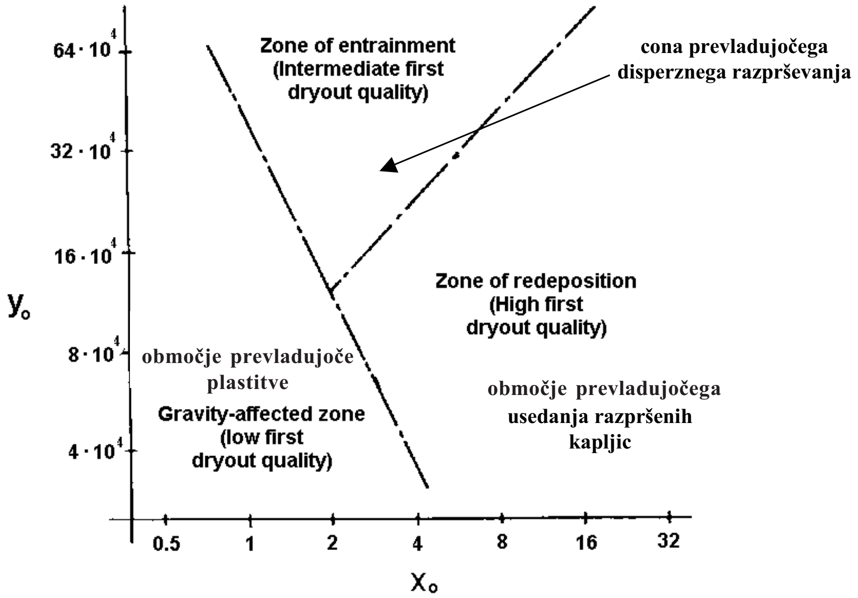
$$F_{fl,m} = x_1 F_{fl,1} + x_2 F_{fl,2} \quad (24).$$

Podani izrazi veljajo za področje popolne omočenosti cevne stene. V področju izsuševanja cevne stene se razmere spremenijo zaradi postopnega razširjanja neomočenega dela cevnega oboda. Parametri, ki najbolj vplivajo na razmere v področju izsuševanja, so sistemski tlak p, premer vijačnice D_c, gostota toplotnega toka $\dot{q}$ in gostota masnega toka G. Berthoud in Jayanti [4] sta na podlagi vpliva sistemskih parametrov določila tri karakteristična področja, v katerih prevladuje eden izmed vodilnih mehanizmov izsuševanja, in sicer: (a) področje prevladujočega disperznega razprševanja, (b) področje prevladujočega usedanja razpršenih kapljic in (c) področje prevladujoče plastitve toka. Na sliki 4 je prikazan diagram, s katerim določimo cono prevladujočih mehanizmov izsuševanja cevne stene v vijačni cevni spirali.

Brezrazsežno število $x_0 = G\Big/\left(\rho_v\sqrt{gD_c}\right)$ podaja vpliv sredobežnih sil, ki delujejo na parno fazo toka in v njej razpršene kapljice. Vpliv tega števila je najbolj pomemben v področju prevladujočega vnovičnega usedanja razpršenih kapljic. Brezrazsežno število $y_0 = G \cdot d_{in} \cdot \left(d_{in}/0{,}02\right)^{1/2}\Big/\mu_l$ je Re število kapljevite faze toka, ki je spremenimo s popravnim količnikom notranjega cevnega premera. Vpliv tega števila je prevladujoč v področju razprševanja kapljic v parno jedro toka. Za podane sistemske parametre uparjalnika je plastovito izsuševanje cevne stene prevladujoč mehanizem. Izraz za določitev masnega deleža parne faze ob začetni izsušitvi za področje

The expressions given above can be used if the tube walls are completely wetted. In the region of tube-wall dryout, the conditions are changed as non-wetted portions of the tube walls are gradually spread. The main system parameters leading to the tube-wall dryout process are the system pressure p, the helical coil diameter D_c and the heat and mass flux, $\dot{q}$ and G, respectively. By analysing the system parameters Berthoud and Jayanti [4] defined three regions with different governing mechanisms of dryout: (a) region where the dispersed entrainment is dominant, (b) region with the intensified redeposition of dispersed drops and (c) region where the flow-stratification effects dominate. In Figure 4 different zones of governing dryout mechanisms in helically coiled tubes are presented.

The nondimensional number $x_0 = G\Big/\left(\rho_v\sqrt{gD_c}\right)$ accounts for the centrifugal forces's influence on vapour phase and the dispersed drops in it. The value of this number is large in the region with the intensified redeposition of dispersed drops. The nondimensional number $y_0 = G \cdot d_{in} \cdot \left(d_{in}/0{,}02\right)^{1/2}\Big/\mu_l$ is the Re number for liquid-phase flow with a modified value of the inside tube diameter. The value of this number is large in the region of the dispersed entrainment in the vapour core of the flow. For selected system parameters the stratification or gravity-dominated dryout of the tube walls is the governing mechanism. The mass quality at the initial stage of dryout for the region in which



Sl.4 *Območja prevladujočih mehanizmov izsuševanja v vijačni cevni spirali [4]*
Fig. 4. *Zones of different dryout mechanisms in helically coiled tubes [4]*

prevladujočega vpliva plastovitosti toka oz. težnostnih sil se glasi [4]:

stratification dryout is the governing mechanism can be calculated by the expression [4]:

$$x_{ini} = 10^{7,068}\left(\frac{\rho_l}{\rho v}\right)^{-2,378}\left(\frac{Gd_{in}}{\mu_l}\right)^{-1,712}\left(\frac{G}{\rho_v\sqrt{gD_c}}\right)^{0,967}\left(\frac{\dot{q}}{Gh_{lv}}\right)^{-0,740} \qquad (25),$$

kjer je μ_l dinamična viskoznost kapljevite faze. Za praktične namene velja ugotovitev, da se popolna izsušitev cevne stene pojavi za ravnotežni masni delež parne faze z vrednostjo x_{tot} = 1. Pri plastnem izsuševanju se točka začetne izsušitve pojavi v zgornji točki cevnega oboda, nato pa se izsušitev simetrično razširja po cevnem obodu. Končni izraz za določitev toplotne prestopnosti v vijačni cevni spirali [25] se glasi:

where μ_l is the dynamic viscosity of the liquid phase. For practical purposes the total dryout of the tube walls can be considered to occur at mass quality x_{tot} = 1. When stratification is the governing mechanism of dryout, the initial dryout point appears at the uppermost circumferential tube position. Thereafter, dryout is symmetrically spread along the tube walls. Thus, the final expression for the estimation of heat-transfer coefficient within the helically coiled tube is written as:

$$\alpha = \alpha_{TP}(1-\Theta) + \alpha_{EP}\Theta \qquad (26),$$

kjer so: Θ trenutni kot omočenja cevne stene v področju uparjanja, α_{EP} toplotna prestopnost v enofaznem področju in α_{TP} toplotna prestopnost v dvofaznem področju (konvektivno uparjanje).

where Θ is the temporary angular position of the dryout propagation front in the convective boiling region, α_{EP} is the heat-transfer coefficient in the single-phase region of flow and α_{TP} is the heat-transfer coefficient in the region of two-phase flow.

5.4 Obtekanje plašča uparjalnika

Uparjalnik je v večini primerov nameščen na odprtem prostoru. Za določitev toplotnih izgub v okolico je treba podati toplotno prestopnost pri obtekanju plašča uparjalnika. Zaradi spremenljivih tokovnih razmer okrog posode uparjalnika je določitev toplotne prestopnosti zelo težavna. Za obtekanje valjaste posode uparjalnika smo uporabili znano odvisnost Churchilla in Bernsteina, ki velja za široko področje *Re* in *Pr* števil. Odvisnost velja ob pogoju $Re \cdot Pr > 0,2$ in se glasi:

5.4 Flow around the revaporizer vessel

Revaporizers are mainly manufactured without any thermal insulation. The heat-transfer coefficient for air flow around the revaporizer has to be defined if we want to allow for heat loses to the surroundings. Unsteadiness of the flow conditions around the revaporizer's shell can make such an estimation very difficult. For the flow around the cylindrical shell the well-known correlation of Churchill and Bernstein is used. The correlation is applicable to a wide range of Re and Pr numbers with the only restriction being $Re \cdot Pr > 0.2$:

$$Nu = 0,3 + \frac{0,62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0,4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5} \tag{27}$$

Snovske lastnosti veljajo za suh zrak. Hitrost zračnih tokov je upoštevana s povprečno vrednostjo hitrosti vetra, ki je usmerjena normalno na plašč uparjalnika. Pri obtekanju dna in pokrova posode smo uporabili izraz:

In equation (27) the physical properties for the dry air are selected. The velocity of the air flow is included by means of an average value of the wind velocity normal to the revaporizer shell. For flow along the bottom and the cover of the revaporizer a correlation for the turbulent flow region is used:

$$Nu = 0,037 \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \tag{28}$$

ki velja za turbulentno področje in je podan v [1].

and it has been taken from [1].

5.5 Električno uporovno gretje [2]

Prostornino, ki jo zaseda električni grelnik, smo nadomestili z porozno snovjo. Gostota toplotnega toka, ki je predpisana na robovih porozne snovi, je izračunana iz moči grelnika in njegove površine. Enačba, ki povezuje električne in toplotne veličine grelnika, se glasi:

5.5 Electrical resistance heating [2]

The revaporizer section where the electrical heater is placed was modelled as a porous region. The heat flux prescribed at boundaries of the porous heater can be calculated from heater's electric power and its surface area, as given by the expression

$$P_{el} = I^2 R_{el} = I^2\left(\frac{\rho_{el} L_w}{S_w}\right) = \frac{V_{el}^{\;2}}{R_{el}} = \dot{Q}_{ht} = \dot{q}_{ht} \cdot A_{ht} \tag{29}$$

Pri določitvi poroznosti in prepustnosti poroznega grelnika smo upoštevali navodila, ki so podana v [7]. V izrazu (29) so: P_{el} električna moč grelnika, $\dot{Q}_{ht}$ toplotna moč grelnika, $\dot{q}_{ht}$ gostota toplotnega toka grelnika in A_{ht} njegova površina.

where P_{el} is the electrical power, $\dot{Q}_{ht}$ is the power of the heater, $\dot{q}_{ht}$ is the heat flux and A_{ht} its surface area. The instruction given in [7] was taken into consideration when the porosity and the permeability of the porous heater were defined.

6 RAČUNSKI ALGORITEM

Računski algoritem, s katerim smo prišli do rešitve, je podan na sliki 5.

6 CALCULATION ALGORITHM

The calculation algorithm used to obtain the final solution of the defined problem is presented in Fig. 5.

7 REZULTATI

Računalniški program FIDAP 8.5 omogoča nastanek nestrukturirane mreže končnih elementov. Uporabljen je algoritem oblaganja za diskretizacijo računskega območja, pri čemer je opravljeno lokalno zgoščevanje mreže ob robovih računskega območja (stene posode in cevni loki). Po testiranju občutljivosti numeričnih rezultatov na gostoto mreže je bila kot primerna izbrana računska mreža s 14.900 elementi v področju toka sekundarne kapljevine in 1900 elementi v področju poroznega grelnika. Hitrosti v polju naravne konvekcije so majhne, tokovni režim je laminaren.

Postopek izračuna (slika 5) smo ponovili tolikokrat, da smo dosegli ujemanje toplotnega toka, ki ga cevni snop sprejme v področju uparjanja $\dot{Q}_{cb}$ in uparjalne entalpije UNP-a $\dot{Q}_{lv}$. Na koncu je doseženo stanje, v katerem so se rezultati nadaljnje določitve povprečne gostote toplotnega toka v področju uparjanja spreminjali le znotraj območja enega cevnega loka. To je obenem tudi največja mogoča natančnost tukaj vpeljanega postopka. Rezultati, ki so bili doseženi v zadnjem koraku izračuna, so podani v nadaljevanju.

7 RESULTS

Unstructured finite-element grids can be created with the FIDAP 8.5 program package. For the computational-region mesh generation we used the paving algorithm. Local mesh refinement in the vicinity of all the region boundaries was carried out. The study of the influence of the grid density on the numerical results resulted in an optimum mesh density with 14,900 finite elements in the region of the secondary liquid flow and 1900 elements in the region of the porous heater. The flow regime was laminar since the *Re* number value for the natural convection inside the secondary liquid flow was below the critical value.

The calculation procedure (Figure 5) had to be repeated several times before we achieved the final operational stage where the total heat received by the tube bundle in the convective boiling region $\dot{Q}_{cb}$ was equal to the vaporisation enthalpy of the LPG $\dot{Q}_{lv}$. The results obtained in the last iteration of the calculation procedure served as the basis for the discussion of the results. Convective boiling occurs inside the 21 turns of the tube bundle. The mass

Preglednica 2. *Toplotni tokovi vzdolž robov računskega območja ob pogoju nespremenljive vrednosti gostote toplotnega toka (prvi računski korak)*
Table 2. *Heat fluxes through the computational domain boundaries (first calculation step – uniform heat-flux distribution along tube bundle assumed when the boundary conditions are defined)*

Rob Boundary	Toplotni tok $[W]$ Heat flow rate $[W]$	Rob Boundary	Toplotni tok $[W]$ Heat flow rate $[W]$
lok1 turn1	30,20	**lok17 turn17**	352,20
lok2 turn2	42,30	**lok18 turn18**	341,80
lok3 turn3	51,10	**lok19 turn19**	338,20
lok4 turn4	62,20	**lok20 turn20**	334,30
lok5 turn5	70,00	**lok21 turn21**	332,10
lok6 turn6	79,40	**lok22 turn22**	281,30
lok7 turn7	89,20	**lok23 turn23**	242,00
lok8 turn8	92,30	**lok24 turn24**	212,80
lok9 turn9	101,80	**lok25 turn25**	171,70
lok10 turn10	111,30	**lok26 turn26**	114,10
lok11 turn11	118,10	**lok27 turn27**	82,30
lok12 turn12	122,20	**lok28 turn28**	43,10
lok13 turn13	131,40	**pokrov cover**	34,10
lok14 turn14	138,60	**plašč shell**	185,10
lok15 turn15	328,50	**dno bottom**	25,10
lok16 turn16	341,20	Σ	5000

Konvektivno uparjanje poteka znotraj 21 cevnih lokov. Masni delež parne faze ob začetni izsušitvi znaša $x_{ini} = 0,41$. Število cevnih lokov, znotraj katerega je opazna popolna omočenost cevnega oboda, je 9. Znotraj 12 lokov poteka izsuševanje cevne stene. Od tod naprej poteka pregrevanje parne faze UNP-a. Za podane parametre je to stanje ustaljenega delovanja uparjalnika.

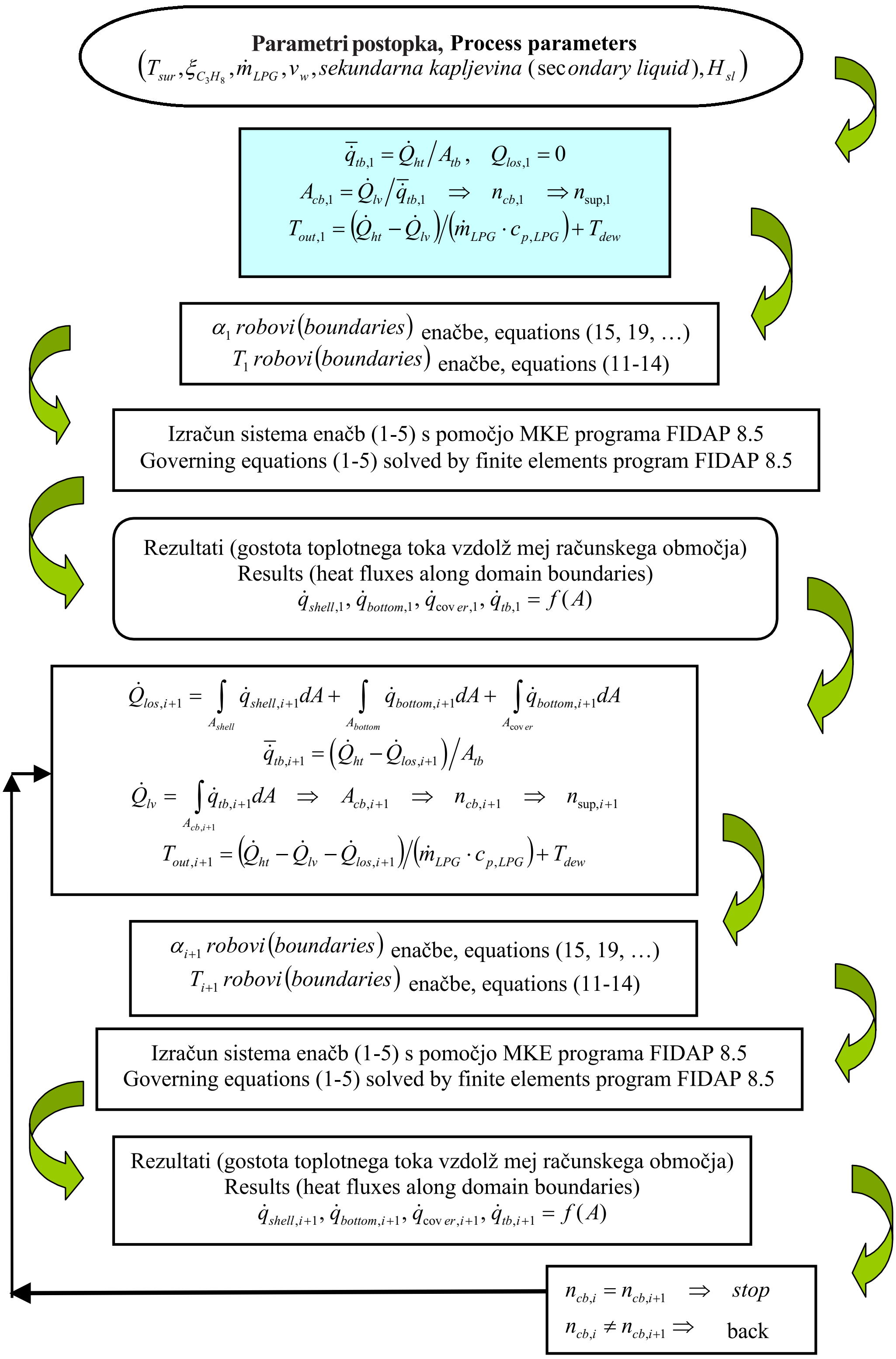
V preglednici 2 so podane vrednosti toplotnih tokov, ki jih sprejmejo posamezni loki cevnega snopa ob pogoju stalne vrednosti gostote toplotnega toka, ki prehaja na cevni snop (začetna domneva). V preglednici 3 so podane vrednosti toplotnih tokov po posameznih lokih cevnega snopa v zadnjem računskem koraku, in sicer, ko je upoštevana neenakomerna porazdelitev gostote toplotnega toka po posameznih lokih cevnega snopa (končno stanje).

Na sliki 6 je podan potek toplotne prestopnosti in temperature (robni pogoji) po posameznih cevnih lokih cevnega snopa v prvem koraku izračuna

quality of the vapour phase at the initial dryout position has a value $x_{ini} = 0.41$. It was found that the total wetting of the tube walls is present inside the first 9 turns of the tube bundle. Dryout of the tube walls takes place inside the next 12 turns of the tube bundle. From that point to the outlet of the tube bundle the superheating of the LPG occurs. For the prescribed working parameters of the revaporizer this is the steady-state operating regime.

In Table 2 the heat-flow values received by particular turns of the tube bundle are presented. As an initial assumption the uniform heat flux distribution along the tube bundle was assumed when correlations to estimate boundary conditions were used. In Table 3 the heat-flow values received by the particular turns of the tube bundle in the last calculating step are presented.

There is nonuniformity of the heat-flow distribution along the tube bundle, and it was taken into account when defining the boundary conditions



Sl.5 *Računski algoritem*
Fig. 5. *Calculating algorithm*

(nespremenljiva gostota toplotnega toka vzdolž cevnega snopa). Na sliki 7 je prikazan potek toplotne prestopnosti in temperature v zadnjem računskem koraku.

Na sliki 8a) je prikazan izsek hitrostnega polja v osnosimetričnem prerezu uparjalnika, od koder je

in the next calculating steps. The heat-transfer coefficient and the temperature distribution along tube turns are presented in Figures 6 and 7, in the first and last calculating step, respectively.

In Figure 8(a) the velocity field in the vicinity of the upper part of the electrical heater is presented. It is evident

Preglednica 3. *Toplotni tokovi vzdolž robov računskega območja v zadnjem računskem koraku, ko je upoštevana neenakomernost gostote toplotnega toka (končno stanje)*
Table 3. *Heat fluxes through the computational domain boundaries (final calculation step – nonuniform heat-flux distribution along the tube bundle taken into account when the boundary conditions are defined)*

Rob Boundary	Toplotni tok [*W*] Heat flow rate [*W*]	Rob Boundary	Toplotni tok [*W*] Heat flow rate [*W*]
lok1 **turn1**	60,00	**lok17** **turn17**	356,00
lok2 **turn2**	65,50	**lok18** **turn18**	366,00
lok3 **turn3**	68,50	**lok19** **turn19**	366,50
lok4 **turn4**	73,00	**lok20** **turn20**	367,00
lok5 **turn5**	82,50	**lok21** **turn21**	368,50
lok6 **turn6**	89,00	**lok22** **turn22**	260,00
lok7 **turn7**	95,50	**lok23** **turn23**	215,50
lok8 **turn8**	102,50	**lok24** **turn24**	106,00
lok9 **turn9**	106,00	**lok25** **turn25**	96,00
lok10 **turn10**	114,50	**lok26** **turn26**	50,50
lok11 **turn11**	119,50	**lok27** **turn27**	49,50
lok12 **turn12**	125,50	**lok28** **turn28**	48,50
lok13 **turn13**	132,00	**pokrov** **cover**	32,00
lok14 **turn14**	139,50	**plašč** **shell**	261,50
lok15 **turn15**	321,50	**dno** **bottom**	25,50
lok16 **turn16**	336,00	Σ	5000

razvidno, da so največje hitrosti grelne kapljevine največje v središčnih območjih uparjalnika (notranjost grelnika). Najmanjše hitrosti sekundarne kapljevine se pojavijo v bližini plašča uparjalnika.

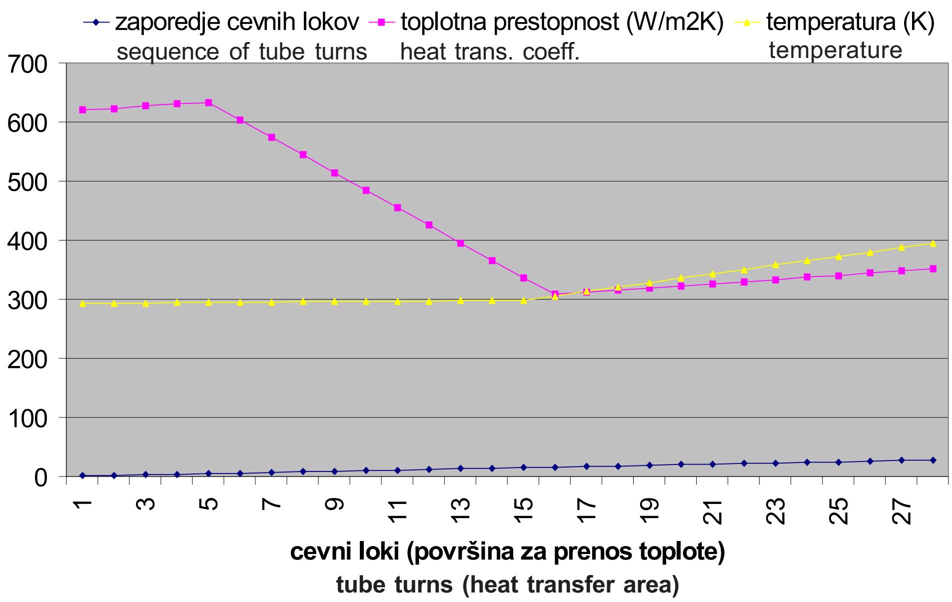
Na sliki 8b) je podan izsek temperaturnega polja v osnosimetričnem prerezu uparjalnika. Področje konvektivnega uparjanja zaseda največji del cevnega snopa. Področje majhne temperaturne razlike med sekundarno kapljevino in cevno steno je vzrok, da je konvektivno izparevanje vodilni mehanizem agregatne spremembe (temnejša področja na sliki 8b). V zgornjem delu električnega grelnika so temperature sekundarne kapljevine največje (slika 8b), vendar pa ne presegajo največje dopustne vrednosti, ki je predpisana s strani proizvajalca (130 °C).

Izstopna temperatura pregrete parne faze UNP-a je podatek, ki smo ga uporabili za preverjanje doseženih rezultatov. Polje naravne konvekcije v uparjalniku je uporabljeno za prenos krmilne veličine od izstopnega loka cevnega snopa na zaznavala

that the maximum velocities of the secondary liquid arise in the central part of the revaporizer (internal section of electrical heater). In contarast, the minimum velocities occur immediately in the vicinity of the revaporizer shell.

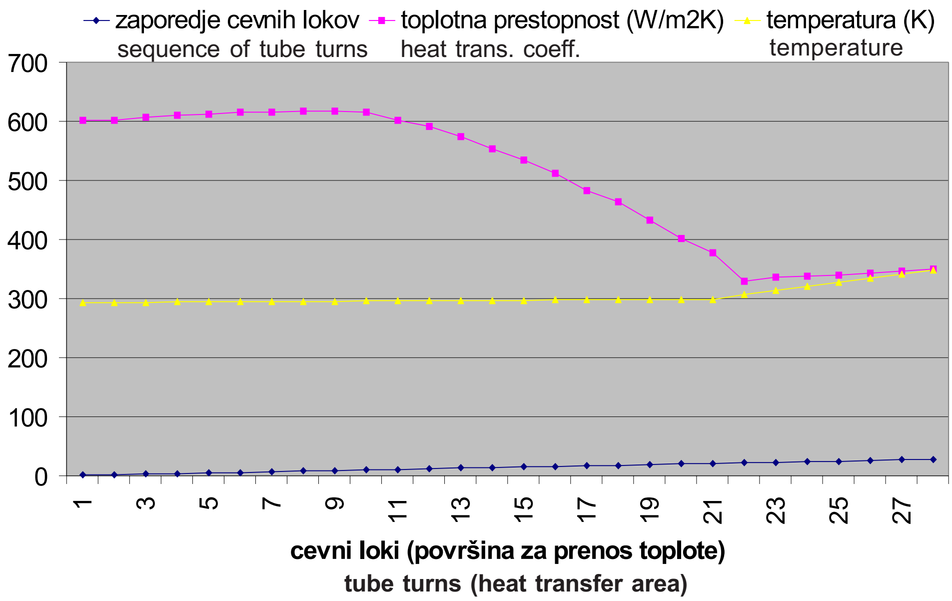
In Figure 8(b) the temperature field in the same view as in Figure 8(a) is shown. It is evident that convective boiling occupies the largest part of the tube bundle. The low temperature difference between the secondary liquid and the tube wall is the reason why the convective evaporation – as a mode of the boiling process – is the governing mechanism of the phase transition (dark regions of the plot). In the upper sections of the electrical heater the temperature reaches its maximum (see Figure 9), but its value does not exceed the allowed value prescribed by the manufacturer (130 °C).

The outlet temperature of the LPG superheated vapour phase is the parameter used for the verification of the achieved results of the numerical analysis. The natural convection field was used for regulating the value transport between the



Sl.6. *Potek toplotne prestopnosti in temperature po posameznih lokih cevnega snopa v prvem računskem koraku (robni pogoji - začetni računski korak)*

Fig. 6. *Heat-transfer coefficient and temperature distribution along the turns of the tube bundle in the first calculation step (boundary conditions – initial state)*

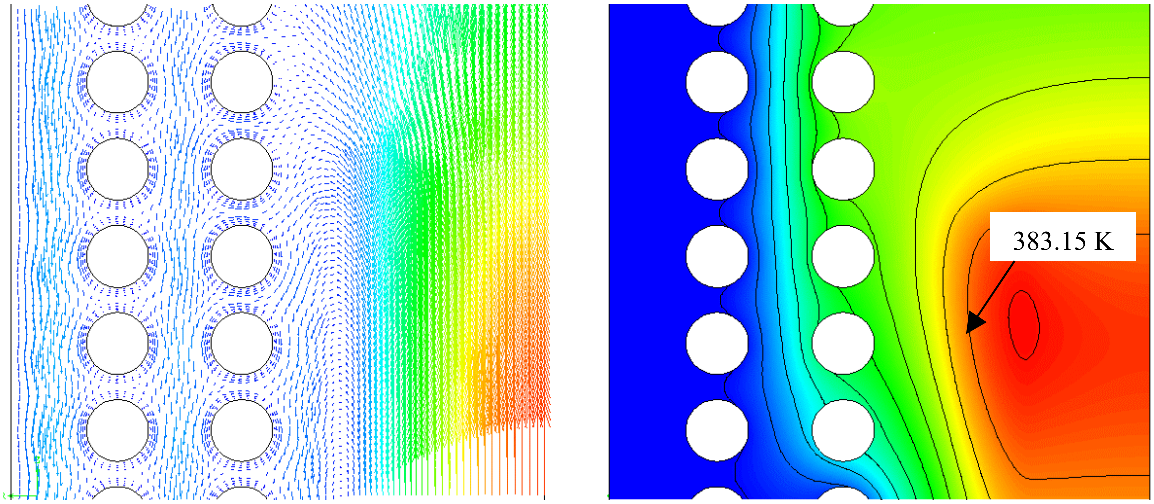


Sl.7. *Potek toplotne prestopnosti in temperature po posameznih lokih cevnega snopa, ko je doseženo končno obratovalno stanje (robni pogoji - zadnji računski korak)*

Fig. 7. *Heat-transfer coefficient and temperature distribution along the turns of the tube bundle in the last calculation step (boundary conditions – final state)*

krmilnih termostatov. Krmiljena veličina je temperatura. Za obratovanje uparjalnika je potrebno, da je temperaturno polje v točki namestitve zaznaval krmilnih termostatov vedno v predpisanem delovnem območju. Delovno območje krmilnih termostatov je od 65 °C do 85 °C. Na podlagi poteka izoterm temperaturnega polja smo ugotovili, da je temperatura v točkah namestitve krmilnih termostatov znotraj predpisanega temperaturnega območja. Temperatura v točki namestitve zaznavala termostata, ki krmili

last turn of tube bundle and the sensor of the control thermostats. The controlled value is the temperature. Undisturbed operating of the revaporizer requires that the temperature value at the thermostat sensor position has to be always within the defined temperature range. The working range of the control thermostats is from 65 °C to 85 °C. Using an isotherms plot it was found that the temperature at the location of the control thermostats lies within the defined temperature range. The temperature at the position of the thermostat



Sl.8. *Potek (a) hitrostnega in (b) temperaturnega polja v osnosimetričnem prerezu uparjalnika v področju zgornjega dela grelnika*

Fig. 8. *(a) Velocity and (b) temperature field in axisymmetrical section of revaporizer in the region of upper parts of heater*

delovanje elektromagnetnega ventila, znaša 76 °C. Doseženo stanje velja ob izbranih parametrih postopka (preglednica 1). Krmilni termostati so oprema uparjalnika, ki daje določene podatke o celostnih značilnostih delovanja naprave. Za vpogled v krajevne razmere v posameznih delih uparjalnika so potrebne podrobne meritve izbranih fizikalnih veličin. Na sliki 9 je podan prikaz temperaturnega polja v točkah namestitve tipal krmilnih termostatov.

sensor controlling the electromagnetic valve has a value of 76 °C. This operating state corresponds to the selected process parameters (Table 1). In Figure 9 the temperature field in the uppermost part of the revaporizer axisymmetrical section is presented. To get a better insight into the local conditions in particular parts of the revaporizer more accurate measurements should be performed, and their results compared with the computational results.

8 SKLEPI

Sočasen nastop večjega števila prenosnih pojavov onemogoča natančno obravnavo obnašanja uparjalnika. Zapletena geometrijska oblika cevnega snopa in električnega grelnika omejuje možnosti uporabe znanih metod dimenzioniranja in nadzora dvofaznih prenosnikov toplote. Uporaba standardnih računskih postopkov za dimenzioniranje uparjalnikov je v danem primeru nezadostna. V splošnem je zelo malo empiričnih podatkov o toplotni prestopnosti pri tokovih z naravno konvekcijo v zapletenih geometrijskih oblikah. Vodilni prenosni pojav v električnem uparjalniku je konvektivno uparjanje ukapljenega naftnega plina. Pravilno vrednotenje tega pojava je zahtevna inženirska naloga.

Pri izračunu smo domnevali, da se uparjalnik obnaša približno kot sistem z vsiljeno nespremenljivo gostoto toplotnega toka. Čeprav je krajevna porazdelitev gostote toplotnega toka neenakomerna, je povprečna vrednost le-te nespremenljiva in določena z močjo in površino grelnika (sistem s posrednim električnim gretjem). Rezultati so pokazali, da se uparjalnik obnaša kot sistem z vsiljeno temperaturno razliko (zunanje področje cevnega snopa), delno pa kot sistem z vsiljeno gostoto toplotnega toka (notranje področje

8 CONCLUSIONS

Due to different transport phenomena occuring in the revaporizer it is impossible to achieve an exact solution of the heat and flow conditions inside the device. The complex tube bundle and the electrical heater geometry restricts the implementation of well-known methods for design and rating calculations of two-phase heat exchangers. In the open literature there are not, in general, empirical data about heat-transfer coefficients due to natural convection in the systems with complex geometry. Likewise, convective boiling of LPG in helically coiled tubes is an unexplored phenomenon. The correct treatment of the latter is a demanding engineering task.

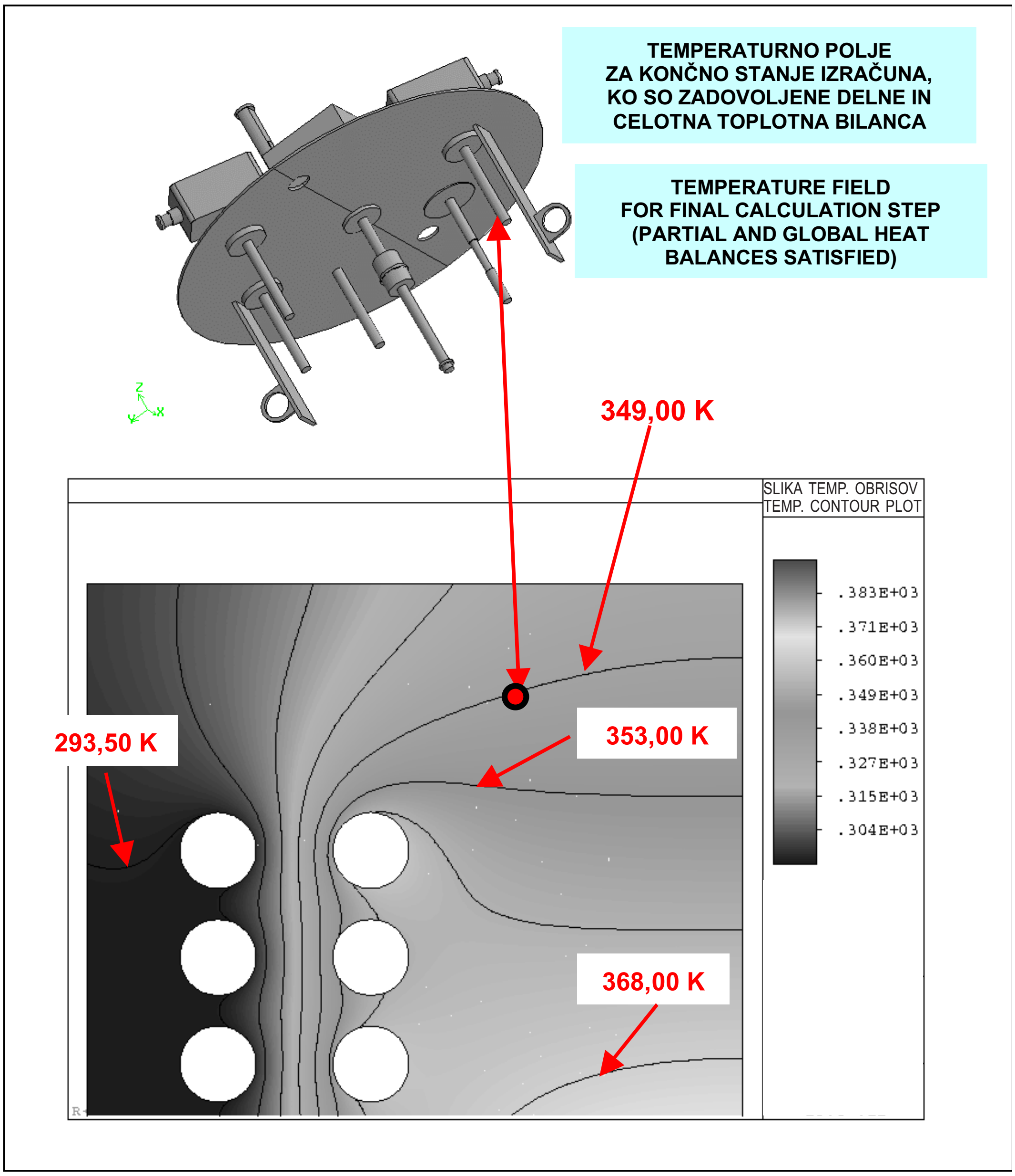
In our approach we assumed that the revaporizer operates as a system with a constantly imposed heat flux. Although the local distribution of heat flux exhibits considerable nonuniformity its averaged value is constant, defined by the heat power and the surface area of the electric heater (system with indirect electrical heating). It can be concluded that the revaporizer operates partly as a system with an imposed temperature difference (external region of the tube bundle) and partly as a system with an imposed heat flux (internal region of the tube bundle).

cevnega snopa). Uporabo preverjene Kandlikarjeve zveze za ravne cevi pri vrednotenju nasičenega uparjanja znotraj vijačne cevne spirale je mogoče pojasniti z nizko vrednostjo gostote toplotnega in masnega toka ter zanemarljivim vplivom centrifugalnih sil. Ker razpršitev ni prevladujoč pojav v področju obročastega toka, je omenjeno povezanost mogoče kombinirati z zvezo za čisto parno fazo in tako določiti toplotno prestopnost v področju izsuševanja cevne stene.

Krajevne razmere so za predpisovanje robnih pogojev na mejah računskega območja odločilnega pomena. Robni pogoji na mejah področja, kjer poteka uparjanje, so zato predpisani na temelju dandanes

The implementation of Kandlikar's correlation for the heat-transfer characteristics' estimation for saturated boiling in helically coiled tubes can be explained by the low heat and mass flux values and the negligible effects caused by centrifugal forces. Due to the fact that the dispersed entrainment is not a dominant phenomenon in the region where annular flow regime exists, Kandlikar's correlation can be combined with the correlation for the heat-transfer coefficient's estimation in the region of the all-vapour phase flow. Thus it is possible to define the heat-transfer coefficient in the dryout region of the tube bundle.

Local conditions in the revaporizer are of great importance when boundary conditions have to be



Sl. 9. *Potek temperaturnega polja v zgornjem delu uparjalnika (temperatura v točki namestitve tipala krmilnega termostata elektromagnetnega ventila)*

Fig. 9. *Temperature field in the upper part of the revaporizer (temperature is shown at the position where the thermostat sensor of the electromagnetic valve is placed)*

najbolj uveljavljenih odvisnosti. Celostni kazalniki obnašanja uparjalnika so po opravljenem toplotnem uravnoteženju pokazali veljavnost vpeljanih hipotez. Za izbrane delovne parametre je temperatura v točki namestitve zaznaval krmilnih termostatov uparjalnika dosegla predpisane vrednosti. Uparjalnik deluje znotraj predpisanega temperaturnega območja v merilnih točkah. Zadovoljene so bile delne in celotna toplotna bilanca. Kolikšen je pomen morebitnih napak, ki izvirajo iz ekstrapolacije uporabljenih odvisnosti na uparjanje UNP-a v vijačni cevni spirali, ni znano. Analiza obratovanja uparjalnika v ekstremnih razmerah oz. na mejah delovnega področja bo pokazala velikost teh napak.

prescribed. Boundary conditions on the boundaries where convective boiling takes place are prescribed on the basis of verified correlations. The observed integral characteristics of the revaporizer confirmed the correctness of our assumptions. For the selected combination of process parameters the temperature at the control sensor is within the prescribed temperature range. The local and global heat balances are satisfied. Some deviations can arise from the extrapolation of used correlations outside of the prescribed ranges. An analysis of the revaporizer operating in extreme conditions, that is in the vicinity of the borders of the working diagram can show the magnitude of these deviations.

9 OZNAKE
9 NOMENCLATURE

toplotna difuzivnost	a	thermal diffusivity
površina	A	area
vrelno število	Bo	Boiling number
konvektivno število	Co	Convective number
specifična izobarna toplota	c_p	specific heat at constant pressure
premer	D	diameter
premer cevi	d	tube diameter
difuzivnost	D_{12}	diffusion coefficient
množitelj Fr števila	$f_2(Fr_{lo})$	Fr number multiplicator
Froudovo število	Fr	Froude number
gostota masnega toka	G	mass flux
težnostni pospešek	g	acceleration due to gravity
specifična entalpija, korak vzpona vijačnice	h	specific enthalpy, helix pitch
višina	H	height
jakost električnega toka	I	electric flow rate
masni pretok	$\dot{m}$	mass flow rate
število cevnih lokov	n	number of tube turns
Nusseltovo število	Nu	Nusselt number
termodinamični tlak	p	thermodynamic pressure
Prandtlovo število	Pr	Prandtl number
gostota toplotnega toka	$\dot{q}$	heat flux
toplotni tok	$\dot{Q}$	heat flow rate
upor prevoda toplote, električna upornost	R	thermal resistance, electric resistance
Reynoldsovo število	Re	Reynolds number
prečni prerez električnega voda	S	transversal section of electrical conductor
čas	t	time
temperatura	T	temperature
hitrost	u, v	velocity
absolutna vrednost hitrostnega vektorja	$\|u\|$	absolute value of velocity vector
hlapljivost, električna napetost	V	volatility
masni delež parne faze, molski delež komponente v kapljeviti fazi	x	quality, mole fraction in liquid phase
molski delež komponente v parni fazi	y	mole fraction in vapour phase
Grški simboli		**Greek Symbols**
efektivna dinamična viskoznost	$\bar{\mu}$	effective dynamic viscosity
koeficient vztrajnosti porozne snovi	ϖ	porous inertia coefficient
modificirana toplotna prestopnost	α^*	modified heat-transfer coefficient
poroznost	ϕ	porosity
debelina cevne stene	δ	tube-wall thickness
dinamična viskoznost	μ	dynamics viscosity

gostota, specifična električna upornost	ρ	density, specific electric resistance
kinematična viskoznost	ν	kinematics viscosity
koeficient upora, masni delež	ξ	friction factor, mass fraction
kot omočenja cevne stene v področju uparjanja	Θ	tube-wall wetting angle in the boiling region
toplotna prestopnost	α	heat-transfer coefficient
toplotna prevodnost	λ	heat conductivity
permeabilnost porozne snovi	κ_I	porous permeability
prostorninski temperaturni raztezek	β_T	volumetric temperature dilatation coefficient
temperaturna razlika med sosednjima cevnima lokoma	ΔT	temperature difference between adjacent tube turns
Podpisi		**Subscripts**
vrelišče	*bub*	bubble point
vijačnica	*c*	helix
propan	C_3H_8	propan
konvektivno vrenje	*cb*	convective boiling
področje prevladujočega konvektivnega izparevanja	*CBD*	convective evaporation dominant region
rosišče	*dew*	dew point
električna veličina	*el*	electrical value
enofazno področje	*EP*	single-phase region
stična površina	*fl*	contact surface
grelnik	*ht*	heater
notranja vijačnica	*ic*	inside helix
notranji	*in*	interior
začetna vrednost	*ini*	initial value
kapljevita faza	*l*	liquid phase
celoten tok zaseda kapljevita faza	*lo*	all-flow liquid
toplotne izgube	*los*	heat losses
kapljevina - para	*lv*	liquid–vapour
modificirana vijačnica	*mc*	modified helix
zunanja vijačnica	*oc*	outside helix
optimalna vrednost veličine	*opt*	optimum value
zunanji	*out*	outer
referenčna vrednost	*ref, 0*	reference value
plašč	*s*	shell
sekundarna kapljevina	*sl*	secondary liquid
pregrevanje	*sup*	superheating
okolica	*sur*	surroundings
cevni snop	*tb*	tube bundle
končna vrednost	*tot*	final value
dvofazno področje	*TP*	two-phase region
ukapljeni naftni plin	*LPG*	liquified petroleum gas
parna faza	*v*	vapour phase
zračni tokovi okrog plašča, prevodna žica	*w*	air flow around vaporizer, conducting wire

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Naslov avtorjev: mag. Sanib Bašič
prof.dr. Leopold Škerget
doc.dr. Matjaž Hriberšek
Univerza v Maribor
Fakulteta za strojništvo
Smetanova 17
2000 Maribor
sanib.basic@uni-mb.si
leo@uni-mb.si
matjaz.hribersek@uni-mb.si

Authors' Address: Mag. Sanib Bašič
Prof.Dr. Leopold Škerget
Doc.Dr. Matjaž Hriberšek
University of Maribor
Faculty of Mechanical Eng.
Smetanova 17
2000 Maribor, Slovenia
sanib.basic@uni-mb.si
leo@uni-mb.si
matjaz.hribersek@uni-mb.si

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Razvoj programskega orodja za izbiro obrisnih postopkov rezanja

The Development of a Software Tool for the Selection of Contour-Cutting Processes

Davorin Kramar - Miha Junkar

Prispevek opisuje programsko opremo za izbiro izdelovalnega postopka pri načrtovanju posameznega strojnega dela. Predstavljen je sistematični postopek izbire za določeno izdelovalno opravilo – obrisno rezanje. Razviti računalniški program uporablja splošne podatke o zmožnostih postopkov in v postopek izbire vključuje postopkovne in stroškovne modele.

Obdelovalnost določenega materiala je utemeljena na razmerju med obnašanjem materiala obdelovanca med obdelavo in po njej in nastavljenimi postopokovnimi parameteri. Prepleteni vplivi so podani v obliki empiričnih pravil, izpeljanih s prilagajanjem funkcij na specifične materialno-postopkovne podatkovne krivulje. V naši študiji so bili tako pridobljeni empirični modeli uporabljeni za razločevanje postopkovnih zmožnosti in optimalno soizbiro materiala in postopka. Zaradi velikega obsega postopkovnih parametrov izbira optimalnega skupka parametrov ponuja možnost občutnega prihranka stroškov izdelave. Rezultati podajajo tehnologu in konstrukterju povratno informacijo o zmožnosti obdelave in stroških izdelave za določeno konstrukcijo kakor tudi napotke za poskusne postopkovne parametre.

(Ključne besede: postopki rezanja, izbor postopkov, rezanje obodno, orodja programska, razvoj orodij)

This paper describes software for the selection of a manufacturing process in the design of a single mechanical part. A systematic selection procedure for a specific manufacturing task – contour cutting – is presented. The developed software uses general data on process capabilities and incorporates process and cost modeling into the selection procedure.

The machinability of a certain material is established by the relationships between the behaviour of a workpiece material during and after processing and by the preset process parameters. Complex interactions are interpreted in the sense of empirical rules derived from experimental and specific, material-process, database curve fits. In our study such empirical models were used for discriminating between processing options, for optimum co-selection of materials and processes. Since many processing parameters are involved, selection of an optimum set of parameters offers the opportunity for a significant cost saving. The results provide the technologist and the designer with feedback on the likely influence of processing, on the viability and cost of design, as well as indicating trial processing parameters.

(Keywords: cutting processes, proces selection, contour cutting, software tools, software development)

0 UVOD

Ključni izziv, ne samo za tehnologa, ampak tudi za konstrukterja, ostaja uporaba ustrezne tehnologije za določeno izdelovalno opravilo. Za izbiro najboljših kandidatov postopkov je bistvena določitev odločitvenega kriterija. Zahteva razumljivo in zanesljivo tehnološko informacijo, s katero lahko učinkovito izvajamo načrtovanje za izdelavo (NZI - DFM) [1]. Veliko dejavnikov npr.: material, geometrijska oblika, tolerance, celovitost površine in stroški, vpliva na izbiro postopka. Pri obravnavi drugačnih konstrukcijskih rešitev z vidika kakovosti in stroškov je treba raziskati še

0 INTRODUCTION

Applying the appropriate technology to a specific manufacturing task remains the basic challenge not only for the technologist but also for the designer. The definition of the decision criteria for the selection of the best process candidates is therefore crucial. It requires comprehensible and reliable technological information, according to which the design for manufacturing (DFM) can be efficiently implemented [1]. There are many factors affecting process selection, these include: material, geometry, tolerances, surface integrity, and costs. In considering alternative design solutions for quality and cost, it is necessary to explore druge možnosti materialov, geometrijskih oblik in toleranc itn. ter mogoče izdelovalne postopke. To zahteva izbiro ustreznega postopka prek vseh možnosti in oceno stroškov izdelave že v fazi razvoja izdelka.

Veliko podjetij običajno sledi zaporednemu razvoju izdelka. Tu izdelovalna vprašanja sledijo konstrukcijskim korakom brez povratne informacije, tako vpliv potencialno slabega načrtovanja na stroške izdelka ni prepoznaven.

Stroške izdelka sestavljajo stroški načrtovanja, stroški izdelave, stroški, povezani z jamstvom in stroški inženirske rekonstrukcije. Načelo NZI pomaga odpravljati rekonstrukcije in stroškovne pasti. Cilj je zmanjšati stroške, potrebne za izdelavo ter izpopolniti in olajšati način izdelave. Tipično načrtovanje prispeva približno 10% celotnih stroškov izdelka, vendar določa 80% izdelovalnih stroškov. Vzrok je v tem, da konstrukcijska raven določa glavne stroškovne postavke: material in izdelavo. Zato ni pomembno, kako ustvarjalni so tehnologi in vodje proizvodnje, saj ne morejo vplivati na stroške izdelave izdelka za več ko 20%. Del dejavnosti NZI je tudi izbira in določevanje ustreznosti materiala in postopka ([2] in [3]).

Konstrukter torej potrebuje sistematično pot za ocenjevanje primernosti različnih materialov in izdelovalnih možnosti. Večina akademskega dela s področja izbire za inženirsko konstruiranje je osredotočena na izbiro materialov [4], medtem ko je delo na izbiri izdelovalnih postopkov manj razvito – posebno na konstrukcijski ravni, oblikovanje [5]. Predpostavimo lahko, da je na tej stopnji konstruiranja večina zahtev primerno določena za izbiro med tehnično izvedljivimi in stroškovno učinkovitimi možnostmi iz ustreznega skupka postopkov in materialov [6]. Ta niz določa dano izdelovalno opravilo.

V prispevku najprej pojasnjujemo problem izbire postopka in opisujemo splošen postopek izbire, na ravni konstruiranja za izdelovalno opravilo, ko so material in postopkovna opravila do določene mere že določeni. Cilj je sistematično identificirati zahteve konstrukcije in zmožnosti postopkov. Najznačilnejše značilnosti postopkov so največkrat specifične za določen razred postopkov.

Izbirni postopek na podlagi izdelovalnega opravila je bil uporabljen na razred obrisnih postopkov rezanja. Na tem mestu je konstrukcija (oblika) v glavnem določena, predpostavimo, da je izbran tudi določen material, tako je problem izbire predvsem kateri postopek uporabiti. Omenjena skupina postopkov vsebuje nekonvencionalne postopke, namreč: rezanje z abrazivnim vodnim curkom (RAVC - AWJ), rezanje z laserjem CO_2, plazemsko rezanje (PzR - PAC), plamensko rezanje (PlR - OFC) in rezanje z žično erozijo (RŽE - WEDM). Njihove tehnološke in ekonomske

candidate materials, geometry, tolerances etc., against possible manufacturing routes. This requires some means of selecting the appropriate processes and estimating the costs of manufacture early on in the product-development stage, across the whole range of options.

Traditionally, many companies followed the sequential approach, to product development. In this approach manufacturing issues follow the design steps without information feedback, so the impact of potentially poor design on product cost is not recognized.

The product cost includes the design cost, the manufacturing cost, expenses associated with product warranties and engineering redesign costs. The DFM principle helps to avoid these redesign and cost pitfalls. Its goal is to reduce the costs required to manufacture a product and improve the ease whit which the product can be made. Typically, design accounts for approximately 10% of the whole product cost, but determinates 80% of the manufacturing costs. The reason is that the design stage is decisive in terms of the main cost constituents: material and manufacturing. Therefore, no matter how creative the manufacturing engineers and the production managers are, they cannot influence the manufacturing costs of the product by more than 20%. Part of DFM is also related to material and process selection and suitability ([2] and [3]).

A designer then needs a systematic way of assessing the various materials and manufacturing options available. Most of the academic work carried out in the field of selection for engineering design has focused on materials [4], the work on processes is less well developed, particularly at the embodiment stage of the design [5]. At this stage of the design, it may be assumed that most of the requirements have been sufficiently well defined for selection between the technically viable and the cost-effective options from an appropriate subset of processes and materials [6]. This set will define a given manufacturing task.

In our paper we first state the problem of process selection and describe a general process selection procedure at the task level in design, when the material and processing operations have, to some extent, already been defined. The goal is to identify systematically the requirements of the design and the capabilities of the processes. The most discriminating characteristics of processes are often specific to the particular class of processes.

The task-based selection procedure was applied to the class of contour-cutting processes. Here the design (shape) is essentially fixed, and we assume that the specific material has been selected, so the selection problem is primarily one of choosing which process to use. This group of processes contains nonconventional processes such as abrasive water-jet cutting (AWJ), CO_2 laser cutting, plasma-arc cutting (PAC), oxygen flame cutting (OFC) and wire electric-discharge machining (WEDM). Their technological and economic information characterise informacije karakterizirajo lastnosti izdelovalnih postopkov, ki jih uporabljamo za obdelavo različnih kovinskih in nekovinskih materialov.

V nadaljevanju sledi opis tehnoloških in ekonomskih podatkov. Določeni so kot odločilni cilji izdelovanega dela za izbrane izdelovalne alternative. Stroškovna analiza in optimizacija stroškov sta pogosto tolmačena različno, tako v različnih, kot tudi znotraj iste organizacije. Poslovne perspekive bi morale upoštevati alternativne investicije, davčne politike, priložnostne stroške in v svoji najboljši verziji tudi prilagodljivost. Prilagodljivost je težko količinsko ovrednotiti, pa vendar je včasih prav ta najpomembnejša pri investiciji v prilagodljivo avtomatsko opremo, kakor je sistem za RAVC ali laserski sistem.

Glavni namen te raziskave je prikazati podporo specifičnih postopkovnih in stroškovnih modelov pri izbirnih pravilih, ki upoštevajo izdelovalne omejitve ob različnih obnašajnih postopkov in njihovo ekonomično učinkovitost pri vodenju izbire. Odločitev o izbiri postopka postane zelo zapletena naloga, saj se pri izbiri srečujemo z različnimi cilji, na voljo pa imamo mnogo alternativ. Enostavnost empiričnih modelov z zadovoljivo natančnostjo rezultatov je tako pomembna pri soočenju s to nalogo.

1 IZBIRA POSTOPKA

Med izbiro materiala in izbiro izdelovalnega postopka obstaja razlika v lastnostih zahtev. Konstrukcijski vidiki prevladujejo pri prvotni izbiri materiala, po drugi strani pa je izbira postopka že v zgodnji fazi z veliko večjo širino gnana z izdelovalnimi in ekonomskimi vidiki [7]. Neodvisno od uporabljene metode za reševanje problema izbire postopka, bo postopek vedno odvisen od stopnje, dosežene v postopku načrtovanja. Tri glavne stopnje inženirskega konstruiranja, zasnova (preliminarna), oblikovanje (vmesna) in podrobnost (končna stopja), določajo raven podrobnosti, potrebnih za izbiro [6]. V nasprotju z ustaljenim načrtovanjem izdelave, je osnovni cilj sočasnega inženirstva obravnavanje

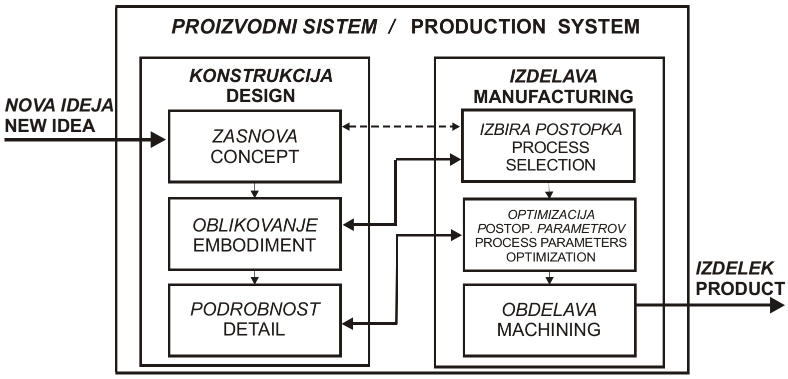
the performance of the machining processes used in the manufacturing of several different metal and nonmetal materials.

Later on come the descriptions of the technological and economic data. They are defined as crucial objectives of the manufactured part for the selected machining alternatives. Cost analysis and cost optimisation are often interpreted differently by various organizations, and sometimes differently within the same organization. The business perspective should take into account alternative investment, tax policies, opportunity costs and its most refined versions for flexibility. While flexibility is the hardest to evaluate in hard numbers, it is also sometimes the most beneficial in terms of investment in flexible automation equipment like, AWJ or laser systems.

The main aim of this research is to present the benefit of specific process and cost modeling in selection rules, taking into account manufacturing restrictions due to the performances of different processes and their economic efficiency. Since there are many objectives we should meet and many alternatives available, the decision on process selection becomes a very complex task. Simplicity with sufficient accuracy of empirical models and their results is therefore important for confronting this task.

1 PROCESS SELECTION

There is a difference in the nature of the requirements for material selection and process selection. The initial selection of a material tends to be dominated by the design aspects, whereas the selection of the process, even at an early stage, is driven to a much larger extent by the manufacturing and economics aspects [7]. Independent of the method used to address this problem of process selection, the approach taken will have to depend on the stage reached in the design process. The three main stages in the engineering design process – conceptual (preliminary), embodiment (intermediate) and detail (final) – determinate the degree of detail required for selection [6]. In contrast to traditional production planning the primary goal of



Sl. 1. *Sočasno načrtovanje proizvodnje [3]*
Fig. 1. *Concurrent production planning [3]*

izdelave pri konstruiranju v čim bolj zgodnji fazi (sl. 1).

V začetni stopnji konstruiranja, ko je določeno le malo konstrukcijskih in materialnih podrobnosti, imajo vsi izdelovalni postopki enako možnost obravnave. To je v primeru preliminarne izbire postopka [5]. Stopnja detajlov z napredovanjem konstruiranja se zvečuje, število ustreznih postopkov pa se zmanjšuje na manjše skupine ali družine postopkov, ki določajo izdelovalni način oz. 'opravilo'. Razumljivo je, da noben izbirni postopek nikoli ne bo zmožen upoštevati raznolikosti vseh izdelovalnih opravil. V naši raziskavi smo sledili splošnemu postopku na podlagi izdelovalnega opravila, ki jo predlagata Lowatt in Shercliff [8].

2 IZBIRNI POSTOPEK NA PODLAGI OPRAVILA

Obdelava podrobnosti za raven izbire na podlagi opravila je v primerjavi s preliminarno izbiro bolj industrijsko usmerjena. Večina akademskega dela s področja izbire postopka je osredotočena na tehnike preliminarne izbire za uporabo na ravni zasnove konstrukcije ([4] in [5]). Za izbiro na podlagi opravila so potrebni bolj osredotočeni postopki za izboljšanje izbire, potem ko so nekatere podrobnosti že določene. Taki postopki nameravajo dopolniti bolj splošne preliminarne metode izbire, s tem da so bolj osredotočeni na podrobnosti specifičnega opravila, brez omejitve po potrebi, da bi bile splošno uporabne. Na tej ravni podrobnosti postane vedno bolj pomembno upoštevati povezave in funkcionalne odvisnosti med lastnostmi materiala, postopkovnimi parameteri in obnašanjem. Potem ko je področje problema izbire določeno, postane vhodni podatek za izbiro niza zahtev. Določitev zahtev je zaporedni postopek, ki sloni na obsežnem znanju o družini postopkov, ki jih obsega določeno izdelovalno opravilo. Postopki in njihove zmožnosti so z namenom, da jih primerjamo z zahtevami konstrukcije opisani s procesnimi prilastki. V primeru preliminarne izbire so prilastki splošni za vse postopke in vrednosti oz. območja izvedljivih postopkovnih razmer [5]. Prilastki pri izbiri na podlagi opravil ne potrebujejo predefiniranih vrednosti in enoličnosti za vse postopke. Obstajajo trije tipi postopkovnih prilastkov, ki vsebujejo različno zapletenost pri hranjenju podatkov:

1. *posamezne vrednosti* npr. združljivost z materialom;
2. *območja*, ki določajo najmanjšo in največjo teoretično možno vrednost in so neodvisna od preostalih prilastkov, npr. debelina materiala, ki jo lahko režemo;
3. *funkcije*, ki prikazujejo odvisnost med različnimi prilastki postopka, npr. rezalna hitrost za dani material je odvisna od debeline, uporabljene moči in v določenih primerih tudi od kakovosti in

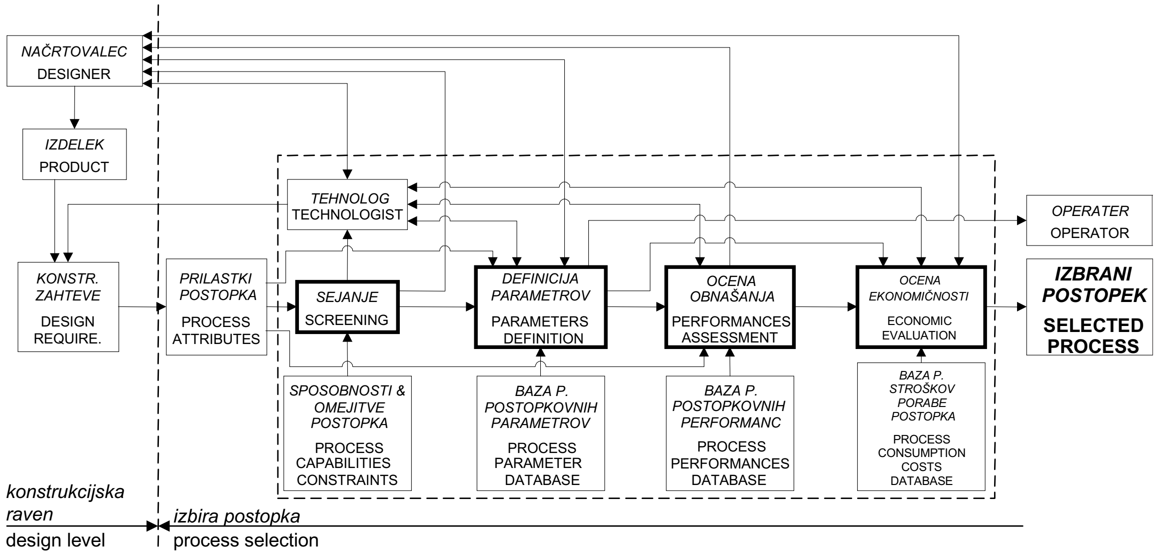
concurrent engineering is to consider manufacturing at as early stage of the design as possible (Fig. 1).

At the beginning of the design process, when little design and material detail has been fixed, all processes have an equal right to be considered. That is the case of preliminary process selection [5]. As the design proceeds, the level of detail increases but suitable processes decrease to smaller groups or families of processes, which define a manufacturing method or 'task'. It is clear that no single selection procedure will ever be able to take all the diversity of the manufacturing tasks into account. In our investigation we have followed the general task-based selection procedure proposed by Lowatt and Shercliff [8].

2 A TASK-BASED SELECTION PROCEDURE

Work at a task-based level of detail tends to be more industrially oriented than that of preliminary selection. Much of the academic work on process selection has focused on preliminary selection techniques for use at the concept stages of design ([4] and [5]). For task-based selection, more focused approaches are required to improve selection once some details have been fixed. Such approaches and procedures are intended to supplement the more general preliminary selection methods, by being more focused on task-specific details, without the constraint of needing to be generally applicable. At this level of detail it becomes increasingly important to consider the correlations and functional dependences between material properties, process parameters and performances. Once the scope of the selection problem has been defined, the inputs to the selection will be a set of requirements. The determination of requirements will be an iterative procedure and it relies on the extensive knowledge of a group of processes that encompass a specific manufacturing task. A process and its capabilities are to be compared to the design requirements described by the process attributes. In the case of preliminary selection, the attributes are universal for all processes and consist of values or ranges for the viable processing conditions [5]. In task-based selection, attributes do not need to take a pre-determined value, and do not need to be the same for all processes. There are three types of process parameters, each implying a different level of complexity in data storage:

1. *single values*, e.g. material compatibility;
2. *ranges*, which define minimum and maximum theoretically possible values and are independent of other attributes, e.g. thickness of the material that can be cut;
3. *functions*, which show correlations between the various process attributes, e.g. cutting velocity for a given material depends on thickness, power used and in some cases also the quality and performance that is required by the design. These



Sl. 2. *Splošna shema izbirnega postopka na podlagi opravila*
Fig. 2. *General scheme of task-based selection procedure*

obnašanja, ki jo zahteva konstrukcija. Te funkcije so navadno predstavljene v obliki postopkovnih modelov. Tip prilastka, ki ga uporabimo, je odvisen od stopnje v izbirnem postopku.

Slika 2 prikazuje splošno shemo izbirnega postopka. Na načrtovalni ravni, načrtovalec skonstruira izdelek z vsemi konstrukcijskimi zahtevami. Te so vstopni podatek za izbiro postopka in se primerjajo s prilastki posameznega postopka. Prva stopnja postopka izbire postopka se imenuje *sejanje*. Cilj te stopnje je izločiti kombinacije material/zahteve konstrukcije/postopek, ki očitno niso mogoče. Na tej ravni je izbira na podlagi prilastkov navadno izvedena z uporabo prilastkov z določenim območjem. Sejanje se lahko izvede za vse konstrukcijske zahteve na nizki ravni podrobnosti. Enostavno sklaplanje med prilastki in zahtevami je lahko izvedeno s primerjavo parameterov posamezno ali v parih [9]. Baza podatkov je lahko organizirana običajno, kakor so preglednice podatkov in/ali različna tehnološka okna, ki so lahko preprosto spremenjena v pogojna pravila za dodatno računalniško podprto sejanje. Rezultat te stopnje izbire je niz postopkov, ki so zmožni izdelave izdelka iz določenega materiala po konstrukcijskih zahtevah. Ta informacija potuje na naslednjo stopnjo izbire, lahko pa je uporabna tudi za tehnologa in konstrukterja. Z zmanjšanjem zahtev in zamenjavo materiala lahko najdeta boljšo rešitev za konstrukcijo izdelka, kar lahko vključuje manj potratne izdelovalne postopke.

Ustrezne kombinacije postopek/material in zahteve konstrukcije so preračunane v naslednji stopnji izbirnega postopka, namreč *definiciji parameterov*. Ta potencialni niz še vedno lahko vsebuje postopke, ki ne morejo izoblikovati izdelka. Eden glavnih vzrokov za to je soodvisnost med

functions are usually presented in the form of process models. The type of attribute we should utilize depends on the stage in the selection procedure.

Figure 2 shows the general scheme of the selection procedure. In the design level the designer constructs the product with all the design requirements. They are the input data for the process selection procedure and are compared to each of the process attributes. The first stage of the selection process procedure is called *screening*. The aim of this stage is to eliminate the material/design requirements/process combinations that are clearly not viable. At this level, attribute-based selection using range-type attributes is usually performed. Screening can take place for all the design requirements at a low level of detail. Simple coupling between the attributes and the requirements can be captured by one-to-one matching or paired-parameter matching [9]. The database may be organised conventionally, such as in the form of data sheets and/or different technological windows, which can be easily transformed into *if-then* rules for additional computer-based screening. The result of this selection stage is a set of processes that are able to manufacture a product out of a certain material under its design requirements. This information passes to the subsequent stage of selection, but could also be useful for the technologist and the designer. They can find a better solution for the design of the product by requirements reduction and material swap, which may incorporate less expensive manufacturing processes.

The viable combinations of process/material and the design requirements are calculated in the next stage of selection procedure: *parameters definition*. This potential set may still contain processes that cannot physically form the product. One of the main reasons for this is the correlation zahtevami in prilastki – na primer, s CO_2 laserjem je mogoče rezati 5mm debelo aluminijasto pločevino z visoko sposobnostjo, toda potrebujemo vsaj 3 kW laser. Uporabimo lahko tudi nižje moči, vendar bo sposobnost povzročena z drugo nastavitvijo parameterov in uporabljenim rezalnim plinom (kisikom namesto dušika), neustrezna. Rezultat tega je, da moramo uporabiti zapleteno združevanje prilastkov [9]. Povezave in funkcijske odvisnosti med spremenljivkami postopka in lastnostmi materiala so podane v modelih postopka. Prednost postopka na podlagi opravila z uporabo modelov je v tem, da lahko izbira poda smernice tudi operaterju v obliki ustreznih razmer za možne postopke. Tehnolog prav tako lahko sodeluje s spremembo predefiniranih nastavitev parameterov na stvarne, tj. nastavitve na lastnih izdelovalnih sistemih ali na sistemih kooperantov.

Stopnja *ocene obnašanja* omogoča, da ocenimo, ali so zahteve obnašanja izdelka lahko dosežene z uporabo nastavitev parametrov iz prejšne stopnje. Preračunavanje interakcij med postopkovnimi spremenljivkami/materialom in inženirskim obnašanjem vsebuje uporabo modelov na enaki ravni podrobnosti kakor pri *definiciji parameterov*. Tako lahko to stopnjo, z uporabo istih modelov za obe stopnji, združimo s stopnjo *definicija parameterov*. Z uporabo ‘hypertext’ postopka lahko vključimo še dodatne informacije. Pri tem so mišljeni razni predlogi v tekstovni obliki za specifične postopkovne razmere.

Ti izdelovalni parameteri lahko pomagajo pri določevanju ekonomskih parameterov (rezalna hitrost, operativni potroški itn.) za naslednjo *oceno ekonomičnosti*. Kalkulacija stroškov izdelave mora na tej ravni podrobnosti vsebovati investicijske, operativne in stroške režije. Prispevek posamezne skupine stroškov k celotnim izdelovalnim stroškom je lahko vgrajen v stroškovne modele. Taki modeli lahko vsebujejo poskusne izdelovalne parametere, nastale med prejšno stopnjo.

Če hočemo doseči končni cilj, zmanjšanje stroškov, moramo tehnološko možne postopke oceniti tudi glede na ekonomsko ustreznost. Končno odločitev in izbiro med možnimi postopki je moč izvesti s primerjavo med izračunanimi izdelovalnimi stroški na kos ali na meter reza za vsako trojico material/zahteve/postopek.

3 PREDLAGAN POSTOPEK

Metodologija na podlagi opravila je bila uporabljena na postopkih obrisnega rezanja, ki so našteti zgoraj. Ključna vprašanja za take tehnologije so: “Kako hitro lahko režem, katere parametere naj uporabim in kakšni bodo stroški za dani material in debelino?” Odgovore na ta vprašanja lahko najdemo z uporabo prej omenjenega izbirnega postopka.

between the requirements and the attributes. For instance, with a CO_2 laser it is possible to cut 5–mm-thick aluminium plate in a high–performance process, but at least a 3-kW laser is needed. A lower power could be used, but the performance resulting from the different parameters and cutting gas (oxygen instead of nitrogen), would be insufficient. As a result, complex attribute coupling [9] should be applied. Correlations and functional dependencies between process variables and material properties are interpreted in process models. A benefit of a task-based approach using models is that selection may also give some guide to the operator by giving the relevant processing conditions for the viable processes. The technologist could also cooperate by changing the predefined parameter settings to the real ones that of the in-house, or that of the cooperator manufacturing systems.

At the stage of *performance assessment* it becomes feasible to assess whether the performance requirements for the product can be achieved using the parameters setting from the previous stage. Accounting interactions between process variables/ material and engineering performance involve the use of models in a similar manner to that detailed for *parameter definition*. It is clear that this stage may be incorporated in a previous *parameter-definition* stage by using the same models for both stages. The inclusion of extra information can be done using a hypertext approach. This means suggestions in the text form for specific process conditions.

These production parameters may help to determine the economic parameters (cutting speed, operation consumables, etc.) for a subsequent *cost evaluation*. The calculation of costs for the processing operation should, at this level of detail, include investment, operational and overhead costs. The contribution of an individual group of costs to the total manufacturing costs can be built into cost models. Such models may include the trial production parameters generated during the previous stage.

To achieve the ultimate aim of minimising cost, technically viable processes must also be assessed for economic viability. The final decision and selection from among possible processes could be done by making a comparison between calculated manufacturing costs per part or per meter of cutting for each material/requirements/process trinity.

3 PROPOSED APPROACH

A task-based methodology was applied to the contour cutting processes listed above. Key questions for such technologies are: “for a given thickness and material, how fast can I cut, what it will cost and which parameters should I use?” The answers to these questions could be foud by utilizing the aforementioned selection procedure. The

Postopek je bil razvit v uporabniku prijazno programsko izbirno orodje – ‘Cutting Master’ (*CM*). Ko je enkrat področje problema izbire določeno, predstavlja niz zahtev vhodnih podatkov postopka izbire. Zahteve v primeru obrisnega rezanja so večinoma vezane na konstrukcijo in so lahko določene iz določil, ki jih lahko najdemo na inženirskih risbah, to so oblika, izdelovalne tolerance in kakovost obdelane površine.

3.1Prilastki postopka

Določiti moramo posebne prilastke postopka, ki karakterizerajo zmožnosti in obnašanja postopkov obrisnega rezanja. Prilastki postopka so različni in odvisni od stopnje v izbirnem postopku. Zahteve materiala in konstrukcije se na stopnji sejanja primerjajo s konstrukcijsko naravnanimi prilastki postopka. Ti prilastki navadno obsegajo geometrične prilastke, ki vodijo do glavnih dejavnikov, ki določajo, ali je izdelek ne glede na podrobnosti obnašanja moč izdelati. V nadaljevanju so na stopnjah definicija parameterov ocena obnašanja in ocena ekonomičnosti izdelave uporabljeni le-tem sorodni prilastki. Ti prilastki pomagajo odgovoriti na vprašanja o praktičnosti in obnašanju ter tudi ekonomičnosti postopka.

3.2 Sejanje

Prilastki postopka za sejalno stopnjo izbirnega postopka so določeni na podlagi osnovnega znanja o konturnih rezalnih tehnologijah.

Energijski žarek ali curek je značilen za vse obrisne rezalne postopke z izjemo RŽE; tako lahko pričakujemo koničen rez. V primerjavi s hladnim mehanskim postopkom namreč RAVC, ostali toplotni postopki (PlR, PzR, lasersko rezanje in RŽE) povzročajo toplotno prizadeto cono (toplotno vplivana cona TVC - HAZ). Glede na izdelovalne tolerance sta PlR in PzR za dekado manj natančna kot RAVC in lasersko rezanje, pri rezanju električno prevodnih kovin pa je RŽE desetkrat bolj natančno od prej omenjena postopka.

Območje materialov, ki jih lahko režemo z laserjem je zelo široko. V tem pogledu je boljši rezalni način RAVC, vendar je postopek navadno veliko počasnejši pri rezanju materialov na območju debelin, kjer postopka tekmujeta. RAVC je primerno za materiale, kjer je laser neučinkovit (odbojni ali debelejši materiali).

PlR se največkrat uporablja za razrez konstrukcijskih jekel, vendar s tem postopkom režemo tudi nekaj drugih eksotermično-oksidnih kovin. PlR ni primerno za uporabo, kjer se mora rezalni postopek hitro ustaviti in ponovno startati; plamen in curek kisika namreč ne moremo enostavno prižigati in ugašati in rez vsakič začeti v sredini pločevine z

procedure has been developed as a user-friendly software-selection tool called ‘Cutting Master’ (*CM*). Once the scope of the selection problem has been defined, the inputs to the selection procedure will be a set of requirements. The equirements in the case of contour cutting are mostly design-related and could be determined from the specifications that might be found on the engineering drawings, such as shape, manufacturing tolerances and surface finish.

3.1 Process attributes

Specific process attributes that characterize the abilities and performances of contour-cutting processes need to be defined. The process attributes are different and depend on the stage in the selection procedure. At the initial screening stage, the material and the design requirements are compared with design-related process attributes. In general, these attributes encompass geometric attributes governing the major factors that determine whether the product can be made, irrespective of performance details. Later on in stage of defining the process *parameters*, *performance assessment* and *economic evaluation,* and manufacturing related attributes are used. These attributes help to answer questions about both the practicalities and the performance, and also about the economics of the process.

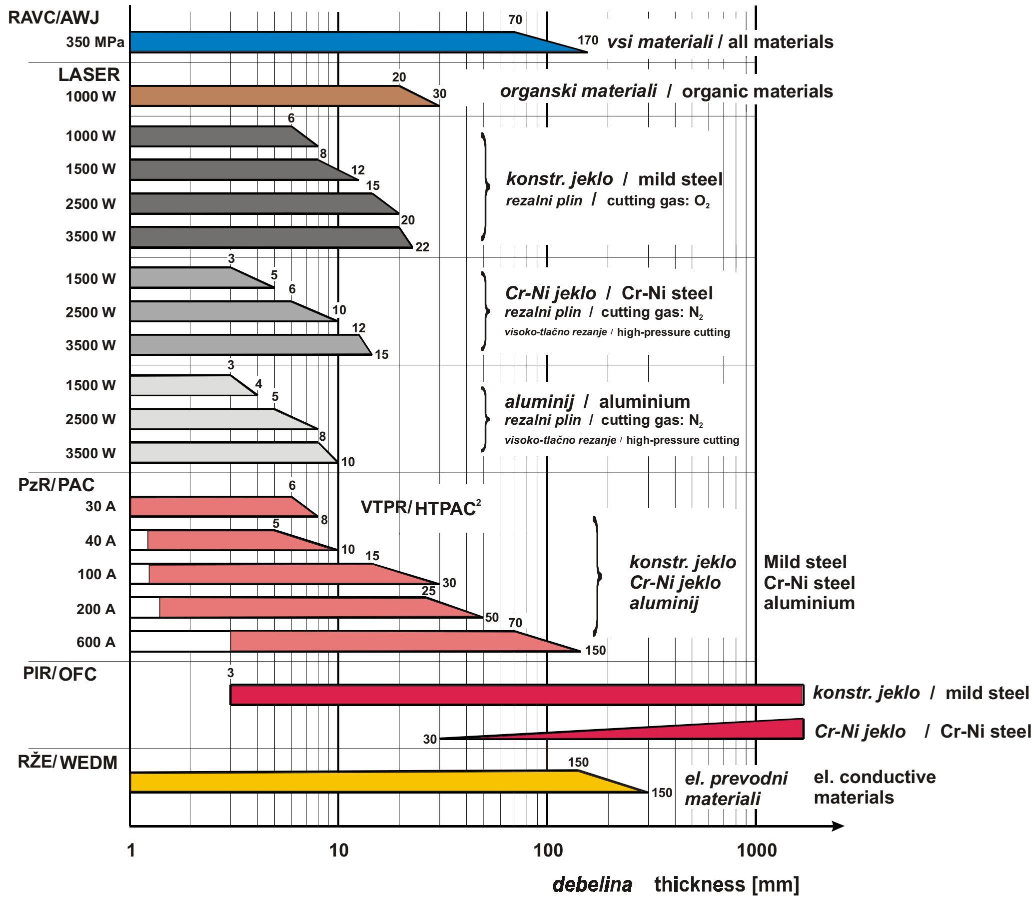
3.2 Screening

The process attributes for the screening stage of the selection procedure are determined from basic knowledge of the contour-cutting technologies.

An energetic beam or jet is characteristic for all the contour-cutting processes, except for WEDM; so a tapered form of kerf should be expected. As distinguished from cold mechanical process, namely AWJ cutting, the three other thermal processes (OFC, PAC, laser cutting) produce a heat-affected zone (Heat Affected Zone - HAZ). When considering manufacturing tolerances OFC and PAC are, by a factor of ten, less precise than AWJ and laser cutting, and WEDM is a factor of ten more precise than the latter for cutting electrically conducting metals.

The range of materials that can be cut by laser is very wide. In this respect the only superior cutting method is AWJ, but the process is generally much slower for cutting materials in the range of thicknesses where the two compete. AWJ cutting is appropriate for materials where a laser is inefficient (reflective or thicker materials).

OFC is most commonly used for mild steel, but some other exothermically oxidising metals can be cut as well. OFC does not lend itself to applications where the cutting process must be repeatedly stopped and restarted; the flame and oxygen jet cannot be rapidly turned on and off with ease and must be initiated at a cut in the middle of the sheet by blowing



Sl. 3. *Območja uporabe obrisnih rezalnih postopkov za različne materiale*
Fig. 3. *Applicable ranges of contour cutting processes for variety of materials*

izpihanjem luknje iz nje, kar povzroča eksplozijski izmet kovine in časovno zakasnitev prebijanja.

Plazemsko rezanje je visoko učinkovit grobi postopek za razrez električno prevodnih kovin. Na razpolago je veliko različnih kombinacij plazemskih in zaščitnih plinov, ki jih lahko uporabimo z namenom, da izboljšamo rezalno obnašanje na različnih kovinskih materialih in uporabah. Natančnost rezanja in kakovost površine reza ne tekmuje z laserskim rezanjem pri pločevinastem materialu in materialu v tankih ploščah. S tem namenom je razvito novo ti. visoko tolerančno plazemsko rezanje VTPR (HTPAC). Ta postopek daje 'lasersko' kakovost reza na tanjših materialih (do 10 mm) pri manjših rezalnih hitrostih.

Slika 3 prikazuje pregled uporabnih območij analiziranih rezalnih postopkov. Pri pregledovanju diagrama lahko opazimo, da so laserski parametri in obnašanje močno odvisni od materiala, ki ga režemo. Po drugi strani parametri rezanja z AVC ostanejo enaki za širok spekter materialov.

Upoštevanje vseh teh podrobnosti in splošnih značilnosti obrisnih rezalnih postopkov omogoča definicijo prilastkov postopkov za prvo stopnjo pri izbiri postopka, namreč *sejanje*. Ti prilastki so vezani na konstrukcijo in material, saj vsak mate-

a hole in it, which results in the explosive ejection of metal and also in a time delay for piercing.

Plasma cutting is highly-effective rough-cutting process for electrically conductive metals. There are many different plasma-and shield-gas combinations available, which can be used to enhance the cut performance for different metal materials and applications. The cutting accuracy and surface quality cannot compete with laser cutting for sheet and thin-plate materials. In efforts to compete the new High Tolerance Plasma Arc Cutting - HTPAC process has been developed. This process produces a "laser" cut quality on thinner materials (up to 10 mm) at lower cutting speeds.

Figure 3 represents an overview of the applicable ranges of the analyzed cutting processes. When examining the diagram, it is clear that the laser parameters and the performance strongly depend on the material being cut. On the other hand, AWJ cutting parameters remain the same for a wide range of materials.

Capturing all these details and the general characteristics of a contour-cutting process enables definition of process attributes for the first step of the process selection, i.e. screening. These attributes are design and material related, since each material

rial določa specifično obnašanje postopka [8]. Predlagali smo niz prilastkov, ki so značilni za obravnavano skupino postopkov:

- Material; določa združljivost postopka.
- Debelina; obdelovalna območja za določeno kombinacijo material/postopek.
- IT tolerančni razred; zmožnost postopka, ki združuje izdelovalno natančnost in hrapavost površine.
- TVC; vsi toplotni postopki dajejo TVC, vendar je količina (širina) odvisna od kombinacije materiala in uporabljenega postopka; RAVC je netoplotni postopek.
- Kot reza; koničnost je karakteristična za to skupino postopkov (z izjemo RŽE), ker 'rezalni curek-žarek' izgublja energijo med prodiranjem v obdelovanec.
- Najmanjši polmer na obrisu; je določen s širino 'rezalnega curka-žarka' oz. premer žice v primeru RŽE.
- Najmanjši premer izvrtine; odvisen je od načina prebijanja.
- Širina reza; določa zmožnost gnezdenja izrezov.
- Širina mostiča; skupaj s širino reza določa zmožnost rezanja mrežastih izdelkov.

Postopkovna podatkovna baza *CM* vsebuje zapise za 8 inženirskih materialov, ki se navadno obdelujejo s temi postopki, z dokumentiranjem njihovih obdelovalnosti v obliki prilastkov postopkov. Preglednica 1 prikazuje značilen zapis baze podatkov za primer rezanja konstrukcijskega jekla. Podatki vsebujejo vrednosti za zgoraj navedene

defines a specific process performance [8]. We have proposed a set of attributes, which are typical for the group of processes under consideration:

- Material; defines the process compatibility.
- Thickness; the ranges of processability for a certain material/process combination.
- IT tolerance class; the ability of a process that incorporates the production accuracy and the surface roughness.
- HAZ; all thermal processes produce a HAZ, but the quantity depends on a combination of the material and the process used; AWJ is non-thermal process.
- Kerf angle; the taper is characteristic for this group of processes (excluding WEDM), since the 'cutting beam' loses its energy when penetrating the workpiece.
- Minimum on-contour radius; is defined by the 'cutting beam' diameter or by the wire diameter in the case of WEDM.
- Minimum hole diameter; depends on the piercing method.
- Width of cut; defines the capability of the process for worpiece nesting.
- Section rate; together with the width of cut defines the ability of processing netlike products.

The *CM* process database contains records for eight engineering materials that are commonly processed with such processes, documenting their manufacturability in terms of process attributes. Table 1 shows a typical database record for the case of mild-steel cutting. The data consist of values for the above described stated process attributes on different thickness ranges. Much of these values, in other words,

Preglednica 1. *Tehnološke karakteristike obrisnih rezalnih postopkov za primer rezanja konstrukcijskega jekla*
Table 1. *Technological characteristics of contour-cutting processes for the case of mild-steel cutting*

Material: konstr. jeklo Mild Steel	**RAVC/AWJ**	**LASER**	**PlR/OFC**	**PzR/PAC**	**RŽE/WEDM**
debelina / thickness t mm	150	20	$5< t<150$	100	150
IT tolerančni razred IT tolerance class	12	11	16	16	6
TVC/HAZ mm	0	0,05t	0,1+0,05t; $t<20$ 0,75+0,015t; $t\geq20$	0,3t; $t<20$ 0,6t; $t\geq20$	0,02
kot reza - koničnost kerf angle - 'taper' mm	0,05; $t\leq10$ 0,1; $10< t<20$ 0,05+0,0025t; $t\geq20$	0,05+0,0025t	0,1+0,015t; $t<10$ 0,6+0,05t; $t\geq10$	0,25+0,025t; $t<5$ 0,6+0,05t; $t\geq5$	0,001
najm. polmer na obrisni r min. on-contour radius r mm	0,5; $t\leq15$ 1; $t>15$	0,5; $t\leq12$ 1; $t>12$	1; $t<20$ 2; $t\geq20$	1,5; $t<20$ 2,5; $t\geq20$	0,15
najm. premer izvrtine ϕ min. hole diameter ϕ mm	1,2; $t<10$ 2; $10\leq t\leq30$ 3; $t>30$	0,5t	15; $t<20$ 20; $t\geq20$	10; $t<20$ 20; $t\geq20$	0,2
širina reza w width of cut w mm	1,2; $t<20$ 1,5; $20\leq t<40$ 2; $t40$	0,2; $t<5$ 0,35; $5\leq t<10$ 0,55; $t\geq10$	1,06+0,035t	2; $t<20$ 4,5; $20\leq t<40$ 5,5; $t\geq40$	0,25; $t<60$ 0,3; $t\geq60$
širina mostička m section rate m mm	1; $t<20$ 2; $t\geq20$	1	6; $t<20$ 10; $t\geq20$	6; $t<20$ 10; $t\geq20$	1

prilastke postopka za različen razpon debelin. Večina teh vrednosti je z drugimi besedami odvisna od debeline obdelovanca *t*. Baza podatkov je plod obsežne raziskave in praktičnega dela s področja obrisnih rezalnih postopkov v Laboratoriju za alternativne tehnologije na Univerzi v Ljubljani. Preostali materiali, ki jih vsebuje baza *CM*, so orodna in nerjavna jekla, aluminij, baker kot kovine in akrilno steklo, najlon in vezana plošča kot nekovine. Za vse je bila izdelana enaka preglednica, ki lahko rabi kot popolni vir informacij za prvi korak izbire postopka.

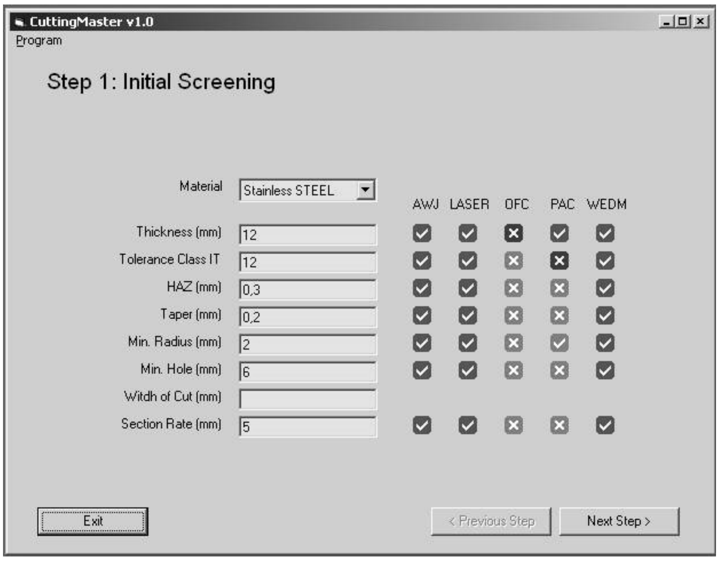
Podatki iz teh preglednic so uporabljeni v obliki pogojnih pravil v računalniško podprto *sejanje*. Slika 4 prikazuje uporabniški vmesnik za to stopnjo izbirnega postopka. Uporabnik izbere material izmed 8 predefiniranih, vnese zahteve konstrukcije in po vsakem vnosu dobi informacije o združljivosti postopka. Računalniški program omogoča iteracijo z zniževanjem zahtev, tako vidimo, kje so meje določenega postopka. Prav tako lahko enostavno primerjamo obdelovalnost različnih materialov pod enakimi konstrukcijskimi zahtevami.

Slika 4 prikazuje primer rezanja 12 mm debelega nerjavnega jekla. Rezanje z AVC, laserjem in RŽE so ustrezni postopki za izdelavo pod zahtevami, določenimi na tak način (*IT razred* 12, *TVC*=0,3mm itn.). PlR je izločeno zaradi nezdružljivosti z materialom, PzR pa je izločeno zaradi previsoko zahtevanega tolerančnega razreda. Naslednji korak v izbirnem postopku sledi za preostale kandidate.

depend upon the workpiece thickness *t*. The database is the result of extensive research and practical work in the Laboratory for Alternative Technologies at the University of Ljubljana in the field of contour-cutting techniques. Other materials included in the *CM* database are tool stel, stainless steel, aluminium, coeper as well as nonmetals such as acrylic glass, nylon and plywood. For each of these materials the same datasheet was formed, which could serve as a complete source of information for the first step of process selection.

The data from such tables are implemented in the form of '*if-then*' rules into the computer-aided screening. Fig. 4 shows a userinterface for this stage of the selection procedure. The user chooses a material from the eight predefined materials, enters the design requirements, and after each requirement is entered, obtains information about the processes compatibilities. The software enables iteration by decreasing the requirements to see where the limits of a certain process are. The machinability of different materials under the same design requirements can also be easily compared.

Figure 4 shows that in the case of 12-mm-thick stainless-steel cutting, AWJ, laser and WEDM are appropriate processes for manufacturing under the requirements defined in such a manner (*IT class* 12 *HAZ*=0.3mm etc.). The OFC is excluded because of material non-compatibility and PAC is excluded because the requested tolerance class is too high. The next step in the selection procedure is applied to the other remaining process candidates.



Simboli, uporabljeni v komunikacijskem oknu:
- postopek je primeren za izdelavo pod takimi konstrukcijskimi zahtevami;
- postopek ne bo izpolnil konstrukcijskh zahtev;
- postopek je načeloma ustrezen, vendar je izločen zaradi nesposobnosti pri prejšnji zahtevi;
- zahteva je previsoka, obenem pa je proces neustrezen že pri predhodnih zahtevah.

Symbols used in dialog screen:
- process is relevant for manufacturing under such a design requirement;
- process will not meet the design requirement;
- process is otherwise appropriate, but is eliminated because it does not meet the preceding requirement;
- requirement is too high, but the process is insufficient based on preceding requirements.

Sl. 4. *Primer CM komunikacijskega okna za stopnjo izbirnega postopka - sejanje*
Fig. 4. *Example of the CM dialog screen for the selection procedure stage - initial screening*

3.3 Definicija parametrov in ocena obnašanja

Predlagamo združitev obeh naslednjih stopenj izbirnega postopka: *'definicija parametrov'* in *'ocena obnašanja'*, saj baza podatkov za obe stopnji vsebuje iste prilastke postopka. Na tej stopnji so prilastki vezani na izdelavo, saj določajo obnašanje postopka v določenih razmerah. To omogoča veliko večje razlikovanje, poleg tega pa podaja pomembne informacije za oceno ekonomičnosti (npr. rezalna hitrost) in navaja ustrezne razmere za poskuse. Vrednosti prilastkov so določene z odvisnostmi med števílnimi veličinami v obliki modelov postopkov.

3.3.1 Modeli postopkov

Modeliranje naj bi zmanjšalo število neodvisnih spremenljivk ali vsaj pokazalo, kako se združujejo in variirajo. To je pomemben korak, ki omogoča zmožnost napovedovanja in naj bi bil osnovni cilj vsake dejavnosti modeliranja. Enostavnost je odločilna pri izbiri postopka. Izogibati se moramo izkoriščanju surove računalniške moči. Modeliranje se ponuja kot močno orodje za razlikovanje med postopkovnimi možnostmi na ravni natančnosti, ki je potrebna za izpolnitev zahtev konstrukcije [9].

Takoj postane jasno, da za vse obravnavane postopke z enim modelom ne moremo odgovoriti tej zahtevi. Potrebna je uporaba različnih postopkovnih parametrov in modelov, ker vsak postopek deluje po povsem drugačnih fizikalnih načelih. V primeru rezanja z AVC smo uporabili postopkovni model, ki je znan iz študij in prakse na področju visokotlačne rezalne tehnike. Drugačen način gradnje izkustvenih modelov smo uprabili za toplotne postopke. Modeli so bili izpeljani z metodo prilagajanja funkcije krivulji rezanja. Metoda se opira na obsežno tehnološko bazo podatkov. Podatki vsebujejo vrednosti za rezalne hitrosti pri ravnem rezu za različne nastavitve postopkovnih parametrov (moč, rezalni plin, premer žice itn.), pri rezanju 8 predefiniranih materialov. Bazo podatkov za vse toplotne postopke rezanja smo zgradili na podlagi različnih virov, kot so baze podatkov lastnih praktičnih študij, veliko baz podatkov za operaterje, medmrežje itn. Obe metodi gradnje postopkovnih modelov sta predstavljeni na primeru RAVC in laserskega rezanja.

Modeliranje rezanja z AVC

Različni raziskovalci so predstavili modele za napovedovanje globine reza in hitrosti rezanja. Izhajali smo iz modela Zenga in Kima [10]. Utemeljen je na približku testnih podatkov za določitev vplivnih stalnic v enačbi modeliranja rezalnega postopka z namenom oblikovati razsežnostna

3.3 Definition of the parameters and performance assessment

Since the database for the definition of the parameters and the performance assessment stage consists of the same process attributes, we propose to incorporate both stages of selection procedure. At this stage the attributes are manufacturing-related, since they determine the process performance under defined conditions. This enables much greater discrimination, along with providing important information for estimating the process economics (i.e. cutting speed) and indicating suitable conditions for trials. The attribute values are determined by a relationship between many quantities in the form of process models.

3.3.1 Process modeling

Modeling should reduce the number of independent variables, or at least identify how they couple and vary. This is an essential step in providing the predictive capability, which should be the ultimate purpose of any modeling activity. Simplicity is crucial for the process selection, and the trap of unnecessarily trying to exploit raw computing power should be avoided. Modeling provides a powerful tool for discriminating between processing options at the level of precision needed to answer the design requirements [9].

It quickly becomes apparent that one model cannot be used to address this requirement for all the processes under consideration. As the processes each use different physical mechanisms, different process parameters and models need to be applied. In the case of AWJ cutting we have utilized process model, that is known from studies and practice in the field of this high-pressure cutting technique. We have used a different approach for building the empirical models for thermal processes. The models were derived using the curve-fitting method. This method relies on an extensive technological database. The data contains the values for cutting velocities for straight cutting for different process parameters (power, cutting gas, wire diameter etc) settings, cutting eight predefined materials. We have constructed a database for all the thermal cutting processes from different sources, such as the database of our own practical studies, many operators' databases, the internet, etc. Both methods of process model building are presented for the case of AWJ and laser cutting.

AWJ Process Modeling

Several researchers have presented models for the depth-of-cut or cutting-speed prediction for the AWJ cutting process. We have followed the model of Zeng and Kim [10]. It is based on the modeling of a cutting process to formulate a dimensional relationship and the use of test-data regression to determine the razmerja. Ko poznamo debelino in material obdelovanca in so izbrane vrednosti vodnega tlaka, velikost mešalne šobe, pretok abraziva, lahko napovemo hitrost rezanja z uporabo naslednje enačbe [10]:

power constants in the relationship. When the workpiece material and thickness are known and the preset values of water pressure, orifice/nozzle size, abrasive flow rate are defined, the cutting speed can than be predicted using the following equation [10]:

$$v = \left(\frac{N p^{1.25} m_w^{0.687} m_a^{0.343}}{C t q d_j^{0.618}} \right)^{1.15} \quad \text{mm/s} \qquad (1)$$

kjer so:
v – rezalna hitrost v mm/s,
p – tlak vode v MPa,
t – debelina materiala v mm,
N – obdelovalno število materiala obdelovanca,
m_w – pretok vode v l/min,
m_a – pretok abraziva v g/s,
d_j – premer mešalne šobe v mm,
C – 8800 konstanta za metrski sistem,
in kjer je q kvalitativni parameter nivoja kakovosti.

Za lažjo predstavo so v nadaljevanju podane razlage za naslednjih pet ravni kakovosti [10]:

Razlaga ravni kakovosti
q = 1 Kriterij za ločilni rez. Navadno se uporablja q > 1,2.
q = 2 Groba površina reza z brazdami v spodnji polovici reza.
q = 3 Gladko/grobi prehodni kriterij. Pojavijo se lahko rahle brazde.
q = 4 Brez brazdavosti za večino materialov.
q = 5 Najboljša površina reza.

Upoštevati je treba, da izbira višjih kakovostnih ravni rezultira v manjših rezalnih hitrostih, torej zviša stroške.

Vrednosti obdelovalnega števila N za obravnavane inženirske materiale so naslednje [10]:

orodno jeklo	80,4
nerjavno jeklo	82
konstrukcijsko jeklo	87
baker	110
aluminij	213
najlon	538
akrilno steklo	690
vezana plošča	1500

Enačba (1) je veljavna na širokem nizu parameterov, vendar le dokler ti parametri zavzemajo vrednosti znotraj normalno sprejemljivega delovanja. Npr., rezalna hitrost se vedno zveča s povečanjem dotoka abraziva, vendar v praksi le do določene meje. Vodni curek namreč lahko sprejme le določeno količino abraziva, nad katero postane prenasičen, kar rezultira v manjši hitrosti rezanja. Nihče si ne želi delovati v takem območju. Priporočena območja veljavnosti enačbe (1) so naslednja: tlak vode: p=240 do 375 MPa; premer vodne šobe d_n=0,18 do 0,56mm; razmerje med mešalno in vodno šobo d_j/d_n=2 do 4; razmerje pretokov abraziv/voda m_a/m_w=0,12 do 0,2 in pretok vode $m_w=1,479 \cdot d_n^2 \cdot p^{1/2}$ [11]. Z namenom, da poenostavimo Zeng in Kimov model, smo izpeljali naslednjo preprosto izkustveno enačbo. Uporabili

where:
v – cutting speed [mm/s],
p – water pressure [MPa],
t – material thickness [mm],
N – machinability number of workpiece material,
m_w – water flow rate [l/min],
m_a – abrasive flow rate [g/s],
d_j – mixing tube diameter [mm],
C – 8800 constant for metric system,
and where q is a qualitative quality-level parameter.

For convenience, descriptions are given for the following five quality levels /11/:

Quality Level Description
q = 1 Criteria for separation cuts. Usually, q > 1.2 should be used.
q = 2 Rough surface finish with striation marks on the lower-half surface.
q = 3 Smooth/rough transition criteria. Slight striations marks may appear.
q = 4 Striation free for most engineering materials.
q = 5 Best surface finish.

It should be noted that the selection of a high quality level results in slow cutting speeds, thereby increasing cost.

The values of the machinability number N for some common engineering materials are as follows [10]:

tool steel	80.4
stainless steel	82
mild steel	87
copper	110
aluminum	213
nylon	538
plexiglass	690
plywood	1500

Equation 1 is valid for a wide range of parameters, as long as the values of these parameters stay within the realm of normally acceptable operation. For example, cutting speed always increases with abrasive flow rate; however, in practise, beyond a certain flow rate, the abrasive-jet mixture begins to get over-saturated, resulting in a reduced cutting speed. And in any case, it would not useful to operate the system in this range. The recommended range of validity for this equation is as follows: water pressure: p=240 to 375 MPa; orifice diameter d_n = 0.18 to 0.56mm; nozzle ratio d_j/d_n =2 to 4; abrasive/water flow-rate ratio m_a/m_w =0.12 to 0.2 and water flow rate is $m_w=1.479 \cdot d_n^2 \cdot p^{1/2}$ [11]. In order to simplify the Zeng and Kim model we derived the following simple empirical equation. The average values of the smo srednje vrednosti predhodno omenjenih priporočenih območji ter določena druga pravila in povezave, povezane z optimalnim delovanjem sistema:

$$v = \left(\frac{Np^{1.765} d_n^{1.442}}{233 \cdot tq} \right)^{1.15} \quad \text{mm/min} \tag{2}$$

kjer so:
v – rezalna hitrost v mm/min,
p – tlak vode v MPa,
t – debelina materiala v mm,
d_n – premer vodne šobe v mm.

Enačba (2) ne upošteva vpliva odmika mešalne šobe od obdelovanca ter vrste in zrnatosti abraziva. Običajno se globina reza zmanjšuje z večanjem odmika mešalne šobe, vendar majhne spremembe odmika, v območju med 1 in 3 mm, bistveno ne vplivajo na spremembe v globini in kakovosti rezanja. Podobno imajo variacije v zrnatosti abraziva v običajnih mejah (zrna 50 do 150) majhen vpliv na največjo dosegljivo hitrost rezanja. Finejši abraziv se običajno uporablja za doseganje gladkejše površine reza. Vrsta abraziva je prav tako pomemben parameter. Uporaba različnih vrst abraziva lahko povzroči znatne spremembe rezalne sposobnosti. Enačbo (2) lahko neznatno spremenimo, če N pomnožimo s konstanto abraziva in tako pri napovedi hitrosti rezanja upoštevamo tudi vrsto abraziva.

Modeliranje toplotnih postopkov

Enak cilj smo imeli za preostale toplotne postopke rezanja. Poskušali smo odkriti povezavo med rezalno hitrostjo pri različnih debelinah materiala in glavnimi parameteri postopka. Zaradi različnosti v konstrukciji sistemov, v vodenju delovnega žarka in materiala ter izvedbah rezalnih glav, je natančno razmerje mogoče podati le z izvedbo preskusov. Rezalne hitrosti so neposredno vezane na gostoto energije v rezalni coni.

Pri laserskem rezanju je ta odvisna od moči laserja in velikosti žarka v gorišču ter lege gorišča. Leče s krajšimi goriščnimi razdaljami dajo manjšo površino žarka v gorišču, kar poveča gostoto energije in posledično vpliva na največjo hitrost rezanja. Način oz. mod laserskega žarka prav tako vpliva na zmožnost fokusiranja leč v majhno pego. Vsako odstopanje od osnovne Gaussove porazdelitve rezultira v povečanem prerezu žarka v gorišču in tako zmanjšuje rezalne hitrosti. Na splošno lahko v praksi vzamemo, da imajo močnejši laserji večji premer žarka v gorišču; lastnost, ki zmanjšuje pričakovane rezalne hitrosti in daje večjo širino reza.

Upoštevati moramo, da za vsako moč laserkega žarka obstaja neka največja debelina materiala, ki jo še kakovostno režemo, značilnost, ki ne bo predstavljena s to tehniko napovedovanja. Metoda gradnje izkustvenih modelov, rezalna hitrost v odvisnosti od debeline materiala in moči laserja, s prilagajanjem delovanja krivulji rezanja se opira na dveh faktorjih, ki ju lahko vzamemo kot pravilna [12]:

aforementioned recommended ranges, some other empirical rules and relations related to the optimal system's operation were used:

where
v – cutting speed [mm/min],
p – water pressure [MPa],
t – material thickness [mm],
d_n – orifice diameter [mm].

Equation 2 does not include the effects of stand-off distance, abrasive type and size. As a general trend, the depth of cut is reduced as the stand-off increases. However, variations of the stand-off over a small distance, in the range between of 1 and 3 mm, does not cause any significant changes in the depth of cut or in the quality of cutting. Similarly, variations in the abrasive size, within the ordinary range (mesh 50 to 150) have little effect on the attainable maximum cutting speed. Finer abrasive is usually used to achieve a smoother surface finish. The abrasive type is an important parameter as well. The use of different types of abrasives may result in a substantial difference in cutting performance. Equation 2 can be slightly modified by multiplying *N* by an abrasive constant to account for different kinds of abrasives.

Modeling for thermal processes

Our aim was the same for the remaining thermal cutting processes. We tried to find information relating to the cutting speeds at various material thickness and the main process parameters. Owing to the diversity of system design, working beam and material manipulation system and cutting-head configurations, accurate information is only made available by making trials. Cutting speeds are directly related to the energy density in the cut zone.

For laser cutting, this is affected by the laser power and the size and position of the focused spot. If a shorter focal length of lens is used, the spot size decreases giving an increase in the energy density and this consequently influences the maximum cutting speed. The mode of the laser beam also affects the ability of the lens to produce a small focal spot. Any variation away from the so-called primary Gaussian cross-section tends to enlarge the focused spot diameter and thus reduce the cutting speeds.

It should be borne in mind that each laser power will have a maximum thickness of material for good quality cutting, a feature that will not be shown up by this forecasting technique. The method of building empirical models of cutting speed versus material thickness and power by curve fitting relies on two factors, which can be assumed to be true [12]:

– Največja hitrost rezanja je sorazmerna moči laserskega žarka (s predpostavko, da je velikost žarka v gorišču nespremenljiva), kar pomeni dvojna moč da dvakratno hitrost.
– Oblika krivulje rezanja je približno enaka za vse materiale, čeprav se dejanske vrednosti, podane na oseh grafa spreminjajo. Tako lahko napovemo približno hitrost rezanja z uporabo testnih rezultatov rezanja in različnih baz podatkov ([13] in [14]) v kombinaciji z naslednjo preprosto formulo:

– The maximum cutting speed is proportional to the laser power (assuming a constant focused spot size), i.e. twice the power gives twice the cutting speed.
– The shape of the cutting curve is approximately the same for all materials, although the actual values given on the axes of the graphs change. So approximate cutting-speed forecasting can be carried out by using the results of cutting trials and different databases ([13] and [14]) in combination with the following simple formula:

$$v = Q \cdot P \cdot t^{-B} \quad (3)$$

kjer so:
v – rezalna hitrost v mm/min
P – laserska moč v W
t – debelina material v mm
Q – eksperimentalno izpeljane stalnice materialov pri uporabi določene laserske fokusirne optike.
B – podaja obliko krivulje rezalne hitrosti.

where
v – cutting speed [mm/min]
P – laser power [W]
t – material thickness [mm]
Q – an experimentally derived constant for the material using a particular laser-focusing optics combination.
B – gives the shape of the cutting curve.

Preglednica 2. *Vrednosti stalnic materiala Q in B, maksimalna debelina in način laserskega rezanja za obravnavane materiale*
Table 2. *Values of the material constants Q and B, thickness limitation and the type of laser cutting for analysed materials*

Material	***Q***	***B***	**najv. debelina max. thickness mm**	**način rezanja / rezalni plin type of cutting / cutting gas**
orodno jeklo tool steel	5,28	1,053	15	III / O_2
nerjavno j. stainless s.	4,65	1,265	12	II / N_2
konstrukcijsko j. mild steel	7,04	1,053	20	III / O_2
aluminij aluminium	4,79	1,495	8	II / N_2
najlon nylon	40	1,350	30	II / *zrak* air
akrilno steklo plexiglass	70	1,350	35	I / *zrak* air

Vsako vpeljano vrednost stalnice Q lahko uporabimo za podajanje približne hitrosti rezanja, saj so rezalni laserji postopoma vedno bolj podobni pri kakovosti izstopnega žarka. Ko je enkrat vrednost stalnice Q ugotovljena s prilagajanjem krivulji reza, je mogoče napovedati hitrost rezanja določenega materiala za široko območje debelin in moči laserja [12].

Preglednica 2 prikazuje vrednosti Q in B stalnic za inženirske materiale, analizirane v naši raziskavi, ki so v splošni rabi laserske rezalne prakse. Podane so tudi največje debeline določenih materialov, pri katerih še dosežemo kakovostne rezultate, kakor tudi načini laserskega rezanja. Obstajajo namreč trije mehanizmi laserskega rezanja, ki jih uporabljamo pri rezanju različnih materialov:

Any established value of Q can be used to give an approximation of the cutting speed, because cutting lasers are becoming progressively more alike in their output beam quality. Once a value of the constant Q has been found by curve fitting it is possible to forecast the cutting speeds for a material over a wide range of thicknesses and laser powers [12].

Table 2 shows the established values of the Q and B constants for the engineering materials analyzed in our investigation, which are commonly used in practical laser cutting. The maximum thickness for quality cutting results achieved on chosen materials and the type of laser-cutting mechanism are presented as well. Namely, there are three mechanisms of laser cutting that can be used for processing different materials:

1. **Lasersko izhlapevno rezanje (I)**: Večina materiala je izparjena z veliko močjo laserskega žarka in izpihnjeno s pretokom inertnega plina.
2. **Lasersko talilno rezanje (II)**: Material je segret in staljen z laserskim žarkom in izpihnjen s pretokom inertnega plina pod visokim pritiskom.
3. **Lasersko plamensko rezanje (III)**: Uporabljen je reaktivni-delovni plin za eksotermično reakcijo, ki vžge z laserjem segret material.

Način laserskega rezanja pomembno vpliva na delovanje in posebej na ekonomičnost rezanja.

Omejitve teh modelov so poleg največjih vrednosti za debeline tudi območja laserskih moči, ki jih lahko uporabimo in še zagotovimo zadovoljivo natančnost. *Enačba (3)* je zanesljiva na območju od 1,5 do 4kW za kovine in 100 do 1500W za nekovine. Pri nekovinah je bila uporabljena 5” leča. Za rezanje kovin so na voljo različne vrste fokusirnih leč.

Opisano modeliranje ne vsebuje parametrov kakovosti reza. Območje kakovostnega rezanja je namreč veliko ožje, kakor v primeru rezanja z AVC. Lasersko rezanje z neustreznimi parametri, npr. prevelika rezalna hitrost, rezultirajo v nižji ceni reza, vendar je kakovost reza na ravni plazemskega ali plamenskega rezanja. Kakovost reza je vezana na standard DIN 2310.

Postopkovni modeli za druge toplotne postopke so bili izpeljani na enak način.

Ti postopkovni modeli so bili vključeni v program za računalniško podprto *definicijo parametrov* in *oceno obnašanja.* Slika 5 prikazuje primer uporabniškega komunikacijskega okna za to stopnjo izbirnega postopka. V tem primeru program izračuna vrednost kakovostnega nivoja, določenega s kunstrukcijskimi zahtevami in vrednost hitrosti rezanja AVC pri predefiniranem

1. **Laser Sublimation Cutting (I)**: Most of the material is vaporised by a high-intensity laser beam and blown out by an inert gas flow.
2. **Laser Fusion Cutting (II)**: Material is heated and melted by the laser beam and blown out by a high-pressure an inert gas flow.
3. **Laser Flame Cutting (III)**: A reactive working gas is used for an exothermic reaction that burns the laser heated material.

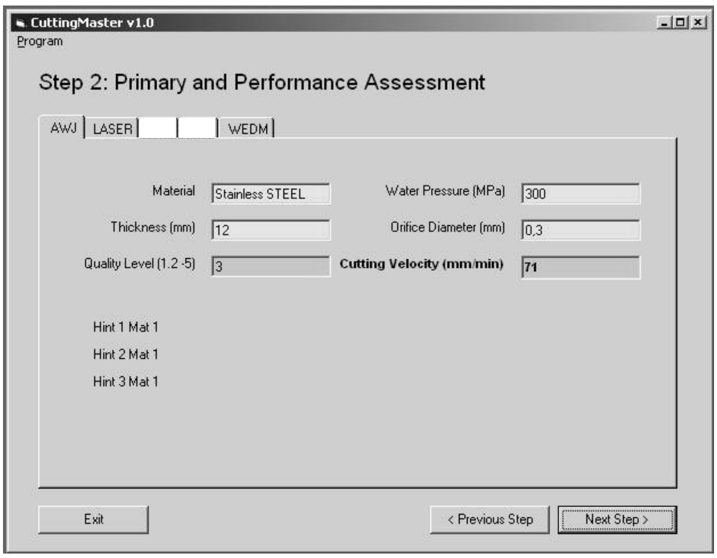
The type of laser cutting mostly influences the cutting performance and especially the cost efficiency.

The limitations of these models are the maximum values of the thickness and the ranges of the laser power that can be used while still ensuring sufficient accuracy. The reliability of Equation 3 is in the range of 1,5 to 4kW for metals and 100 to 1500W for non-metals. For non-metals the 5” lens was used. Various types of focusing lenses are available for metal cutting.

In the present laser-process modeling, no surface quality aspects are included, since the range of performance is much narrower than in the AWJ case. Laser cutting performed with non-appropriate parameter settings, i.e. higher cutting rates, results in lower costs but the quality of th surface is rather in the ‘plasma or flame’ class than in the AWJ class. The quality in these models is related to the DIN 2310 standard.

The process models for other thermal processes were derived in the same manner.

These process models were incorporated into the software for the computer-aided step of *parameters’ definition* and *performance assessment.* Figure 5 shows an example of a user-interface dialog screen for this step in selection procedure. In this case the software calculates the value for the quality level determined by the design requirements and the value for the cutting velocity for AWJ cutting under a predefined quantity



Sl. 5. *Primer komunikacijskega okna programa CM za stopnji definicija parametrov in ocena obnašanja*
Fig. 5. *Example of a CM dialog screen for the stage of parameters’ definition and performance assessment*

tlaku vode in premeru vodne šobe. Vrednosti za ta glavna parametera in za kakovostno raven lahko spremenimo in izračunamo novo vrednost za rezalno hitrost. To omogoča bolj realistično določanje nastavitev postopkovnih parametrov za izdelavo v določenih kakovostnih razmerah. Postopek je enak za oba preostala postopka, tj. lasersko in RŽE. Plr in PzR sta eliminirana že v predhodni fazi izbire. Ti proizvodni parameteri so v pomoč pri določanju ekonomskih parameterov za naslednjo *oceno stroškov*.

3.4 Ocena ekonomičnosti

Trije dejavniki naredijo analizo ekonomičnosti postopkov nekoliko zahtevno: 1) rezultati rezanja so lahko dobljeni z različnimi kombinacijami rezalnih parametrov; 2) prilagodljivost postopkov, zmožnost rezanja različnih oblik domala brez sprememb v strojni opremi je v večini primerov težko ovrednotiti; 3) različni dobavitelji imajo različne postavke ter lahko številne prilastke vrednotijo različno. Pravilna oz. dobra stroškovna analiza naj bi upoštevala te tri dejavnike.

Osnova za izračun strojne ure so stalni in spremenljivi stroški. Stroškovna analiza in izračun temelji na naslednjih postavkah:

Osnova za izračun ***stalnih*** *stroškov:*
– začetni stroški – investicija I v €;
– amortizacijska doba D v letih, letno delovanje oz. raba stroja L_a v h/leto.
Izračun ***stalnih*** *stroškov:*
– izračun amortizacije:

of water pressure and orifice diameter. The values for these two main parameters and also for the quality level could be changed and a new value for the cutting velocity will be calculated. This allows a more realistic determination of the process-parameter settings for manufacturing under certain quality conditions. The procedure is the same for the other remaining processes, in this case laser and WEDM cutting. The OFC and PAC were excluded at the previous stage of the selection. These production parameters help to determine the economic parameters for a subsequent *economic evaluation*.

3.4 Economic evaluation

Three factors make process-cost analysis somewhat difficult: 1) some cutting results can be achieved by many different combinations of cutting parameters; 2) the flexibility of the processes, ability to cut different profiles almost without hardware changes, is hard to value in most cases; 3) different customers have different objectives and they may value various attributes differently. Thus, a good economic analysis model should account for these three factors.

Fixed and variable costs are part of machine costs on an hourly basis. The economic analysis and calculation basis are made up as follows:

Calculation basis for the ***fixed*** *costs:*
– initial cost I [€];
– depreciation period D [years], machine utilization L_a [h/year].
Calculation of fixed costs:
– calculated depreciation:

$$C_d = \frac{I}{D \cdot L_a} \quad \text{€/h} \qquad (4)$$

V tem izračunu stalnih stroškov niso vštete obrestne mere in stroški prostora. Obe postavki dodata približno 20% stalnim stroškom, vendar zaradi podobnih lastnosti in zahtev vseh tehnologij nista pomembni pri primerjanju ekonomičnosti med njimi.

Osnova za izračun ***spremenljivih*** *stroškov:*

Izračun spremenljivih stroškov je specifičen za vsak postopek. Vsi postopki so gnani električno, vendar vsak uporablja različno vrsto rezalnega vira in parametre, tako je tudi poraba povezana s temi procesnimi parameteri in njihovimi nastavitvami. Ocena spremenljivih stroškov je predstavljena na primeru rezanja z AVC:
– poraba električne moči (celoten sistem) E v kW, cena električne energije c_e v €/kWh;
– stroški vzdrževanja letno M v €/leto.

Poraba RAVC:
– poraba rezalne in hladilne vode $m_w + W$ v l/min, cena vode c_w v €/l;
– poraba abraziva m_a v kg/min, cena abraziva c_a v €/kg;

In this calculation of fixed costs no interest rate and no cost for floor space are included. Both items usually add about 20 % to fixed costs, but are for all technologies much the same and as such not so meaningful when a comparison based on economic efficiency has to be made.

Calculation basis for the ***variable*** *costs:*

The calculation for variable costs is specific to the process. All processes are electrically driven, but each process uses a different kind of cutting source and parameters, so consumption is connected with these process parameters and their settings. The assessment of variable costs is presented for the case of AWJ cutting.
– electrical power consumption (entire system) E [kW], electricity costs c_e [€/kWh];
– maintenance costs per year M [€/year].

AWJ consumption special:
– cutting-and cooling-water consumption $m_w + W$ [l/min], water price c_w [€/l];
– abrasive material consumption m_a [kg/min], abrasive price c_a [€/kg];

– potrošni in obrabni deli; cena vodne šobe c_n v €/kos, doba trajanja vodne šobe L_n v h/kos, cena mešalne šobe c_m v €/kos, doba trajanja mešalne šobe L_m v h/kos.

Spremenljivi stroški:

– stroški električne energije:

– replacement and wearing parts; orifice price c_n [€/part], orifice lifetime L_n [h/part], mixing-tube price c_m [€/part], mixing-tube lifetime L_m [h/part].

Calculation of ***variable*** *costs:*

– electric energy costs:

$$C_e = c_e \cdot E \quad \text{€/h} \tag{5}$$

– stroški vzdrževanja:

– maintenance costs:

$$C_m = \frac{M}{L_a} \quad \text{€/h} \tag{6}$$

Izračun ***spremenljivih*** stroškov za **AVC**:

– stroški rezalne in hladilne vode:

Calculation of special ***AWJ variable costs****:*

– cutting-and cooling-water cost:

$$C_w = 60 \cdot c_w (m_w + W) \quad \text{€/h} \tag{7}$$

kjer je:

where:

$$W = K_w \cdot E \tag{8}$$

– stroški abraziva:

– cost of abrasive:

$$C_a = 60 \cdot c_a m_a \quad \text{€/h} \tag{9}$$

– stroški potrošnih delov (šob):

– costs of replacement and wearing parts (nozzles)

$$C_r = C_n + C_m = \frac{c_n}{L_n} + \frac{c_m}{L_m} \quad \text{€/h} \tag{10}$$

V tem izračunu niso upoštevani stroški delavca. Vse analizirane tehnologije zahtevajo izkušenega delavca za vodenje in vzdrževanje sistema. Sistemi delujejo neprekinjeno, kar zahteva polno zasedene delavce.

In these calculations no direct labor costs are included. All technologies reqiure skilled operators to operate and maintain the system. Since systems are continously operating, full-time operators are required.

Stroškovno modeliranje rezanja z AVC

Celotni obratovalni stroški na uro oz. strojna ura $C_{AVC,\ h}$ so računani s seštetjem stalnih in spremenljivih stroškov in vsebujejo investicijske stroške in stroške vzdrževanja, kakor prikazuje naslednja enačba:

AWJ cutting cost modeling

Total operating costs per hour $C_{awj,\ h}$ are calculated by adding the fixed costs to the variable, including also capital investment costs and the cost of maintenance, as shown in the following equation:

$$C_{awj,h} = C_d + C_e + C_w + C_a + C_r + C_m \quad \text{€/h} \tag{11}$$

Ključni parameter, ki vpliva na pretok vode ali posredno na hitrost rezanja je premer vodne šobe. Druga dva parametera, ki močno vplivata na hitrost, sta tlak sistema in pretok abraziva. Vseeno optimalne vrednosti teh parametrov niso povsem neodvisne. Optimalni pretok abraziva je odvisen od pretoka rezalne vode, kakor je to že prikazano. Parametra, premer vodne šobe in tlak vode tudi vplivata na obratovalne stroške. To prikazuje naslednja enačba v povezavi s porabo električne energije oz. moči [11]:

The key parameter that controls cutting speed is the orifice diameter or, indirectly, the cutting-water flow rate. The other two parameters that greatly influence the speed are the system pressure and the abrasive flow rate. However, the optimum values of these parameters are not totally independent. The optimum abrasive flow rate can be related to the cutting-water flow rate, as indicated earlier. These two parameters, i.e. orifice diameter and system pressure also mostly influence the operating costs, as shown among other relations, and also the following equation relating to the electric power consumption [11]:

$$E = 0.0455 \cdot d_n^{\,2} \sqrt{p^3} \quad \text{kW} \tag{12}$$

Celotni stroški na podlagi obratovalne ure oz. strojna ura so lahko za namen izbire postopka vezani na prej omenjena pomembna sistemska parametera, tj. tlak p in premer vodne šobe d_n in so podani z:

The total costs, based on per hour of operation, can be, for process selection purposes, related to the aforementioned significant system parameters, i.e. the pressure p and the orifice diameter d_n, and are given by:

$$C_{awj,h} = \frac{I}{D \cdot L_a} + \left[0.0455 \cdot (c_e + 15c_w)\, p + 1.479 \cdot (10.2 c_a + 60 c_w)\right] \cdot {d_n}^2 \sqrt{p} + \frac{1}{100} c_m + \frac{1}{60} c_n + \frac{M}{L_a} \qquad (13).$$

Za končno primerjavo z drugimi postopki vpeljemo stroške na meter reza in jih izračunamo kot:

The costs, based on per meter of cutting, in order to make the final comparison with other processes' cutting costs, are established as:

$$C_{awj,m} = \frac{16,67 \cdot C_{awj,h}}{v} \quad \text{€/m} \qquad (14).$$

Stroškovni modeli za druge postopke so razviti na enak način. Vsak vsebuje parametre, specifične za postopek, upoštevajoč vrednosti za specifične nastavitve material/konstrukcija. Stroškovne modele vseh postopkov smo vgradili v program '*CM*' za zadnji korak v izbirnem postopku. Slika 6 prikazuje primer *CM* komunikacijskega okna za zadnjo stopnjo o*ceno ekonomičnosti*. Preračun je ponovno izveden samo za izdelavo ustreznega postopka. V program so vključene predefinirane vrednosti deležev stalnih in spremenljivih stroškov, vendar lahko uporabnik te vrednosti spremeni in računa s specifičnimi za krajevne razmere. Program izračuna celotne proizvodne stroške na uro in celotne proizvodne stroške na meter ravnega reza.

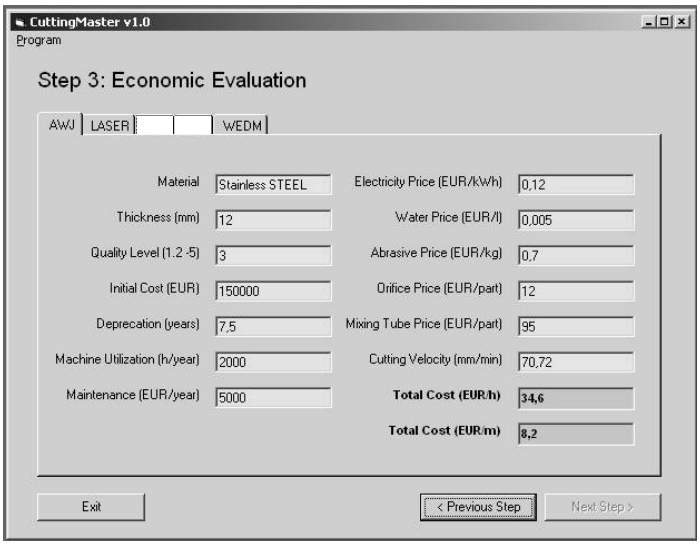
The cost models for other processes were developed in the same manner. Each includes the process-specific parameters considering their values for the specific material/design settings. All processes' cost models were implemented in '*CM*' software for the final step of selection procedure. Figure 6 shows an example of the *CM* dialog screen for the stage of *economic evaluation*. The calculation is again made only for the viable processes. The program incorporates predefined values for the components of fixed and variable costs, but the user could change these values and then calculate with those specific to the local situation. The program calculates the total production costs on an hourly basis and the total production costs for a meter of straight cutting.

4 SKLEPI

4 CONCLUSIONS

Večina člankov objavljenih na področju izbire postopka, je osredotočenih na preliminarno izbiro, kjer so upoštevani vsi postopki ([4] in [5]). Ta prispevek podaja podrobnejšo informacijo o izbiri postopka, kakor je bila podana v naših prejšnjih

Most of the papers published in the field of process selection are focused on preliminary selection, where all the processes are considered ([4] and [5]). This paper provides more detailed process-selection procedure than was made in our previous investigations [15] and



Sl. 6. *Primer komunikacijskega okna programa CM za stopnjo ocena ekonomičnosti*
Fig. 6. *Example of a CM dialog screen for the stage of economic evaluation*

objavah [15] in [16]. Metodologija obsega načelo strukturirane izbire za specifično izdelovalno opravilo – obrisno rezanje. Posebej obravnava vpliv tehnoloških in ekonomskih dejavnikov. Postopkovni podatki so zbrani na ustrezen specifično materialno raven, ki omogoča potrebno ločevanje za preučevano izdelovalno opravilo. Izbira uporablja kombinacijo empirično utemeljenih postopkovnih modelov, ki olajšajo določitev ustreznih postopkovnih informacij. Cilj je izvleči ustrezeno raven natančnosti, ki še omogoča uporabno razločevanje. Kakovost izbire je močno odvisna od kakovosti podatkov in izluščenega znanja, kakor tudi od ocene rezultatov postopka. Posebna zapletenost fizike vseh postopkov prav tako narekuje določeno stopnjo pragmatizma. Tako so uporabljeni zgolj empirični modeli, ki zagotavljajo široko območje preučevanih možnosti. Na prvi pogled se zdita izračuna stroškov in optimizacijski problem brezupno zapletena, saj je število parametrov, ki vplivajo na strukturo stroškov, ekstremno veliko. Vseeno lahko problem močno poenostavimo z uporabo lokalne podoptimizacije. Prikazano je, da je optimizacija lahko izvedena s samo dvema parametroma za primer rezanja z AVC, tj. tlak in premer vodne šobe, in z enim za lasersko rezanje, tj. laserska moč.

Ostaja torej izziv, kako določiti najboljši postopek čim hitreje, torej tako da določimo karakteristične veličine izdelka, tj. zahteve konstrukcije, ki jih uskladimo z zmožnostmi. Izbira je vodena sekvenčno z uporabo preddefiniranih vrednosti. Na ta način lahko vodi prek ustreznih odločitev tudi manj izkušene konstrukterje. V načrtu je verifikacija programskega orodja s testiranjem na izbranih učnih primerih iz industrijske prakse.

[16]. The methodology embodies the principle of structured selection for a specific manufacturing task – contour cutting. It accounts separately for the influences of technical and economic factors. The process data are assembled at an appropriate material-specific level to provide the discrimination needed for the manufacturing task being considered. Selection uses a combination of empirically based process models to help determine the relevant processing information. The challenge is to extract an appropriate level of detail and approximation to provide a useful discrimination. The quality of the selection, however, depends greatly on the quality of the data and the extracted knowledge as well as on the estimation of the process objectives. The inherent complexity of process physics also calls for a degree of pragmatism, so that purely empirical models are used if required in order that as wide a range of options as possible is considered. At first sight, the cost calculation and optimisation problem seems hopelessly complex, since the number of parameters affecting the cost structure is extremely large. However, by using local sub optimisation, the problem can be greatly simplified. It is shown that the optimisation can be conducted with only two parameters for AWJ cutting, i.e. pressure and orifice diameter. The economic evaluation incorporates these parameters as factors in the process cost modeling.

In order to determine the best process as early as possible, the selection procedure is implemented in a computer-aided process-selection algorithm, which enables simultaneous process definition by the designer and the technologist. The selection is conducted sequentially using predefined parameter values, so that less-experienced designers are guided through the appropriate decisions. The verification of the software tool is planned by testing it on selected case studies from industrial practice.

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Naslov avtorjev: mag. Davorin Kramar
prof.dr. Miha Junkar
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
davorin.kramar@fs.uni-lj.si
miha.junkar@fs.uni-lj.si

Authors' Address: Mag. Davorin Kramar
Prof.Dr. Miha Junkar
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
davorin.kramar@fs.uni-lj.si
miha.junkar@fs.uni-lj.si

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Personal Events

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DOKTORATI

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svojo doktorsko disertacijo, in sicer:
dne 23. junija 2003: **mag. Boštjan Bremec**, z naslovom: “Geometrijska optimizacija stabilnosti dvakrat povezane plošče v elasto-plastičnem območju”.

Na Fakulteti za strojništvo Univerze v Mariboru so z uspehom zagovarjali svoje doktorske disertacije, in sicer:
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dne 18. junija 2003: **Dejan Žiher,** z naslovom: “Kombinirana proizvodnja električne, toplotne in hladilne energije” in
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S tem so navedeni kandidati dosegli akademsko stopnjo magistra tehničnih znanosti.

SPECIALIZACIJE

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S tem je navedeni kandidat dosegel akademsko stopnjo specialista.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:
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Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

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

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Članek naj bo napisan v naslednji obliki:
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- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
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- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

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Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalniku Microsoft Word. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

Prosimo, da ne uporabljate urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata. V urejevalniku LaTeX oblikujte grafe, preglednice in enačbe in jih stiskajte na kakovostnem laserskem tiskalniku, da jih bomo lahko presneli.

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

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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).

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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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- 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].

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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.).

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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.

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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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The list of references

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[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.

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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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