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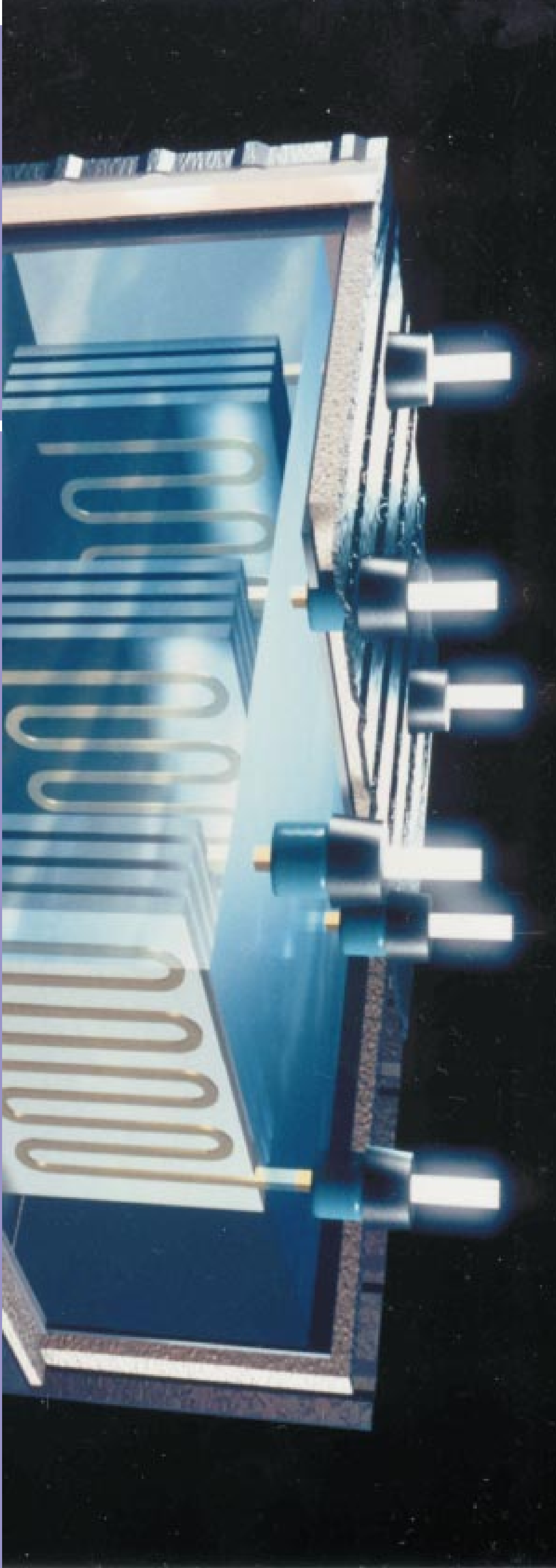

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Simuliranje nastajanja gruč dispergiranih delcev pod vplivom zunanjega magnetnega polja

A Simulation of the Cluster-Formation Process in a Dispersion of Fine Particles Under the Influence of an External Magnetic Field

Andrej Pristovnik - Jurij Krope - Lucija Črepinšek-Lipuš

Naprave za magnetno obdelavo vode (MOV) so učinkovita, gospodarna in dobra ekološka rešitev za preprečevanje izločanja vodnega kamna. Na podlagi laboratorijskih preskusov so ugotovili, da je učinkovitost MOV odvisna od sestave obdelovanega disperznega sistema in obratovalnih razmer naprave. Na temelju teorije Derjagin-Landau in Verway-Overbeek (DLVO) in statistične metode Monte Carlo Metropolis smo razvili teoretični model nastajanja gruč dispergiranih delcev pod vplivom zunanjega magnetnega polja. Nadalje smo po načelu "odprtega vira" na podlagi omenjenega modela razvili računalniški program za simulacijo in grafično predstavitev nastajanja gruč pod vplivom zunanjega magnetnega polja. Rezultate izračunov smo analizirali z metodo delitve in metodo stopenjske porazdelitve.

(Ključne besede: obdelava vode magnetna, vodni kamen, metode Monte Carlo Metropolis, analize gruč)

Magnetic water-treatment (MWT) devices for scale control can be used with good economic and ecological benefits. From experimental results under well-controlled laboratory conditions we have established that the effects of MWT devices are very dependent on the composition of the treated dispersion system and their working conditions. To investigate the effects of magnetic field on the process of cluster formation in a fine-particle dispersion under the influence of the external magnetic field of a MWT device a theoretical model based on the Derjagin-Landau and Verway-Overbeek (DVLO) theory and the statistical Monte Carlo Metropolis method was used. The open-source computer programs for the simulation and the graphical presentation of clustering under the influence of an external magnetic field were developed. The results were analysed by cluster analysis, based on the partitioning and hierarchical methods.

(Keywords: magnetic water treatment, scale prevention, Metropolis Monte Carlo, cluster analysis)

0 UVOD

Magnetna obdelava vode je pogosto uporabljana metoda nekemične obdelave vode za nadzor izločanja vodnega kamna. Nadzor vodnega kamna se dosega z vodenjem napajane vode skozi magnetno polje. Je gospodarna metoda, vendar še vedno daje nezanesljive rezultate. Kljub več desetletnim proučevanjem na tem področju še ni izdelana dokončna znanstvena teorija, kako te naprave natančno delujejo in kakšni so pogoji za njihovo optimalno delovanje.

Naravne vode so bogati disperzni sistemi, ki vsebujejo različne koloide, ione in druge sestavine. Zaradi naravne prenasičenosti ali pa vzpostavitve prenasičenja ob spremembah med predelavo vode (npr. sprememba temperature, tlaka ali *pH*) lahko na stenah cevovodov in naprav pride do izločanja nekaterih izmed teh snovi v obliki težko odstranljivih

0 INTRODUCTION

Magnetic water-treatment is a frequently used non-chemical method for scale control. The scale prevention is achieved by passing the water through the magnetic field. It is an economically favorable technique, but it still gives unreliable results. Despite several decades of intensive research done in this area, no scientifically confirmed theoretical explanation exists yet that adequately describes how MWT devices work and the conditions for their effective and optimum operation.

Natural waters are rich dispersion systems that contain many colloids, ions, etc. Due to the natural supersaturating of water supplied to various systems or the supersaturating as a result of changed conditions during water processing (such as pressure drop, temperature and *pH*) a hard scale precipitates on the pipeline and the walls of the equipment. The oblog vodnega kamna. MOV je še posebej obetavna metoda za uravnavanje interakcij med koloidnimi delci v vodnih disperzijah [1].

Čeprav mnogi postopki vplivajo na koloidni sistem, pomeni ravnotežje med interakcijami privlakov in odbojev (pri določeni termični dejavnosti) kriterij za stabilnost koloidnih disperzij v naravnih vodah. Natančnejše razumevanje tega vzajemnega delovanja podaja teorija DLVO [2]. Težnji delcev, da bi se združili zaradi delovanja van der Waals–Londonovih sil kratkega dosega, nasprotuje električni naboj na trdni površini, ki deluje tudi na večjih razdaljah med delci. Tako je celotna interakcijska energija med dvema koloidnima delcema (E_t) vsota energije elektrostatskega odboja (E_r; ko se električni dvojni plasti delcev prekrivata) in energije medmolekularnega privlaka (E_a; delovanje van der Waals–Londonovih sil) [2]:

MOV is a particularly promising technique for controlling the interactions among colloidal particles in water dispersions [1].

Although many processes affect colloidal behavior, the balance between attraction and repulsion interactions (for a particular level of thermal activity) is a criterion for the stability in colloid dispersions. A detailed understanding of this interplay is the basis of the DLVO theory [2]. The tendency of particles to aggregate as a result of the short-range van der Waals–London forces is counter acted by the electrically charged layer on the particles' surfaces. Thus, the total interaction energy (E_t) between two colloidal particles is the sum of the repulsion energy (E_r; electric repulsion, when double layers of two particles overlap) and the attraction energy (E_a; the particles' interaction as a result of the van der Waals–London forces) [2]:

$$E_t = E_r + E_a \qquad (1).$$

Energija elektrostatskega odboja (E_r) med delcema je odvisna od polmera teh delcev (a), razdalje med njunima centroma (R), elektrokinetskega potenciala (φ_δ) in dielektrične konstante disperznega medija (ε_r). Med enakima, okroglima, razmeroma majhnima delcema s široko električno dvojno plastjo (majhen $\kappa\alpha$) je energija odboja:

The repulsion energy (E_r) between two particles depends on the radius (a), the distance between the centres of the particles (R), the electrokinetic potential (φ_δ) and the dielectric constant (ε_r) of the dispersion medium. For identical, spherical and relatively small particles with a wide electric double layer ($\kappa\alpha$ is small) the repulsion energy is:

$$E_r = \frac{\varepsilon_r \varepsilon_0 a \varphi_\delta^2}{s} \exp(-\kappa a (s-2)) \qquad (2),$$

kjer sta: s razmerje med razdaljo med središčem in premerom delca ($s=R/a$) in κ Debye-Hückelov parameter (njegova obratna vrednost je v prvem približku enaka debelini električne dvojne plasti):

where parameter s is the ratio between the distance and the radius ($s=R/a$) and κ is the Debye-Hückel parameter (its reciprocal value is considered as a first approximation for the length of the electric double layer):

$$\kappa = \sqrt{\frac{2 e_0^2 N_A \sum_i z_i^2 c_i}{\varepsilon_r \varepsilon_0 k_B T}} \qquad (3).$$

Za okside, dispergirane v vodi, je električni potencial na trdni površini (φ_δ) določen s pH disperzije ([2] in [3]). Energija medmolekularnega privlaka (E_a) med dvema enako velikima, okroglima delcema je določena z enačbo:

For oxide minerals in water, the surface potential (φ_δ) of the particles is determined by the pH of the dispersion ([2] and [3]). The energy of attraction (E_a) between two spherical particles with an identical radius is defined by the equation:

$$E_a = -\frac{k_H}{6}\left(\frac{2}{s^2-4} + \frac{2}{s^2} + \ln\frac{s^2-4}{s^2}\right) \qquad (4),$$

kjer je k_H Hamakerjeva konstanta.

Magnetostatične interakcije med delci spreminjajo obnašanje tekočine in lahko destabilizirajo koloidni sistem. Ko je disperzija koloidnih delcev izpostavljena zunanjemu magnetnemu polju, se pojavijo magnetne sile, ki zmanjšujejo stabilnost koloidnega sistema. Energija magnetnega privlaka (E_m) med dvema okroglima delcema na razdalji R_{ij} je odvisna od gostote (B) in smeri delovanja zunanjega magnetnega polja, velikosti delcev (a) in magnetnih lastnosti minerala. Pri vzporedni usmeritvi magnetnih

where the parameter k_H is the Hamaker constant.

Magnetostatic particle interactions modify the behavior of the fluid and can affect the colloidal stability. When a dispersion of colloid particles is placed in an external magnetic field an additional magnetic force arises, which decreases the stability of the colloid system. The energy of the magnetic attraction (E_m) between two spherical particles separated by a distance R_{ij} depends on the magnetic density (B) and the angle of the external magnetic field, the radius of the particles (a) and the magnetic properties of the particles. For the momentov dveh enakih, okroglih delcev je energija magnetnega privlaka:

parallel-orientated magnetic moments of two identical particles, the energy of the magnetic interaction is:

$$E_m = -\frac{32\pi^2 a^6 \chi^2 B^2}{9\mu_0 R_{ij}^3} \qquad (5).$$

Celotna energija (E_t) interakcij med koloidnima delcema v sistemu, izpostavljenemu zunanjemu magnetnemu polju, je tako:

Thus, the total energy of the interaction (E_t) for colloid particles in an external magnetic field is:

$$E_t = E_r + E_a + E_m \qquad (6).$$

Statistične numerične metode, znane kot metode Monte Carlo, za simulacijo uporabljajo zaporedja naključnih števil. Model za proučevanje lastnosti koloidnih vodnih disperzij pod vplivom magnetnega polja ([2] do [8]) temelji na metodi Monte Carlo Metropolis ([4] in [13]).

Osnova modela je dvorazsežna kvadratna celica z dolžino stranice *A* , z *N*-timi naključno razporejenimi delci (sl.1). Vsi delci so okrogli in enaki. Lega slehernega delca je znana in označena s koordinatami (x, y,θ), kjer je θ kot med magnetnim momentom delca in zunanjim magnetnim poljem [6] (sl.2).

Celotna energija sistema (E_S) je enaka vsoti vseh energij interakcij med koloidnimi delci v prostoru:

Statistical numerical methods, known as Monte Carlo methods, are methods that utilize sequences of random numbers to perform the simulation. The presented model is based on the Monte Carlo Metropolis ([4] and [13]) method and has been used to investigate the properties of colloid particle dispersions in water under the influence of a magnetic field ([2] to [8]).

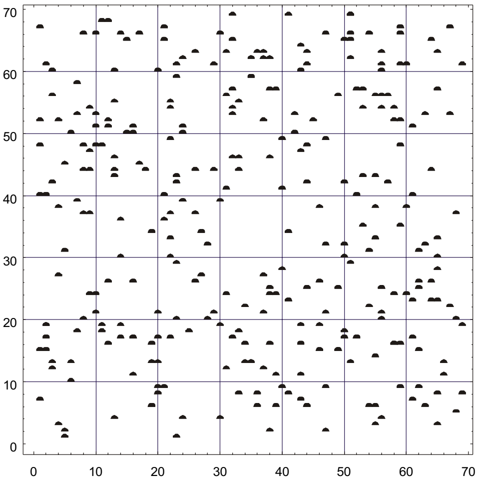
The model is based on a two-dimensional square cell with a side of length *A*, containing *N* randomly distributed particles (Fig. 1). All the particles are spherical and identical. The position of any particle is known and can be specified with coordinates (x, y,θ), where θ is the angle between the magnetic moment of the particle and the applied magnetic field [6] (Fig. 2).

The total energy of the system (E_S) is the sum of the total energies of the interactions amongst all the colloid particles:

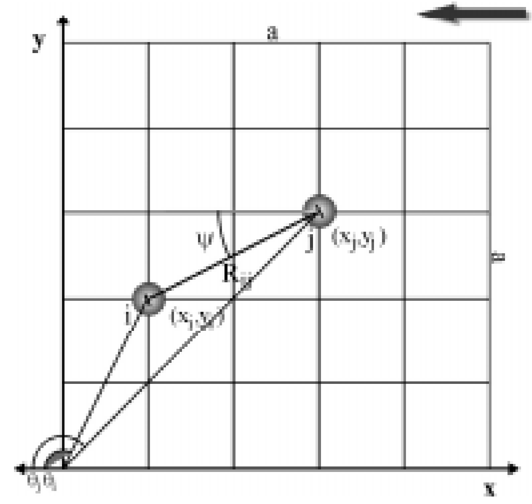
$$E_S = \sum_{i=1}^{N} E_{t(i)} \qquad (7).$$

Metoda vsebuje izračunavanje energijskih sprememb (ΔE), medtem ko se koordinate enega delca v analizirani celici naključno spremenijo za majhne

The method consists of calculating the energy change (ΔE) when the coordinates of one particle in the analyzed cell are changed, at random, by small



Sl. 1. *Naključna porazdelitev okroglih delcev v dvorazsežnem prostoru kvadratne oblike (A=70 μm, α=0,5 μm, N=300)*
Fig. 1. *Randomly distributed spherical particles in a two-dimensional square cell (A=70 μm, α=0.5 μm, N=300)*



Sl. 2. *Par delcev (i,j) - okrogle oblike v dvorazsežni celici ob delovanju zunanjega magnetnega polja pod kotom ψ [9]*
Fig. 2. *A pair of spherical particles (i,j) in a two-dimensional square cell under a magnetic field applied at an angle ψ[9]*

vrednosti. V primeru, da je nova vrednost celotne energije sistema nižja od predhodne, delec ostane v novi legi; v nasprotnem primeru se izračuna faktor P in primerja z naključno vrednostjo ξ, $\xi \in [0,1]$:

$$P = \exp\left(-\Delta E / k_B T\right) \tag{8}$$

Če je faktor P večji od naključnega števila, delec ohrani novo lego, sicer se vrne na prvotno lego. Opisani postopek se izvede za vseh N delcev v kvadratni celici.

1 RAČUNALNIŠKI PROGRAM ZA SIMULACIJO NASTAJANJA GRUČ

Pri proučevanju magnetne obdelave vode smo uporabili teorijo koloidov, matematike in statistike. Računalniški program Open Source (MCM) [15] smo priredili za dvorazsežno simulacijo postopka nastajanja gruč v finih disperzijah pod vplivom zunanjega magnetnega polja. Do takšnega nastajanja naj bi namreč prišlo v napravah MOV, kot predvidevajo nekateri avtorji ([10] in [11]). Za grafično predstavitev smo uporabili sklop računalniških programov MCM View [9] in za analizo gruč Fanny in Twins [12].

Podatki so vneseni z dvema vhodnima datotekama. V prvi datoteki so podani: velikost celice, število in fizikalne lastnosti delcev; določena je tudi struktura vmesnih izhodnih datotek. V drugi vhodni datoteki je določena izhodiščna lega delcev.

Rezultati simulacije so zapisani v različnih oblikah in so lahko predstavljeni s programi, kakršna sta Microsoft Excel [15] ali Microcal Origin [15]. Za grafično predstavitev je razvit CM View program Compaq Array Visualizer [15]. Rezultati so bili nadalje ovrednoteni z metodo delitve in metodo stopenjske porazdelitve za analizo gruč po Kaufmanu in Rousseauwu [12]. V ta namen sta bila uporabljena programa Fanny in Twins.

2 REZULTATI SIMULACIJE

Kot primerjalni podatki za primarne numerične izračune so bile uporabljene fizikalne lastnosti hematitnih delcev (Fe_2O_3) v vodni disperziji. Na podlagi tega so bili izvedeni numerični izračuni za nekatere minerale, ki ustvarjajo vodni kamen v vodi: diamagnetni kalcijev karbonat ($CaCO_3$), kalcijev sulfat ($CaSO_4$), silicijev dioksid (SiO_2), antiferomagnetna hematit (Fe_2O_3), getit (FeOOH) in feromagnetni magnetit (Fe_3O_4).

Za vse naštete minerale je bila simulacija nastajanja gruč izvedena v naslednjih razmerah:

- različno število delcev v kvadratni celici in različni polmer a,

amounts. If the new total energy of the system is less than the previous one the particle stays in its new position; otherwise a factor P is calculated and compared with the random number ξ, $\xi \in [0,1]$.

If the P factor is greater than the random number the particle retains its new position, otherwise it is returned to its original position. This procedure is applied for all N particles in a square cell.

1 A COMPUTER PROGRAM FOR THE SIMULATION OF CLUSTER FORMATION

Well-known theories from the field of colloid science, statistics and mathematics have been taken into consideration and applied in magnetic water-treatment research. An open-source computer program (MCM) [15] for the two-dimensional simulation of the cluster-formation process in a fine-particles dispersion under the influence of an external magnetic field was developed. According to some authors ([10] and [11]) such a cluster formation might occur in MWT devices. A set of computer programs, MCM View [9] and Fanny and Twins [12], were used for the graphical presentation and the cluster analysis, respectively.

The data are entered with two input files. In the first input file the size of the cell, the number and the physical properties of the particles are determined and the structure for the intermediate output files is defined. In the second input file the original position of the particles is determined.

The results of the simulation are written in various formats and can be presented with the programs such as Microsoft Excel [15] or Microcal Origin [15]. For the graphical presentation, the MCM View program was developed on the basis of the Compaq Array Visualizer [15]. The results were further analysed with the partitioning and hierarchical methods for cluster analysis of Kaufman and Rousseauw [12]. For this purpose we used the Fanny and Twins programs.

2 RESULTS OF THE SIMULATION

As the reference data for the primary numerical calculations, the physical properties of hematite particles (Fe_2O_3) in an aqueous dispersion were used. On this basis, the numerical calculations for some of the scale-forming minerals in the water, such as diamagnetic calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), silicon dioxide (SiO_2), antiferromagnetic hematite (Fe_2O_3), goethite (FeOOH) and ferromagnetic magnetite (Fe_3O_4), were carried out.

For all these minerals a simulation of cluster formation was carried out for the following conditions:

- a different number of particles in the square cell and a different radius a

- različni kot ψ uporabljenega magnetnega polja (0, 30, 60 in 90^0),
- različni elektrokinetski potencial φ_δ (10, 20 in 30 mV),
- različna gostota B uporabljenega magnetnega polja (od 0 do 1T) in
- različne pH vrednosti vodnih disperzij in drugo [9].

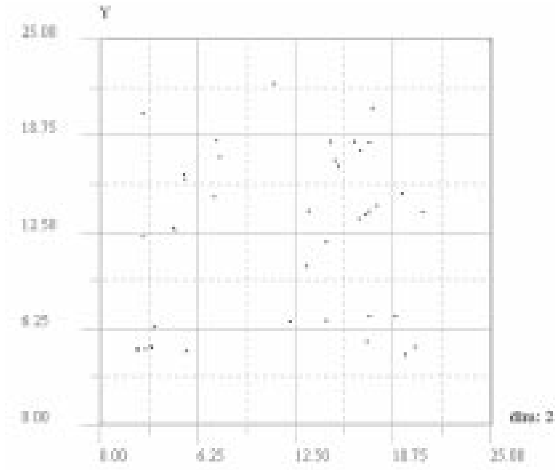
Celotna energija interakcije je bila izračunana za delce hematita (N=40 do 300) s polmerom a=0,5 do 5 μm, volumsko magnetno susceptibilnostjo χ=0,02 in Hamakerjevo konstanto k_H=5·10^{-20} J v kvadratni celici z dolžino stranice A=25 do 70 μm. Absolutna temperatura disperzije je bila nastavljena na 300 K in pH na 7,0.

Konvergenca je glede na prejšnje raziskave [6] naravnana na 600 premikov na delec. Izhodiščna lega delcev je bila naravnana z matriko 5 × 8. Slika 3 prikazuje lego delcev pri 10 in 600 premikih pod vplivom magnetnega polja z gostoto 0,5 T in kotom 30°.

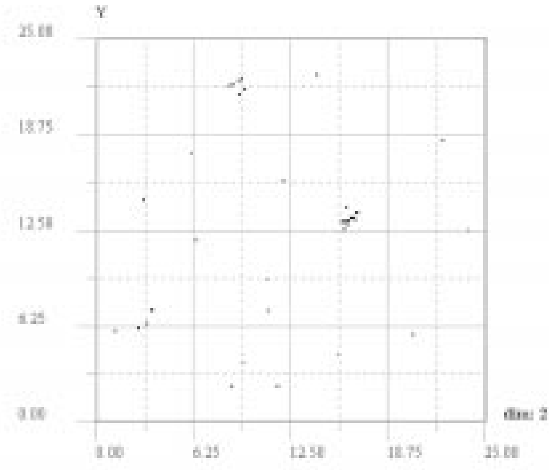
- a different angle ψ of the applied magnetic field (0, 30, 60 and 90^0)
- a different electrokinetic potential φ_δ (10, 20 and 30 mV)
- a different density B of the applied magnetic field (from 0 to 1T)
- different pH values of the aqueous dispersions and others [9].

The total interaction energy for the hematite particles (N = 40 to 300) with the radius a=0.5 to 5 μm the volume magnetic susceptibility χ=0.02 and the Hamaker constant k_H=5·10^{-20} J in a square unit cell with side length A=25 to 70 μm was computed. The absolute temperature was set to 300 K and the pH was set to 7.0.

According to earlier research [6], the recommended rate of convergence is up to 600 shifts per particle. The original position of the particles was set up as a 5×8 matrix. Figure 3 shows the positions of the particles after 10 and 600 shifts under a magnetic field of 0.5 T, applied at an angle of 30°.



Sl. 3.a. *Porazdelitev delcev po 10 premikih [9]*
Fig. 3.a. *Position of the particles after 10 shifts [9]*



b. *Porazdelitev delcev po 600 premikih[9]*
b. *Position of the particles after 600 shifts [9]*

Na sliki 3.b je razvidno nastajanje ene večje in dveh manjših gruč, ki so razporejene v smeri magnetnega polja. Iz slike ni moč neposredno ovrednotiti intenzivnosti in velikosti gruč, zato je treba rezultate analizirati z ustrezno matematično metodo. V računalniškem programu Fanny je bila uporabljena metoda logično mehke tvorbe gruč, ki je posplošitev metode delitve. Intenzivnost postopka nastajanja gruč je bila ovrednotena z normalizirano vrednostjo razdelitvenega koeficienta ($\bar{s}_{k=5}$).

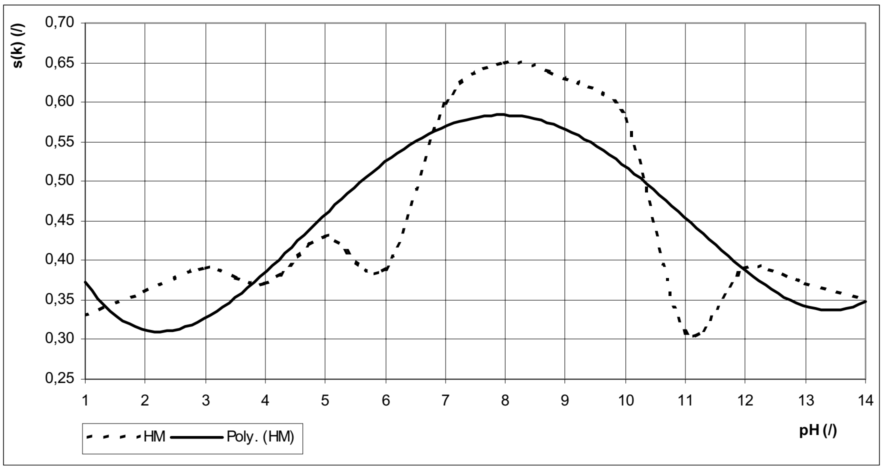
Slika 5 prikazuje intenzivnost postopka nastajanja gruč delcev hematita pri različnih elektrokinetskih potencialih in različnih kotih uporabljenega magnetnega polja.

V skladu z eksperimentalnimi rezultati [13] so učinki naprav za magnetno obdelavo vode močno odvisni od sestave obdelovanega disperznega sistema in obratovalnih razmer. Vrednost pH v sistemu

In Figure 3.b the formation of one major and two minor clusters is very clear, these are well aligned in the direction of the applied magnetic field. From the same figure the intensity and the size of the cluster cannot be evaluated directly, thus the results have to be analyzed with an appropriate mathematical method. The fuzzy clustering method, as a generalization of partitioning, was used in the Fanny computer program. The intensity of the cluster-formation process was measured with the value of the normalized version of the partition coefficient ($\bar{s}_{k=5}$).

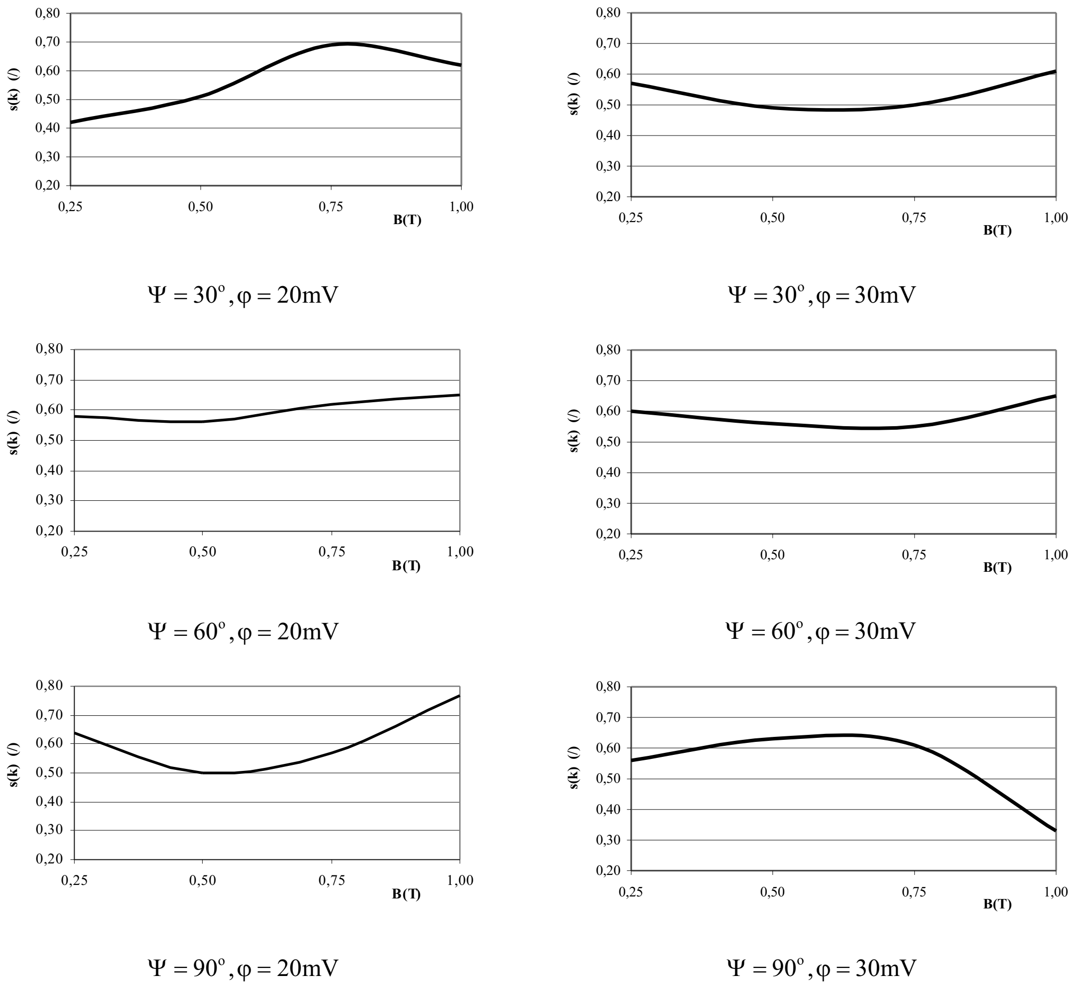
Figure 5 shows the intensity of the cluster-formation process of the hematite particles at the different electrokinetic potentials and under a magnetic field applied at different angles.

According to the experimental results [13], the effects of magnetic water-treatment devices are very dependent on the composition of the treated dispersion system and working conditions. The pH value of



Sl. 4. *Intenzivnost nastajanja gruč v odvisnosti od pH obdelovanega sistema in aproksimacija krivulje s polinomom druge stopnje [9]*

Fig. 4. *The intensity of the cluster-formation process versus pH and a graphical approximation with a polynomial of the second order [9]*



$\Psi = 30^{\circ}, \varphi = 20\mathrm{mV}$

$\Psi = 30^{\circ}, \varphi = 30\mathrm{mV}$

$\Psi = 60^{\circ}, \varphi = 20\mathrm{mV}$

$\Psi = 60^{\circ}, \varphi = 30\mathrm{mV}$

$\Psi = 90^{\circ}, \varphi = 20\mathrm{mV}$

$\Psi = 90^{\circ}, \varphi = 30\mathrm{mV}$

Sl. 5. *Intenzivnost nastajanja gruč (normalizirana vrednost Dunnovega koeficienta $\bar{s}_{k=5}$) pod vplivom zunanjega magnetnega polja gostote 0,5 T pri različnih kotih in različnih vrednostih elektrokinetskega potenciala [9]*

Fig. 5. *The intensity of the cluster-formation process (normalized version of Dunn's partition coefficient, $\bar{s}_{k=5}$) under a magnetic field of 0.5 T applied at different angles and different retardation potentials [9]*

je eden najbolj vplivnih parametrov v postopku nastajanja gruč. Za uspešno nastajanje gruč delcev hematita je optimalni *pH* v obdelovani disperziji 5,6 do 10,3 (sl. 4).

3 SKLEP

V zadnjih desetletjih je bilo opravljenih veliko raziskav na področju magnetne obdelave vode, a je še vedno vprašljiv sam mehanizem delovanja naprav za MOV. Mehanizem je zapleten in neposredno odvisen od kemične sestave vode in obratovalnih razmer naprave MOV. Zaradi slabega poznavanja mehanizma delovanja ostaja tako njihova učinkovitost naključna.

Model simulacije nastajanja gruč smo priredili za področje magnetne obdelave. Začetni izračuni so temeljili na delcih hematita. Model je utemeljen na teoriji DLVO, statistični metodi Monte Carlo Metropolis in na teoriji analize gruč. Na temelju predstavljenega modela smo z računalniškim programom simulirali in analizirali nastajanje gruč za večino snovi, ki ustvarjajo vodni kamen. Predstavljeni rezultati dobro ponazarjajo pogoje delovanja naprav za MOV ob znani kemični sestavi vode.

the system is one of the most influential parameters for the cluster-formation process. For the successful clustering of hematite particles, the optimum *pH* range of the treated dispersion is from 5.6 to 10.3 (Fig. 4).

3 CONCLUSION

Despite the large amount of research work over past decades a theoretical understanding of the MWT mechanism is still incomplete. This is the main problem when it comes to the design of efficient MWT devices. The MWT mechanism is complex and directly depends on the chemical composition of the water and the working conditions.

A theoretical model for the simulation of cluster formation with hematite particles as reference data was supplemented to the region of magnetic water-treatment. The model is based on the DLVO theory, the Monte Carlo Metropolis method and the cluster-analysis theory. Numerical calculations for most of the scale-forming minerals were done with computer programs based on the presented model. The obtained results show that the model predicts well the operational conditions for the effective use of MWT devices, providing the chemical composition of the supplied water is known.

4 OZNAČBE
4 SYMBOLS

polmer delca	a	m	radius of interacting spheres
gostota magnetnega polja	B	Vs/m^2	magnetic field density
molarna koncentracija ionov i v raztopini	c_i	mol/L	molar concentration of ions i in the solution
osnovni električni naboj (1,6·10^{-19} As)	e_o	As	electron charge (1,6·10^{-19} As)
energija medmolekularnega privlaka	E_a	J	inter-molecular attraction energy
energija elektrostatskega odboja	E_r	J	electrostatic repulsion energy
energija magnetnega privlaka	E_m	J	magnetic attraction energy
celotna energija interakcij	E_t	J	total interaction energy)
Boltzmannova konstanta (1,38·10^{-23} J/K)	k_B	J/K	Boltzmann constant (1,38·10^{-23} J/K)
Hamakerjeva konstanta	k_H	J	Hamaker constant
število delcev	N		number of particles
Avogadrovo število delcev (6,022·10^{23}/mol)	N_A	1/mol	Avogadro number of particles (6,022·10^{23}/mol)
faktor po enačbi (8)	P		factor by equation (8)
razdalja med središčema delcev	R	m	distance between centers of particles
razmerje med razdaljo *R* in polmerom *a*	s		ratio between distance *R* and radius *a*
absolutna temperatura	T	K	absolute temperature
koordinati lege delca	x,y	m	coordinates of particle's position
valenca iona	z_i		valence of ion i
magnetna susceptibilnost minerala	χ	m	magnetic susceptibility of the mineral
dielektrična konstanta vakuuma (8,85·10^{-12} As/Vm)	ε_0	As/Vm	dielectric constant of vacuum (8,85·10^{-12} As/Vm)
relativna dielektrična konstanta vode	ε_r		relative dielectric constant of water
elektrokinetski potencial na trdni površini	φ_δ	V	electrokinetic potential at a solid surface
Debye-Hückelov parameter	κ	1/m	Debye-Hűckel parameter
magnetna permeabilnost vakuuma (4π·10^{-7} Vs/Am)	μ_0	Vs/Am	magnetic permeability of vacuum (4π·10^{-7} Vs/Am)
kot med magnetnim momentom delca in uporabljenim magnetnim poljem	θ	rad	angle between the magnetic moment of the particle and the applied magnetic field
naključna vrednost med 0 in 1	ξ		random number from 0 to 1
kot delovanja zunanjega magnetnega polja	ψ	rad	angle of the external magnetic field

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Analiza parametrov reverzibilne črpalne francisove turbine

An Analysis of the Parameters of Reversible Francis-Type Pump Turbines

Milo Mrkić

Pri projektiranju reverzibilnih hidroelektrarn (RHE) mora imeti projektant na voljo čim bolj podrobne podatke o parametrih hidravličnih strojev, ki bodo v hidroelektrarno vgrajeni. Ta pogoj je še posebej pomemben, kadar gre za reverzibilne črpalno-turbinske agregate, saj morajo le-ti optimalno ustrezati režimu obratovanja v obeh smereh pretoka (črpalni in turbinski režim), da bi bila lahko vgrajena moč agregata optimalno izrabljena, tako pri polnjenju kakor tudi pri praznjenju zgornje akumulacije, in to v skladu z zahtevami elektroenergetskega sistema.

Ko se projektant loti projektiranja RHE, izbere po nomenklaturi ustrezen tip turbine, potem pa – upoštevajoč splošne karakteristike in nomenklaturne diagrame – določa osnovne parametre reverzibilne črpalke – turbine (RPT).

Glede na to, da je nomenklatura RPT pomanjkljiva in da obstajajo splošne karakteristike samo za omejeno število tipov, je primerno v začetni fazi projekta najprej definirati osnovne parametre RPT, v prvem koraku na temelju specifične vrtilne frekvence.

V prispevku je podanih nekaj rezultatov študij razpoložljive tehnične literature kakor tudi rezultatov teoretičnega dela, modelnih preiskav in preiskav v dejanskih razmerah, ki so bile ob sodelovanju avtorja prispevka opravljene na Katedri za izkoriščanje vodnih virov v Moskvi (Inštitut MISI).

(Ključne besede: projektiranje hidroelektrarn, turbine francis, črpalke reverzibilne, analize parameterske)

When designing pumping reservoir hydroelectric power stations the designer must have available detailed data on the parameters of the hydraulic machines that will be installed in the power plant. This is particularly important when reversible pumping-turbine units are installed, since they must best suit the working mode in both directions of the flow (pumping and turbine mode) so that the installed power of the unit is best utilized in the case of filling as well as emptying the upstream reservoir in accordance with the requirements of the public electric power system.

When the planning engineer starts to project, according to the nomenclature he chooses the appropriate type of turbine and then determines the basic parameters for the reversible pump-turbine (RPT) by using universal characteristics or graphical nomenclature.

Since the RPT nomenclature still does not exist and the universal characteristics only exist for a limited number of types it is appropriate at the initial stage of the design to define the basic parameters of the RPT, initially according to the specific number of revolutions.

In the work in this context some results of the study of available technical literature as well as the results of theoretical works are given. The results of model researches and researches in real conditions which were performed in "exploitation of water power" university department in Moscow (institute MISI), with participation of the author are also presented.

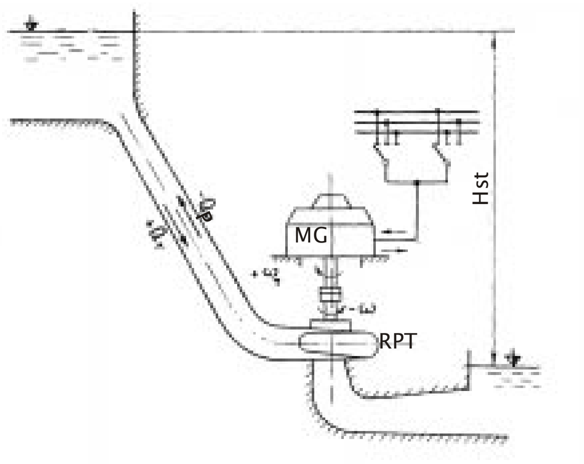
(Keywords: hydroelectric power stations, Francis turbines, reversible pump turbines, parameter analysis)

1 OSNOVNE KARAKTERISTIKE DELOVNEGA PROCESA RPT

Reverzibilni hidravlični stroj francisovega tipa ima značilnosti, ki se kažejo pri razliki njihovih osnovnih geometrijskih parametrov in obratovalnih karakteristik glede na klasične črpalke in turbine.

1 BASIC CHARACTERISTICS OF WORKING PROCESS RPT THEORY

A reversible hydraulic machine of the Francis type has some specific features whose basic geometrical parameters and operating characteristics differ from the conventional pump and turbine.



Sl. 1. *Shema reverzibilne hidroelektrarne*
Fig. 1. *Working plan of the reversible hydro power station*

Predvsem je treba vedeti, da sta padec vode reverzibilne hidroelektrarne (RHE) v turbinskem režimu (H_t) in višina RHE v črpalnem režimu (H_p) različna (sl. 1).

V turbinskem režimu je padec vode določen kot:

In particualr, it is necessary to realise that the fall of the reversible hydroelectric power plant in the turbine working mode (H_t) and the head in the pump working (H_p) mode are different (Fig. 1).

In the turbine working mode the fall is defined as follows.

$$H_t = H_{st} - h_t \tag{1}$$,

v črpalnem režimu pa višina kot:

and the head in the pump working mode is defined as:

$$H_p = H_{st} + h_p \tag{2}$$,

pri čemer so:

H_{st} - hidrostatični padec vode (višina)
h_t, h_p - hidravlične izgube.

Hidravlične izgube pri turbinskem obratovanju (h_t) niso enake izgubam v črpalnem režimu (h_p) obratovanja, ker sta pretoka v enem in drugem režimu v osnovi različna in ker tudi koeficienti lokalnih izgub v dovodnem in odvodnem sistemu niso enaki v turbinski in črpalni smeri pretoka vode (sl. 3).

Eulerjeva enačba za hidravlični reverzibilni stroj ima obliko:

- za turbinski režim

where:

H_{st} is the water head
h_t, h_p are the hydraulic losses

The hydraulic losses during turbine operation (h_t) are not the same as the losses in the pump working mode (h_p) because in principle the two flows in the first and second modes are different, and also because the coefficients of the local losses in the conduit and in the outflow system are not identical in the turbine direction and in the pump direction of the water flow (Fig. 3).

Euler´s equation for a reversible hydraulic machine has the following form:

- for the turbine working mode

$$\eta_t = \frac{u_1 \cdot c_0 \cdot \cos\ \alpha_0 - u_2 \cdot c_3 \cdot \cos\ \alpha_3}{g \cdot H_t} = \frac{\omega_t\left(\Gamma_1 - \Gamma_2\right)}{2 \cdot \pi \cdot g \cdot H_t} = \frac{\Delta\Gamma_t \cdot \omega_t}{2 \cdot \pi \cdot g \cdot H_t} \tag{3}$$,

- za črpalni režim

- for the pump working mode

$$\eta_p = \frac{g \cdot H_p}{u_1 \cdot c_0 \cdot \cos\ \alpha_0 - u_2 \cdot c_3 \cdot \cos\ \alpha_3} = \frac{2 \cdot \pi \cdot g \cdot H_p}{\omega_p\left(\Gamma_1 - \Gamma_2\right)} = \frac{2 \cdot \pi \cdot g \cdot H_p}{\Delta\Gamma_p \cdot \omega_p} \tag{4}$$,

pri čemer je:

$\Gamma = 2 \cdot \pi \cdot r \cdot c_u$ - obtok (cirkulacija),

$\omega = \frac{\pi \cdot n}{30}$ - kotna hitrost.

Indeks 1 se nanaša na vhod v delovno kolo, indeks 2 pa na izhod iz delovnega kolesa v turbinskem režimu. Ustrezajoči trikotniki hitrosti za

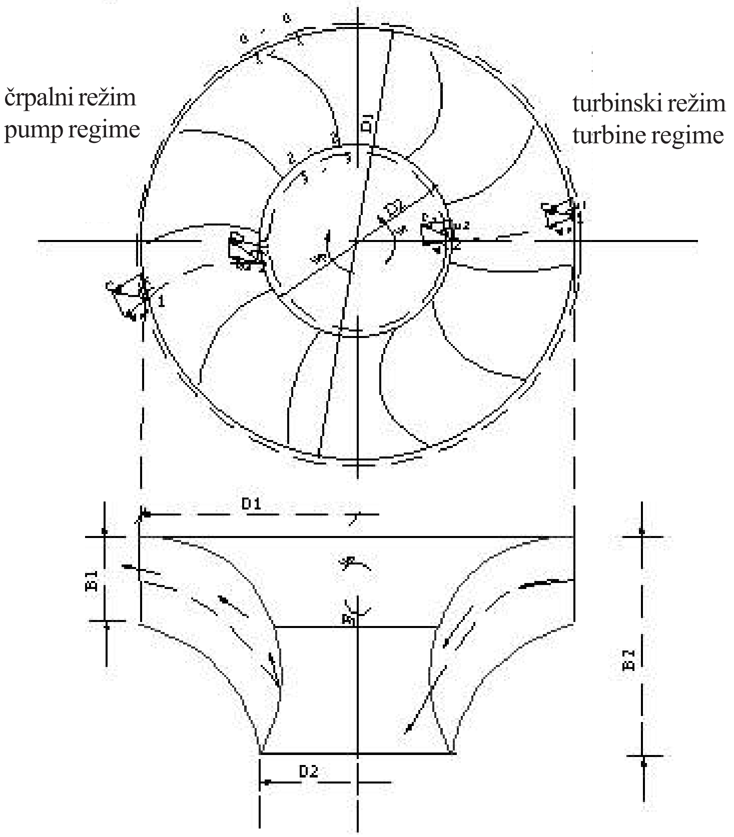
where:

$\Gamma = 2 \cdot \pi \cdot r \cdot c_u$ is the circulation

$\omega = \frac{\pi \cdot n}{30}$ is the angular speed

The index 1 refers to the inlet to the working wheel and the index 2 refers to the outlet from the working wheel in the turbine working mode. Figure 1 črpalni in turbinski režim so prikazani na sliki 2. Črte vhodnih (0-0) in izhodnih (3-3) površin delovnega področja kolesa so glede na črte vhodnih (1-1) in izhodnih (2-2) robov lopatic pomaknjene, da bi se izognili vplivu končnega števila lopatic na pretok vhodnih in izhodnih prerezov (sl. 2.).

shows the relevant triangles of the speeds in the pump and turbine working modes. The contours of the input (0-0) and outputs (3-3) working area surfaces are shifted with respect to the contours of the input (1-1) and output (2-2) edges of the moving blades to avoid influence at definitive numbers of blades on the flow in input and output cross sections (Fig. 2.).



Sl. 2. *Osnovni geometrijski parametri RPT francisovega tipa in trikotniki hitrosti v črpalnem in turbinskem režimu*

Fig. 2. *Basic geometrical parameters of the reversible pump - turbine of Francis type and triangles of speeds in the pump and turbine working modes*

Če vpeljemo oznaki: $\Gamma_1-\Gamma_2=\Delta\Gamma$ oziroma $\Gamma_1-\Gamma_2=\Delta\Gamma_p$, dobita enačbi (3) in (4) obliko:

If the terms $\Gamma_1-\Gamma_2=\Delta\Gamma$ and $\Gamma_1-\Gamma_2=\Delta\Gamma_p$ are introduced, equations (3) and (4) assume the following form :

$$\Delta\Gamma_t\cdot\omega_t=2\cdot\pi\cdot g\cdot H_t\cdot\eta_t \tag{3'}$$

$$\Delta\Gamma_p\cdot\omega_p=\frac{2\cdot\pi\cdot g\cdot H_p}{\eta_p} \tag{4'}$$

oziroma razmerje:

and/or the ratio :

$$\frac{\Delta\Gamma_p\cdot\omega_p}{\Delta\Gamma_t\cdot\omega_t}=\frac{H_p}{\eta_p\cdot\eta_t\cdot H_t} \tag{5}.$$

Če predpostavimo, da so izgube višine v turbinskem in črpalnem režimu enake in znašajo $h_t=h_p=0{,}05\cdot H_{st}$, potem je skladno z (1) in (2):

If it is assumed that the head losses in the turbine and the pump working modes are identical and amount to $h_t=h_p=0.05\cdot H_{st}$, the following applies in accordance with (1) and (2):

$$H_t=0{,}95\cdot H_{st}\ ;\ H_p=1{,}05\cdot H_{st}$$

2 ODVISNOST OSNOVNIH PARAMETROV RPT OD SPECIFIČNE VRTILNE FREKVENCE

Glede na to, da v obratovanjih RHE ni mogoče doseči enako velike stopnje izkoristka, je ugodneje imeti večjo stopnjo izkoristka v turbinskem režimu obratovanja kakor v črpalnem režimu (sl. 3), saj je cena vršne električne energije nekajkrat večja od cene električne energije v obdobjih najmanjše obremenitve elektroenergetskega sistema (sl. 4).

Predpostavimo, da sta $\eta_t = 0,93$ in $\eta_p = 0,90$, ti dve vrednosti vstavimo v enačbo (5), dobimo:

2 DEPENDENCE OF BASIC RPT PARAMETERS ON SPECIFIC NUMBER OF REVOLUTIONS

As an identical degree of efficiency cannot be reached with reversible hydroelectric power plants in both working modes (Fig. 3.) it is more convenient to have a higher degree of efficiency in the turbine working mode than in the pump working mode since the price of peak electric power is several times higher than the price of electric power during the period of least loading of the public electric power system, i.e. the price of free energy in the public electric power system (at the time when the reversible power plant operates in the pump working mode) Fig. 4.

If it is assumed accordingly that $\eta_t = 0,93$ and $\eta_p = 0,90$ and if these values are entered into equation (5), the following is obtained:

$$\frac{\Delta\Gamma_p \cdot \omega_p}{\Delta\Gamma_t \cdot \omega_t} = \frac{1,05 \cdot H_{st}}{0,90 \cdot 0,93 \cdot 0,95 \cdot H_{st}} \cong 1,3 \qquad (5')$$

Na podlagi analize (5′) lahko povzamemo, da moramo pri definiranju obratovalnih karakteristik reverzibilne črpalne turbine upoštevati naslednji predpostavki:

1. Če predpostavimo, da je razlika obtoka (cirkulacije) na vstopu in izstopu iz delovnega kolesa v turbinskem in črpalnem režimu enaka, to je $\Delta\Gamma_p = \Delta\Gamma_t$, potem mora biti vrtilna frekvenca v črpalnem režimu večje od vrtilne frekvence v turbinskem režimu ($\omega_p \cong 1,3 \cdot \omega_t$). V praksi pomeni to uporabo dvohitrostnih generatorjev (MG), ki imajo dve vrtilni frekvenci, vendar v nasprotnih smereh. Pri tem je treba pri prehodu iz enega v drugi režim obratovanja zamenjati število parov polov, ki so trenutno v obratovanju. Pomanjkljivost te rešitve je, da se cena generatorja, električnih aparatov, sistema avtomatike in zaščite v tem primeru poveča za 25 do 30 % ob hkratnem zmanjšanju stopnje izkoristka generatorja (sl. 1).
2. V primeru enake vrtilne frekvence $\left(\omega_p = \omega_t\right)$ je treba zagotoviti pogoj $\Delta\Gamma_p \cong 1,3 \cdot \Delta\Gamma_t$. To je mogoče doseči samo s predpostavko, da je premer delovnega kolesa v črpalnem režimu večji od premera delovnega kolesa v turbinskem režimu.

Za rešitev tega problema je uporabljenih več konstrukcijskih rešitev reverzibilnih hidravličnih strojev z dvema delovnima kolesoma (črpalnim in turbinskim), ki se s posebnimi napravami vključujeta v en ali drug režim obratovanja. Primeri take rešitve so reverzibilne črpalne turbine Isogyre (Švica), Hone (ČSSR) in druge. Znane so tudi konstrukcijske rešitve s samo enim vgrajenim delovnim kolesom, katerega premer se spreminja glede na vrsto obratovanja. Vse te rešitve pa so dokaj zapletene, zato pridejo v poštev samo za agregate manjših moči.

V svetovni praksi gradnje reverzibilnih agregatov velikih moči prevladuje uporaba

After analyzing equation (5') we come to the conclusion that for defining the operating characteristics of the reversible pump-turbine the following assumptions must be taken into account:

1. If it is assumed that the difference of circulation at the entry into and the exit from the working wheel in the turbine and pump working mode is identical, i.e. $\Delta\Gamma_p = \Delta\Gamma_t$, then the number of revolutions in the pump working mode must be greater than the number of revolutions in the turbine working mode ($\omega_p \cong 1,3 \cdot \omega_t$). In practice this imposes the use of two-speed generators (MG), having two rotating speeds in opposite directions. When switching from one to the other working mode it is necessary to change the number of pole pairs currently in operation. A disadvantage of this solution is that in this case the price of the generator, the electrical equipment and the automatic control system and protection is increased by 25–30 %, whereas the degree of efficiency of the generator is reduced (Fig. 1.).
2. In the case of an identical number of revolutions $\left(\omega_p = \omega_t\right)$ it is necessary to ensure the condition $\Delta\Gamma_p \cong 1,3 \cdot \Delta\Gamma_t$. This can only be reached with the assumption that the diameter of the working wheel in the pump working mode is greater than the diameter of the working wheel in the turbine working mode.

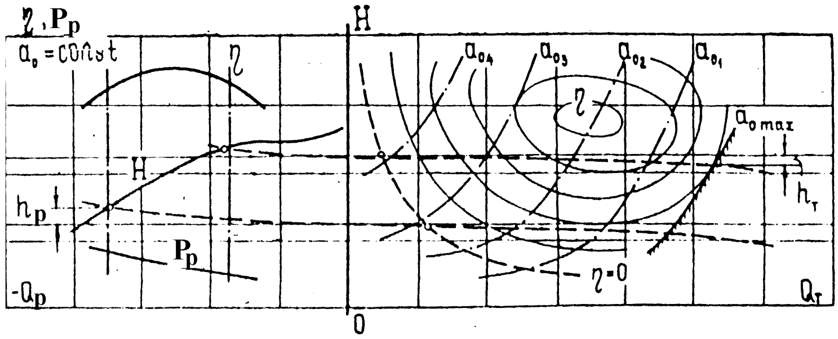
In order to solve this problem in practice several design solutions for reversible hydraulic machines with two working wheels (pump and turbine working wheel), activated in one or other operating mode by special devices, are used. Examples of such a solution are the reversible pump-turbines Isogyre (Switzerland) and Hone (Czechoslovakia). In addition, design solutions with one incorporated working wheel, whose diameter changes with respect to the working mode, are well known. However, all these solutions are rather complicated, and so they can only be considered for low-power generating units.

In most parts of the world, when building reversible power-generation units, the prevailing generatorjev z eno hitrostjo z izbiro primerne konstrukcijske rešitve delovnega kolesa hidravličnega reverzibilnega stroja z visokimi energijskimi lastnostmi v turbinskem in črpalnem režimu obratovanja (zaradi pravilne izbire profila lopatic delovnega kolesa in lopatic vodilnika).

Toda iz navedenih razlogov tudi v tem primeru ni mogoče doseči optimalnih karakteristik črpalnega im turbinskega režima. To je razvidno s slike 3, na kateri so v koordinatah Q - H predstavljene tipične delovne karakteristike črpalke - turbine, pri čemer ima pretok v črpalnem režimu negativni predznak. Posebno konstrukcijo je razvil prof. Krivčenko [6]. Ta ima zaradi učinka delno pomičnih lopatic delovnega kolesa skoraj optimalno vrtljivo rešetko delovnih lopatic v turbinskem in črpalnem režimu.

concept is the use of one-speed generators with the selection of a compromise design solution of the working wheel of the hydraulic reversible machine with high-power properties in the turbine and pump working mode (as a consequence of the correct selection of the contour of the working wheel blades and flow device blades).

However, for the above reasons it is also not possible in this case to achieve the optimum characteristics of the pump and turbine working mode. This can be seen in Figure 3, showing in coordinates Q – H the typical working characteristics of the pump-turbine where the flow in the pump working mode has a negative sign. A special structure of RPT was developed by Prof. Krivchenko, who has a nearly optimal rotation grating of the working blade in the turbine and pump modes, on the basis of the effect at partly moveable mobile blades of the working wheel (1).



Sl. 3. *Tipične delovne karakteristike francisove RPT v obeh režimih obratovanja*

Fig. 3. *Typical operating characteristics of the Francis reversible pump-turbine in both working modes*

Na sliki 3 je karakteristika črpalnega režima prikazana za primer nspremenljivega odprtja vodilnika (a_0), kakor je to na RHE običajno. Sprememba a_0 malo vpliva na vrednost pretoka, moč in stopnje izkoristka, odstopanje od optimalne vrednosti a_0 pa povzroča pojav precejšnjih utripov tlaka v pretočnem prostoru turbine. Za turbinski režim so podane krivulje nespremenljivih odprtij vodilnika a_0 in stopnje izkoristka do $\eta = 0$, to je do režima pobega turbine. Povečanje višine z namenom prehajanja delovnega področja na področje optimalnega izkoristka turbine pomeni hkrati prehod na področje zelo majhnih pretokov in nizkih stopenj izkoristka v primeru črpalnega režima (sl. 3).

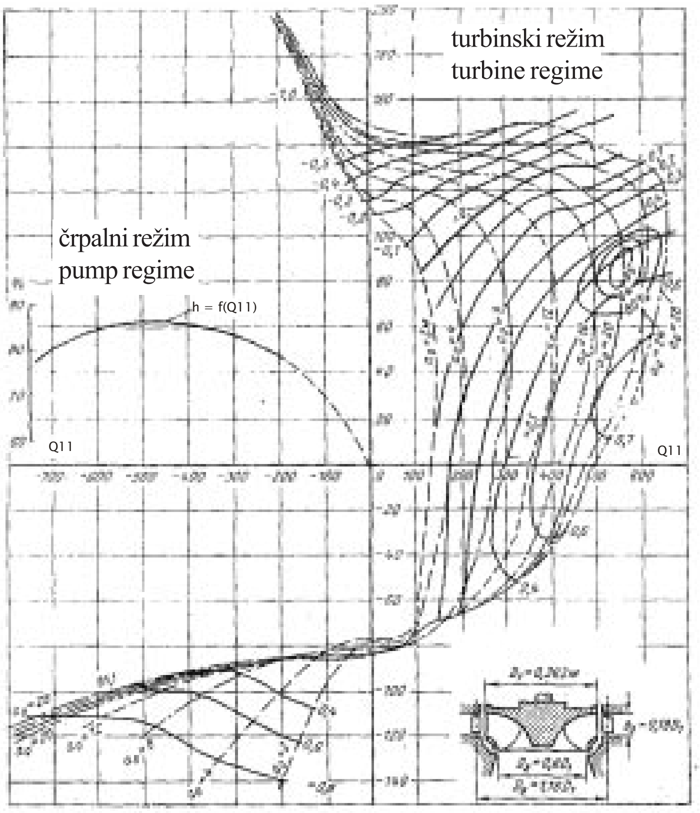
Nomenklatura reverzibilnih črpalnih turbin je pomanjkljiva, obstajajo pa glavne univerzalne karakteristike za zelo omejeno število tipov. Toda, glede na to, da se dandanes projektira vrsta RHE za zelo širok pas višin od 100 do 1200 metrov, se pokaže potreba po določanju osnovnih parametrov črpalnih turbin, v odvisnosti od teh parametrov pa tudi potreba po določanju samih RHE.

Na današnji stopnji raziskav lahko izbiro reverzibilnih črpalnih turbin opravljamo na temelju

In addition, Figure 3 shows the characteristic pump working mode for the case of a constant cross section of the flow device (a_0), as is usual for reversible hydroelectric power plants, since the change $a_{0\ only}$ slightly influences the value of the flow, the power and the degree of efficiency, and the deviation from the optimum value a_0 results in considerable fluctuations of the pressure in the turbine flow space. For the turbine working mode the isoclines of constant cross section of the flow device a_0 and of the degree of efficiency up to $\eta = 0$ i.e. up to the turbine over speed are given. The increase of the head, aimed at the working area passing into the range of optimum efficiency of the turbine, simultaneously implies passing into the range of very small flows and low degrees of efficiency in the case of the pump working mode (Fig. 3).

The parts lists of reversible pump-turbines are not yet available, whereas the principal universal characteristics for a very limited number of types are available. However, considering the fact that nowadays the type of reversible hydroelectric power plants for a very wide range of heads from 100 to 1200 m is designed, the need for determining the basic parameters of the pump-turbines and, depending on those parameters, the need for determining the reversible hydroelectric power plant itself are imposed.

At today's level of research the selection of reversible pump-turbines can be made on the basis of



Sl. 4. *Glavna splošna karakteristika RPT*
Fig. 4. *Main universal characteristic of RPT (1)*

sistematizacije in analize statističnih podatkov sedanjih RHE, ki so že v obratovanju ali pa so v fazi projektiranja oziroma gradnje.

Na inštitutu MISI v Moskvi, na Katedri za izkoriščanje vodne moči, je bila pod vodstvom prof. Aršenevskega in ob sodelovanju avtorja tega prispevka opravljena analiza več ko 40 reverzibilnih agregatov različnih zahodnih izdelovalcev. Ob tej priložnosti je bila ugotovljena naslednja odvisnost specifične vrtilne frekvence francisovih reverzibilnih črpalnih turbin v turbinskem režimu:

the systematization and analysis of statistical data from the reversible hydroelectric power plants that are already in operation, being designed, or being built.

At the MISI institute in Moscow, in the Department of Utilization of Water Power, an analysis of more than 40 reversible power generation units from different Western manufactures was made under the leadership of Professor Arshenevski, in cooperation with the author of this paper. On that occasion the following dependence of the specific number of revolutions of the Francis reversible pump-turbines in the turbine working mode was found:

$$n_{s_{RPT}} = \frac{n\cdot\sqrt{1,36\cdot P}}{H_{t\max}\sqrt[4]{H_{t\max}}} = \frac{1212}{H_{t\max}^{0.4}} \qquad (6),$$

pri čemer so:
n - vrtilna frekvenca, min^{-1}
P - največja moč, kW
H_t - največji turbinski padec RHE, m.

where
n is the rated number of revolutions (min^{-1})
P is the maximum power (kW)
H_t is the maximum turbine fall on the reversible hydroelectric power plant (m)

Z analizo podatkov [1] se dobi naslednja enačba:

If these facts are processed (1) the following ratio is obtained:

$$n_{s_{RPT}} = \frac{1000 \div 1300}{H_{t\max}^{0,4}} \qquad (6').$$

Analiza parametrov reverzibilnih hidravličnih strojev nekaterih RHE v nekdanji ZSSR in v ZDA je pokazala, da obstaja tendenca povečanja specifične vrtilne frekvence, zato je bolj

However, an analysis of the parameters of reversible hydraulic machines on some reversible hydroelectric power plants in the former USSR and the USA showed that there is a tendency towards an primeren naslednji izraz:

increase in the specific number of revolutions, therefore the following relation is more appropriate:

$$n_{s_{RPT}} = \frac{1200 \div 1500}{H_{t\max}^{0.4}} \qquad (6").$$

Zanimivo je primerjati specifično vrtilno frekvenco običajnih turbin $\left(n_{st}\right)$ in reverzibilnih črpalnih turbin $\left(n_{s_{RPT}}\right)$. Za klasične HE s francisovimi turbinami lahko ta parameter izrazimo kot funkcijo imenskega padca [3]:

It is interesting to make a comparison of the specific number of revolutions of a conventional turbine $\left(n_{st}\right)$ and that of reversible pump-turbines $\left(n_{s_{RPT}}\right)$. For conventional hydroelectric power plants with Francis turbines this parameter can be expressed as a function of the rated fall:

$$n_{st} = \frac{2300}{\sqrt{H_{opt}}} \qquad (7).$$

Za klasične HE velja razmerje:

On the other hand, the following ratio applies for conventional hydroelectric power plants:

$$\frac{H_{opt}}{H_{\max}} = 0,78 - 0,95$$

Če vzamemo srednjo vrednost $H_{opt}/H_{max} = 0,88$, dobi enačba (7) obliko:

If the mean value $H_{opt}/H_{max} = 0.88$ is adopted, equation (7) assumes the following form:

$$n_{st} = \frac{2070}{\sqrt{H_{\max}}} \qquad (8).$$

Razmerje med specifično vrtilno frekvenco reverzibilnih in klasičnih francisovih turbin tako izračunamo z enačbo:

The ratio of the specific number of revolutions of the reversible and conventional Francis turbines gives the following relation:

$$\frac{n_{s_{RPT}}}{n_{st}} = 0,58 H_{t\max}^{0.1} \qquad (9).$$

Na podlagi H_{tmax} in P lahko po enačbi (6) določimo vrtilno frekvenco turbine:

As H_{tmax}, and P are known, the number of turbine revolutions can be determined according to equation (6):

$$n = 1040 \frac{H_{t\max}^{0.5}}{\sqrt{P}} \qquad (10).$$

Dobljeno vrednost zaokrožimo na najbližjo sinhrono vrtilno frekvenco.

Na sliki 5 so podani rezultati analize odvisnosti glavnih izmer delovnih koles nekaterih že izvedenih reverzibilnih črpalnih turbin (RPT) pri H_{tmax} od specifične vrtilne frekvence $n_{s_{RPT}}$.

Odvisnost enotske vrtilne frekvence $n_{11} = f\left(n_{s_{RPT}}\right)$ lahko na temelju izvedene analize priporočimo v obliki:

The value obtained is approximated to the nearest synchronous number of revolutions.

Figure 5 gives the results of the analysis of dependence of the main working wheel dimensions of some reversible pump-turbines already in operation, with H_{tmax} on the specific number of revolutions $n_{s_{RPT}}$.

The dependence $n_{11} = f\left(n_{s_{RPT}}\right)$ can be recommended in the following form on the basis of the analysis carried out:

$$n_{11} = 82 + 0,05 \cdot n_{s_{RPT}} \qquad (11).$$

V tem primeru bo premer delovnega kolesa:

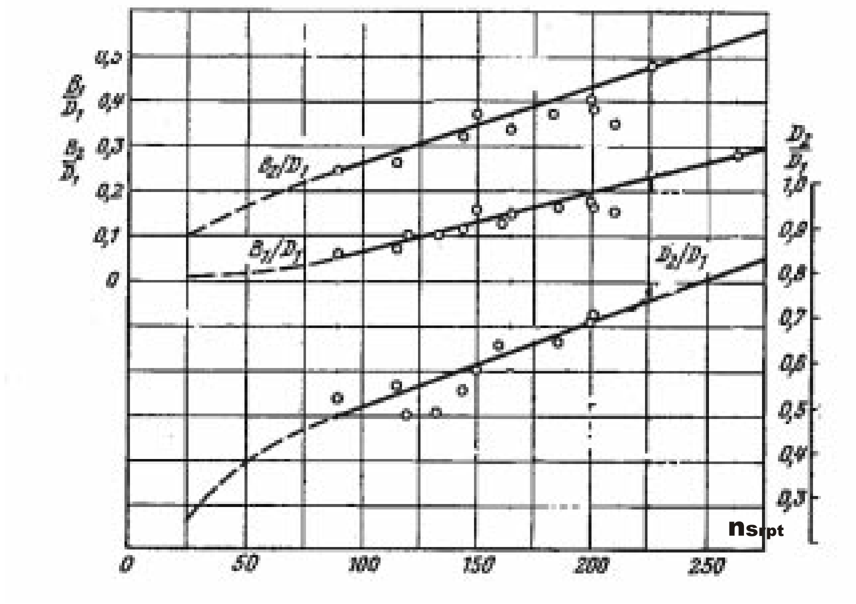
In this case the working wheel diameter will be:

$$D_1 = \frac{n_{11}\sqrt{H_{t\max}}}{n} = \frac{\left(82 + 0,05 \cdot n_{s_{RPT}}\right)\sqrt{P \cdot H_{t\max}}}{1040 \cdot H_{t\max}^{0.85}} \qquad (12).$$

Če dobljeno vrednost D_1 zaokrožimo na višjo vrednost do 0,1 m, moramo preveriti, ali smo dobili največjo višino v črpalnem režimu. Iz teorije črpalk je poznano razmerje [5]:

If the obtained value D_1 is approximated to a higher value of up to 0.1 m it is necessary to check whether the maximum head in the pump working mode has been obtained. The following ratio is known from the theory of pumps:

$$H_{p\max} = K\frac{u_1^2}{2g} = \frac{K}{2g}\left(\frac{\pi \cdot D_1 \cdot n}{60}\right)^2 \qquad (13),$$



Sl. 5. *Odvisnost izmer delovnega kolesa RPT od n_s [2]*
Fig. 5. *Dependence of RPT working wheel dimensions on n_s [2]*

pri čemer je K=0,8 - 0,9, iz tega izhaja:

where K=0.8–0.9, therefore:

$$H_{p\max} = \left(0{,}000111 - 0{,}000126\right) \cdot n^2 \cdot D_1^2 \qquad (14).$$

Tako dobimo premer $D_{1,}$ ki ne sme biti manjši od:

Thus the diameter D_1 is obtained, which must not be smaller than:

$$D_1 = \frac{\left(89 - 95\right)\sqrt{H_{p\max}}}{n} \qquad (15).$$

Obdelava statističnih podatkov že izdelanih reverzibilnih hidravličnih strojev je pripeljala do izkustvene odvisnosti enotnega pretoka Q_{11} (l/s) pri obratovanju v turbinskem režimu pri H_{tmax} v obliki [2]:

The processing of statistical data on reversible hydraulic machines that are already built has led to the experimental dependence of the unit flow Q_{11} (l/s) in the case of maximum operation in the turbine working mode in the following form [2]:

$$Q_{11} = \left(0{,}008 - 0{,}012\right) n_{s_{RPT}}^2 \qquad (16).$$

Po drugi strani pa lahko vrednost Q_{11} določimo po enačbi za specifično vrtilno frekvenco [2]:

On the other hand, the value Q_{11} can be determined according to the equation for the specific number of revolutions:

$$n_s = 3{,}65 \cdot n_{11} \cdot \sqrt{Q_{11} \cdot \eta} \qquad (17),$$

pri čemer ima Q_{11} mero m^3/s. Če vzamemo vrednost $\eta = 0{,}9$, dobimo povezavo:

where Q_{11} has the dimension m^3/s. If the value $\eta = 0.9$ is assumed, the following relation is obtained:

$$Q_{11} = \left(0{,}029 - 0{,}032\right) n_{s_{RPT}}^{1.8} \qquad (18).$$

Glede na to je premer delovnega kolesa upoštevajoč (11) in (16):

So the diameter of the working wheel considering (16) and (11) is:

$$D_1 = \frac{1{,}166 \cdot n_{11} \cdot \sqrt{P}}{n_{s_{RPT}} \cdot H_{t\max}^{3/4}} \qquad (19).$$

Premer delovnega kolesa se lahko izračuna tudi iz enačbe za moč in enotski pretok Q_{11} z upoštevanjem enačb (16) in (18):

On the otherr hand, from the equation for the power and unit flow Q_{11} and by taking into account the relation (16) and (18) it is also possible to calculate the diameter of the working wheel:

$$D_1 = \sqrt{\frac{P}{9{,}81 \cdot H\sqrt{H} \cdot Q_{11} \cdot \eta}} \qquad (20).$$

Bodimo pozorni na koeficiente v števcu enačbe (15). To so vrednosti n_{11} v črpalnem režimu za H_{pmax}, kjer je $n_{11t} > n_{11p}$, saj je $H_{t\max} < H_{p\max}$. Ob znani vrednosti D_1 lahko izhodni premer delovnega kolesa (v turbinskem režimu) D_2, višino dovodnega aparata B_1 in celotno višino delovnega kolesa B_2 (sl. 2) določimo po diagramu na sliki 5.

3 DOLOČITEV SESALNE VIŠINE RPT

Eden izmed najpomembnejših parametrov, ki odločujoče vpliva tudi na zasnovo RHE, je lega delovnega kolesa reverzibilnega stroja glede na najmanjšo koto vode v spodnji akumulaciji oziroma sesalna višina reverzibilnih hidravličnih strojev. Za RHE je značilno, da je treba sesalno višino določiti izhajajoč iz pogojev obratovanja v črpalnem režimu. Koeficient kavitacije je v tem režimu večji kakor v turbinskem režimu. Tako je na primer za RPT Kijevske RHE kavitacijski koeficient v optimalnem turbinskem obratovanju $\sigma_T = 0{,}12$ v črpalnem pa $\sigma_P = 0{,}33$. To je razlog, da je črpalka v primeru trojnih agregatov vedno vgrajena pod turbino.

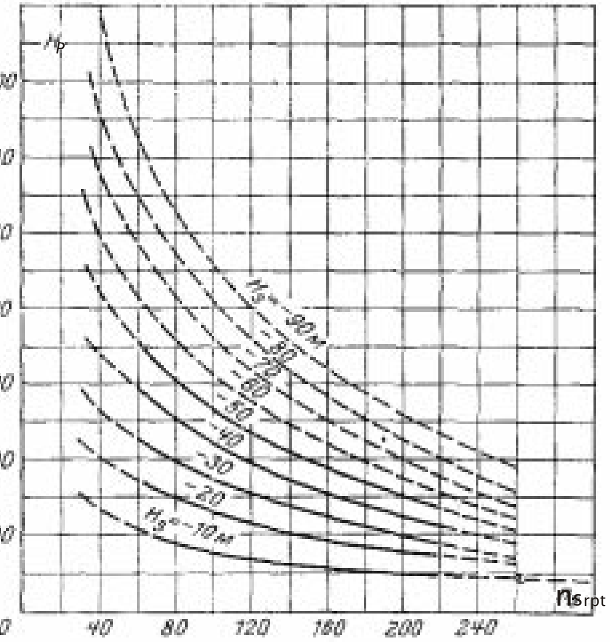
Po drugi strani pa je vgradnja delovnega kolesa na globinah 20 do 50 m ali več odvisna od zasnove podzemeljske ali polpodzemeljske strojnice RHE, kar ima za posledico povečanje

Let us look at the coefficients in the numerator of equation (15). These are the values n_{11} in the pump working mode for H_{pmax}, where $n_{11t} > n_{11p}$, because of $H_{t\max} < H_{p\max}$. Since we know the value D_1 the outlet diameter of the working wheel D_2 (with respect to the turbine working mode), the head of the flow device B_1 and the total head of the working wheel B_2 (Fig. 2) can be determined according to the graphics in Figure 5.

3 DETERMINATION OF THE INTAKE ALTITUDE RPT

One of the most important parameters that also decisively influences the concept of reversible hydroelectric power plants is the altitude position of the working wheel of the reversible machine in relation to the minimum level of the downstream reservoir and/or the suction height of the reversible hydraulic machines. It is characteristic of reversible hydroelectric powers plants that it is necessary to determine the suction height starting from the operating condition in the pump working mode, taking into account that the cavitations coefficient is greater in this working mode than in the turbine working mode. In this way for the RPT of the Kiev RHEPP the coefficient of cavitations in the optimum turbine regime $\sigma_T = 0.12$ in the turbine working mode and $\sigma_P = 0.33$ in the pump working mode.

On the other hand, the requirement for the installation of the working wheel at 20–50-m depths or more, conditions the concept of an underground or semi-underground powerhouse of the reversible hydroelectric



Sl. 6. *Vrednosti H_s v odvisnosti od H_p in n_{srpt} [3]*
Fig. 6. *Values of H_s as a function of H_p and n_{srpt} [3]*

dolžine odvodnih sistemov. Ti sistemi so zaradi precejšnjih nihanj nivoja vode v spodnji akumulaciji pogosto izvedeni pod tlakom [4].

Če analiziramo podatke že zgrajenih RHE in RHE v fazi projektiranja, opazimo, da sesalna višina v mnogočem prekaša vrednosti, ki jih srečujemo pri običajnih turbinah z enako vrtilno frekvenco. V preglednici 1 so prikazane sesalne višine nekaterih že izvedenih in karakterističnih RHE [3].

power plant, which results in the increase of the length of outflow systems which are frequently designed pressurized due to considerable fluctuation of the water level in the downstream reservoir [4].

If the data on the reversible hydroelectric power plants already constructed or under construction are analyzed it can be seen that the suction height, in many aspects, exceeds the values occurring on the conventional turbines with an identical number of specific revolutions. Table 1 shows the suction heights of some characteristic reversible hydroelectric power plants already constructed [3].

Preglednica 1
Table 1

RHE Reversible hydroelectric power plant	Država Country	Sesalna višina Suction height (m)	Črpalna višina Head (m)	Pretok v črpalni smeri Flow rate at pumping (m^3/s)	Vrtilna frekvneca Number of revolutions (min^{-1})
Vianden	Luksemburg Luxemburg	- 26,0	300	71,1	333,30
Krauchan	Velika Britanija Great Britain	- 45,2	358	28,6	500,00
Numapara	Japonska Japan	- 55,0	528	50,0	375,00
Katrua-Pon.	Belgija Belgium	- 20,0	259	46,0	300,00

V prvem približku lahko sesalno višino RPT določimo po diagramu na sliki 6.

Analitična enačba za izračun sesalne višine je:

The suction height RPT can be determined according to figure 6 as a first approximation.

The analytical expression for the calculation of the intake altitude is:

$$H_s = 10 - \frac{\dot{\nabla}}{900} - h_{us} - k_\sigma \cdot H_p \cdot \sigma_p \qquad (21),$$

pri čemer so:

$\dot{\nabla}$ - absolutna kota vgradnje delovnega kolesa,
h_{us} - hidravlične izgube v odvodnem sistemu pod pritiskom,
σ_p - koeficient kavitacije v črpalnem režimu,
H_p - črpalna višina RHE,
$k\sigma$ - koeficient rezerve.

Glede na to, da obstaja zelo majhno število modelnih univerzalnih karakteristik reverzibilnih hidravličnih strojev, ki vsebujejo podatke o koeficientu kavitacije, koeficienta kavitacije ni mogoče definirati na način, kakor je to običajno pri običajnih turbinah. Zato ostaja možnost uporabe empiričnih enačb. Iz teorije črpalk je znana enačba Rudneva za kritični koeficient kavitacije črpalk v optimalnem režimu obratovanja, in sicer v odvisnosti od vrtilne frekvence [6]:

where:

$\dot{\nabla}$ is the absolute elevation of the installation of the working wheel
h_{us} is the hydraulic loss in the pressurized outflow system
σ_p is the cavitations coefficient in the pump working mode
H_p is the head of the reversible hydroelectric power plant
$k\sigma$ is the coefficient of reserve

As there are only a small number of universal characteristics for the model of reversible hydraulic machines and, especially with information about the coefficient of cavitations, the cavitations coefficient cannot be defined in the usual way for conventional turbines. Therefore, the possibility for using on experimental equation remains. Rudnev's equation for the critical coefficient of the pump cavitations in the optimum working mode depending on the specific number of revolutions is known from the theory of pumps [6]:

$$\sigma_p = n^{4/3} / \mathrm{A}\ ;\ \mathrm{A} = 4700 \div 6300 \qquad (22),$$

pri čemer je koeficient A odvisen od konstrukcijske izvedbe delovnega kolesa in n_{sp}, A=4700 pri n_s=110; A=6300 pri n_s=180 [8]. Nekaj večjo vrednost

where the coefficient A depends on the structural design of the working wheel and n_{sp}, A=4700 at n_s=110; A=6300 at n_s=180 [8]. A somewhat higher koeficienta kavitacije dobimo, če uporabimo enačbo:

value of the cavitations coefficient is obtained if the following equation is used:

$$\sigma_p = n^{4/3} / 4000 \qquad (23).$$

Koeficient rezerve $k\sigma$ definiramo analogno kakor pri določanju sesalne višine turbine. Predvsem moramo upoštevati možne napake pri povzemanju modelnih kavitacijskih karakteristik, prav tako pa tudi odstopanja, ki so posledica dejstva, da ne moremo zagotoviti popolne geometrijske in dinamične podobnosti modela in dejanskega stroja. V primeru kaplanovih turbin običajno jemljemo koeficient $k\sigma$= 1,1; pri francisovih turbinah za padce do 250 m je $k\sigma$ = 1,15 do 1,2, za padce prek 250 m pa se ta koeficient ne upošteva, to je $k\sigma$= 1,0.

Ker za reverzibilne hidravlične stroje do sedaj še ni na voljo dovolj podatkov za njihovo nomenklaturo, se vrednost tega koeficienta jemlje analogno nomenklaturi običajnih hidravličnih turbin velikih moči: $k\sigma$ = 1,1 do 1,15 [2].

Japonski strokovnjaki priporočajo enačbo (23) v obliki [3]:

The reserve coefficient kσ is defined analogously to the determination of the turbine suction height. In particular, it is necessary to take into consideration the mistakes in obtaining the model cavitations characteristic as well as the deviation resulting from the fact that it is not possible to ensure complete geometrical and dynamic equality of the model and the actual machine. For the case of Kaplans turbines the coefficient $k\sigma$= 1.1 is usually assumed; in the case of Francis turbines for 250 m falls the coefficient $k\sigma$= 1.15–1.2 , whereas for falls over 250 m that coefficient is not taken into account, i.e. $k\sigma$= 1.0.

For the time being, sufficient data are not available for parts lists of the reversible hydraulic machines, the value of that coefficient is taken in the same way as the parts lists of conventional hydraulic turbines of high powers: $k\sigma$= 1.1–1.15 [2].

Japanese experts recommend equation (23) in the following form [3]:

$$H_s \le 10 - \frac{\left(n\sqrt{Q_p}\right)^{4/3}}{1000} = 10 - \frac{n_s^{4/3} \cdot Hp}{5620} \qquad (24),$$

kjer velja: $n_s = 3,65 \cdot \frac{n\sqrt{Q}}{H^{3/4}}$ in $\sigma_p = \frac{n_{sp}^{4/3}}{5620}$, kjer je Q_p srednji pretok v črpalnem režimu.

V območju črpalnih višin do 100 m se vrednosti dejanskih sesalnih višin večine RHE dobro ujemajo z vrednostmi, po enačbi (24). S povečanjem črpalne višine se vrednost H_S po enačbi (24) zmanjša. Zato je treba enačbo (24) popraviti takole [2]:

considering relation: $n_s = 3,65 \cdot \frac{n\sqrt{Q}}{H^{3/4}}$, that is $\sigma_p = \frac{n_{sp}^{4/3}}{5620}$, where Q_p is the mean flow rate in the pump working mode.

In the range of falls of up to 100 m the value of the actual suction height on most reversible hydroelectric power plants coincides well with the value obtained from equation (24). With an increase of the water head, however, the value H_s according to equation (24) decreases. Therefore, a correction must be entered in the water head and the following equation is obtained [2]:

$$H_s \le 10 - \frac{n_s^{4/3} \cdot H_p}{5620 - 3,94 \cdot H_{p\max}} \qquad (25).$$

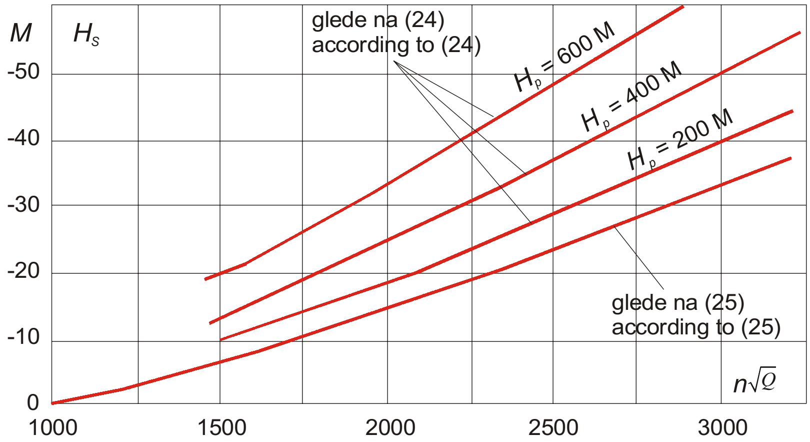


Fig. 7. *Primerjava teoretičnih in praktičnih vrednosti Hs [3]*
Fig. 7. *Comparison between Hs from theoretical and practical values [3]*

S primerjavo vrednosti H_S, dobljenih po enačbah (24) in (25), z dejanskimi vrednostmi na že izdelanih RHE pridemo do ugotovitve, da daje enačba (25) dobre rezultate za črpalne višine od 100 do 500 m. Iz te primerjave je tudi očitno, da se vrednost H_S z večanjem črpalne višine močno poveča.

4 SKLEP

Reverzibilna hidroelektrarna (RHE) je vsekakor učinkovit vir vršne energije. Ta tip elektrarne zato že dalj časa vzbuja povečano zanimanje pri mnogih projektantskih organizacijah, raziskovalcih in konstrukterjih.

V prispevku je podana analiza nekaterih vprašanj, ki se pojavijo pri projektiranju tovrstnega tipa hidroelektrarne. Podane so namreč osnovne teorije delovnega procesa reverzibilnih črpalnih turbin. Razen tega je podana tudi analiza osnovnih rešitev nekaterih že izvedenih RPT francisovega tipa.

V nadaljevanju so obravnavana razmerja med parametri, ki se uporabljajo pri običajnih črpalkah in turbinah ter na podlagi le-teh opravljena analiza režimov, v katerih lahko obratuje tudi RPT.

Dognana je povezava med osnovnimi parametri RTP francisovega tipa in vrtilno frekvenco, opravljena pa je tudi analiza sesalne višine v odvisnosti od specifične vrtilne frekvence.

By comparing the H_s values obtained according to equations (24) and (25) with the actual values on the reversible hydroelectric power plants already constructed we find that equation (25) gives good results for the heads from 100 to 500 m, and is also recommendable for that range of falls. The comparison shows that the value H_s strongly increases with an increase of the head and becomes infinite.

4 CONCLUSION

A reversible hydroelectric power plant (RHEPP) is surely the most real and the most efficient source of uppermost energy, and that is why many project departments, researchers and designers have, for a long time, shown great interest in this type of power plant.

In this context, an analysis of some questions concerning the planning of hydro-electric power plants of such type are given in this paper. Namely, basic theories of the working process of reversible pump turbines are given and conceptual solutions of some performed RTP of the Francis type are analyzed.

Then, relations between parameters are given, which are applied to classical pumps and turbines, and concerning that the regimes in which RPT can be found are analyzed.

A connection between basic parameters of RPT of the Francis type and a specific number of revolutions is established. An analysis of the intake altitude of sucking as a function of n_s is made.

5 OZNAKE
5 SYMBOLS

hidravlične izgube v črpalnem režimu	h_p	hydraulic losses in pump working mode
hidravlične izgube v turbinskem režimu	h_t	hydraulic losses in turbine working mode
hidravlične izgube v odvodnem sistemu pod pritiskom	h_{us}	hydraulic losses in pressurized outflow system
padec reverzibilne hidroelektrarne v črpalnem režimu	H_p	head of the reversible hydraulic power plant in pump working mode
sesalna višina	H_s	suction height
hidrostatični padec (višina)	H_{st}	head
padec reverzibilne hidroelektrarne v turbinskem režimu	H_t	head of reversible HEPP in turbine working mode
koeficient rezerve	$k\sigma$	coefficient of reserve
število vrtljajev	n	number of revolutions
specifična vrtilna frekvenca	$n_{s_{RPT}}$	specific rotating speed
največja moč	P	maximum power
srednji pretok v črpalnem režimu	Q_p	average flow in pump working mode
koeficient kavitacije v črpalnem režimu	σ_p	cavitation coefficient in pump working mode
kotna hitrost	ω	angular speed
absolutna kota vgradnje delovnega kolesa	$\dot{\nabla}$	elevation of installation of working wheel

6 LITERATURA
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Analiza shranjevanja toplote v vodonosnikih - možnost uporabe v Sloveniji

The Analysis of Thermal Energy Storage in Aquifers - the Possibility of Application in Slovenia

Uroš Stritih - Sašo Studen - Miha Brenčič – Andrej Lapanje

Že nekaj desetletij se pojavljajo težnje po učinkovitejši rabi energije. K temu so pripeljale ugotovitve o razpoložljivih količinah fosilnih goriv in pa naraščajoča ekološka osveščenost ljudi. Zanemarljive pri tem niso bile niti nenehno rastoče cene goriv. Ker se v prihodnosti pričakuje še povečana raba energije, se raziskujejo možnosti za povečano izrabo obnovljivih virov in kakovostnejše izrabe energije. Kakovost rabe se večinoma povečuje s shranjevanjem energije (predvsem termalne) v različnih hranilnikih. To velja predvsem za odpadno toploto, ki jo pridobimo pri določenih tehnoloških postopkih in jo večinoma zavržemo. To toploto je mogoče koristno izkoristiti v ogrevalnih sistemih z nizkimi temperaturami. Enako velja za toploto, odvzeto s kondenzatorjev klimatizacijskih naprav.

Ena od rešitev je shranjevanje te energije v sezonskih hranilnikih, med katere spada tudi vodonosnik. Ker so ti precej obsežni, je vanje mogoče shraniti velike količine energije.

Namen prispevka je raziskati pregled metod za analiziranje shranjevanja toplote v vodonosnikih, predstavitev teh hranilnikov v svetu z osnovnim matematičnim popisom dogajanja v vodonosniku ter možnost za uporabo v Sloveniji.

(Ključne besede: hranilniki toplote, vodonosniki, prenos toplote, prenos snovi)

Tendencies towards rational energy use have been appearing for the last decades due to the fact of limited quantities of fossil fuels and increased ecological awareness. Also the rising prices of all fuels should be taken into account. Since energy consumption will increase in the future, the possibility of using renewable energy resources and rational energy use are investigated. The quality of energy exploitation can be increased by storing thermal energy in different types of storage. This is especially important for waste heat from industrial processes, which is usually thrown away. This heat can be efficiently used in low-temperature heating systems. The same holds true for heat from condensing units of air-conditioning systems.

One of the solutions is thermal energy storage in seasonal storage, where aquifers are one of the possibilities. Since they are very large, the amount of heat that can be stored is very high.

The paper gives a review of thermal energy storage methods in aquifers, describes such storage in the world with a basic mathematical description of the processes in aquifers, and presents the possibilities of use in Slovenia.

(Keywords: thermal storage, aquifers, heat transfer, mass transfer)

1 SPLOŠNO O HRANILNIKIH TOPLOTE

Namen hranilnikov je shranjevanje energije takrat, ko je ne potrebujemo, hkrati pa morajo omogočati odvzem energije, ko jo potrebujemo [1].

Tak primer je toplotna energija, ki jo pridobivamo poleti. Proizvodnja je v tem letnem času lahko precej večja od porabe. V tem primeru toploto shranimo in jo v ogrevalni sezoni ponovno odvzamemo. Enako velja tudi za toploto, ki jo odvajamo s kondenzatorjev hladilnih naprav. Brez prevelikega

1 GENERAL ABOUT THERMAL STORAGE

Thermal storage is used for storing energy at the time when it is available and must be able to release energy when it is needed [1].

An example of this is energy that is stored during the summer. The production of heat at this time is much larger than its utilization. In this case energy is stored and extracted during the heating season. The same principle is used with heat from condensers of cooling devices. Without additional truda in vlaganja energije lahko v zimskih mesecih shranjujemo hlad. Proizvodnja hladu v poletnih mesecih je namreč izredno draga. Tako hranilniki termalne energije omogočajo izboljšanje izkoristka sistema, s tem pa precejšnje zmanjšanje stroškov ogrevanja in hlajenja.

Dolgotrajni hranilniki toplote so namenjeni sezonskemu shranjevanju termalne energije. Ločimo zemeljske, vodne in kombinirane dolgotrajne hranilnike toplote. Pri vračanju toplote si pri nižjih temperaturah pomagamo z uporabo toplotnih črpalk.

2 VODONOSNIKI

Podzemno vodo opredeljujemo kot vodo, ki se pojavlja pod površjem, ne glede na to, ali imamo opraviti z vodo v tleh, naplavinah ali kamninah. Pojav podzemne vode v odvisnosti od geoloških razmer opredelimo s hidrogeološko analizo in modelom. Tako kakor pri vsakem modelu tudi tukaj izhajamo iz nekaterih zasnov, ki pomagajo natančneje opisati in opredeliti dejanske razmere, ki vladajo v naravi. Tako je v središču zanimanja za podzemno vodo in njeno izkoriščanje model vodonosnika in njegov shematski profil.

Vodonosnik razdelimo na dva dela, ki ju med seboj ločuje gladina podzemne vode. Zgornji del vodonosnika pomeni nezasičeno območje. V tem predelu voda, ki prodira skozi tla, teče navpično navzdol skozi z vodo neprežete pore proti gladini podzemne vode. Pod slednjo leži zasičeno območje, v katerem so vse pore prežete z vodo. V tem predelu je tok vode pod vplivom gradienta in ga praviloma poenostavimo kot vodoravni. Zasičeno območje v spodnjem delu omejuje slabo prepustna podlaga vodonosnika [2].

Gladina podzemne vode lahko prosto niha, v kakšni meri niha, je odvisno od intenzivnosti napajanja in od hidrogeoloških lastnosti vodonosnika. Takšen tip vodonosnika imenujemo odprt vodonosnik. Poleg tega poznamo še zaprt tip vodonosnika, v katerem gladina podzemne vode ne niha prosto, ker je zgornji del vodonosnika neprepustna plast. V takšnem vodonosniku se spreminja le hidrostatični tlak. Če takšen vodonosnik prevrtamo z vrtino, se voda praviloma prelije na površino in opraviti imamo z arteškim vodnjakom. Seveda med obema tipoma vodonosnika obstajajo tudi prehodi, tako poznamo polodprt in polzaprt vodonosnik [2].

V hidrogeologiji označujemo kot vodonosnike praviloma tiste kamnine ali naplavine, ki so dovolj prepustni, da je iz njih mogoče izkoriščati podzemno vodo pod gospodarnimi pogoji. Dosedanje izkušnje kažejo, da se v Sloveniji podzemno vodo v večjih količinah izkorišča v rudninah, kjer so koeficienti hidravlične prevodnosti večji od 10^{-6} m/s, v zadnjem času pa tudi pri hidravličnih prevodnostih, večjih od 10^{-7} m/s. Takšna definicija je seveda nekoliko nenatančna in odvisna od trenutnih potreb po oskrbi z

energy, cold can be stored during winter, while the production of cold in the summer time is very expensive. In this way thermal energy storage can reduce costs for heating and cooling.

Long-term thermal storage is used for seasonal thermal storage, enabling the storage of waste heat and its use in the cold season. There are earth, water and combined long-term thermal storage. Heat pumps can be used at lower heat temperatures.

2 AQUIFERS

Groundwater is defined as water stored beneath the surface, either in the soil, sediments or rocks. The appearance of groundwater in relation to geological conditions is defined on the basis of hydrogeological analyisis and model. As in every model, some conceptual schemes are used as the starting point to enable a more precise description and determination of the actual conditions occurring in nature. In this way the aquifer model and its schematic profile become the centre of interest for groundwater and its exploitation.

The aquifer is divided into two parts, separated by groundwater table. The upper part of the aquifer is the unsaturated zone. In this zone, water that is infiltrated through the soil penetrates vertically through unsaturated pores down towards the water table. Beneath the water table lies the saturated zone where all pores are filled with water. In this zone, water flow is influenced by the gradient and is as a rule simply defined as horizontal. The lower part of the saturated zone is confined by a low-permeable aquifer bedrock [2].

Aquifers where the groundwater level can change freely, depending on the intensity of recharge and on the hydrogeological properties of the aquifer, are called unconfined aquifers. On the other hand, there is the confined type of aquifer, where the groundwater table cannot change freely, because the upper part of the aquifer is overlain by an impermeable layer. In such an aquifer, only the hydrostatic pressure changes. If such aquifer is penetrated by a well, the water flows to the surface, and this is an artesian aquifer. Of course there are also intermediate stages between the two aquifer types, known as semi-unconfined and semi-confined aquifers [2].

Hydrogeology defines as aquifers generally those rocks or sediments which are permeable enough to enable an economical exploitation of groundwater. Experience so far shows that in Slovenia groundwater is exploited in larger quantities in cases where permeability exceeds 10^{-6} m/s, and recently also when permeability is greater than 10^{-7} m/s. Such definition is of course somewhat inaccurate and depends on momentary demands of water supply or other groundwater uses. For vodo ali kakšni drugi uporabi podzemne vode. Glede na hidrogeološke lastnosti rudnine se je zato v praksi uveljavila tudi razdelitev, ki je odvisna od koeficienta hidravlične prevodnosti *K*. Kamnine ali naplavine, katerih koeficient hidravlične prevodnosti *K* je večji od 10^{-6} m/s uvrščamo v vodonosnike. Rudnine, v katerih še zasledimo podzemno vodo, imenujemo akviklude, zanje so značilne hidravlične prevodnosti med 10^{-6} in 10^{-12} m/s. Za kamnine ali naplavine, ki jih lahko s praktičnega vidika štejemo za neprepustne pa uporabljamo izraz akvifob, njihov koeficient hidravlične prevodnosti *K* je manjši od 10^{-12} m/s.

V kamninah in naplavinah je voda v porah povezanih med seboj, ki lahko glede na geometrijsko obliko zavzamejo različne oblike. Tako v naplavinah zasledimo medzrnsko poroznost, ki jo povzroči stik med zrni. V kamninah zasledimo razpoklinsko poroznost, ki nastane zaradi razpok. Tretji tip poroznosti je kanalska poroznost, ki jo predstavljajo kanali različnih izmer. Značilni vodonosniki s kanalsko poroznostjo so kraški vodonosniki, v katerih pogosto zasledimo kanale večmetrskih izmer. V rudnini lahko obstaja tudi kombinacija vseh tipov poroznosti. Tako poznamo vodonosnike z dvojno poroznostjo, ali pa celo s trojno poroznostjo.

3 MATEMATIČNI POPIS SHRANJEVANJA TOPLOTE V VODONOSNIKIH

Prenos toplote in snovi v vodonosniku je kombinacija prevoda, konvekcije in difuzije [3]. Splošno lahko to popišemo s teorijo potencialov. Zaradi zapletene narave fizikalnega pojava je treba uporabiti nekaj poenostavitev, kakor je predpostavka laminarnega toka podzemne vode. Nadalje predpostavimo nespremenljivo gostoto in viskoznost podzemne vode pri obravnavanih temperaturah.

3.1 Difuzija snovi

Matematični opis toka podzemne vode temelji na Darcyjevem zakonu. Ta popisuje linearno odvisnost med specifičnim pretokom *q* in gradientom hidravličnega potenciala grad *h*.

Darcyjev zakon je primeren le za popis poroznih teles in laminarnega toka. Na mikroskopski skali je tok posamezne molekule v porah vodonosnika turbulenten, vendar pa na makro skali še vedno lahko govorimo o laminarnem toku. Ker je hidravlična prevodnost *K* nespremenljiva in le statistična vrednost popisa makroskopskega toka, velja le za majhna Reynoldsova števila (Re<10).

this reason, the division based on the coefficient of hydraulic conductivity *K* with regard to hydrogeological properties of the geological medium is also widely used. Rocks or sediments that have a coefficient of hydraulic conductivity *K* greater than 10^{-6} are classified as aquifers. Geological media where groundwater still occurs are called aquicludes and have conductivities between 10^{-6} and 10^{-12} m/s. Rocks and sediments which are practically impermeable are called aquifobes and their coefficient of hydraulic conductivity *K* is smaller than 10^{-12} m/s.

Water in rocks and sediments is found in interconnected pores that can take different forms with regard to geometry. Thus sediments have intergranular porosity, resulting from the contact between grains, interstitial porosity is found in rocks, due to the presence of interstices. The third type is channel porosity, represented by channels of different dimensions. Channel porosity is typical of karst aquifers where underground rivers flow in several metre wide channels. A geological medium can also have a combination of all types of porosity, e. g. there are aquifers with double or even triple porosity.

3 MATHEMATICAL DESCRIPTION OF HEAT STORAGE IN AQUIFERS

Heat- and mass- transport in aquifers is a combination of conduction, diffusion and convection processes [3]. In general, these processes can be described by the theory of potentials. The complex nature of physical phenomena requires some simplification, e.g. assuming fluid flow as laminar for groundwater flow calculations. Also density and viscosity of groundwater is assumed constant within the temperature range found in shallow underground.

3.1 Mass diffusion

Mathematical description of groundwater flow is based on Darcy's law. It describes a linear correlation between the specific flow *q* and the gradient in hydraulic potential grad *h*.

$$q = \frac{Q}{A} = -K \cdot grad\ \mathrm{h} \qquad (1).$$

Darcy's law is only valid for porous media and laminar flow. In microscopic scale the individual water molecules have varying velocity due to variations in pore space leading to turbulence. The turbulent flow of the individual water molecules is leveled out in large volumes, and the flow can be considered as laminar. Hence Darcy's law with the constant *K* is a statistical description of macroscopic flow and is valid for small Reynolds numbers values (Re<10).

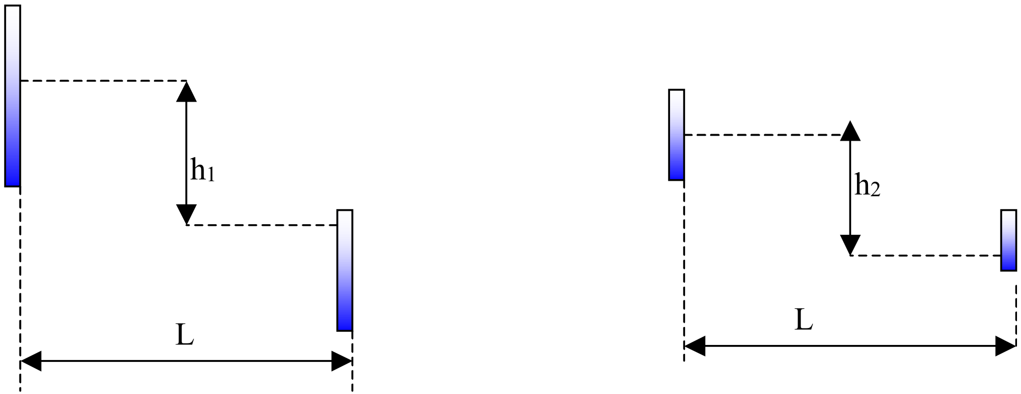
Za enorazsežen tok se zakon lahko poenostavi v obliko:

For one-dimensional flow the law can be simplified into:

$$q = \frac{Q}{A} = k\frac{h}{l} \qquad (2).$$

Pretok podzemne vode *Q* med dvema točkama je sorazmeren spremembi višine med točkama *h*, razdalje med točkama *l* in hidravlične prevodnosti snovi *K*, skozi katero teče tok. Hidravlična prevodnost je definirana s prepustnostjo snovi, hitrostjo tekočine in gravitacijsko silo. Slednji dve komponenti imata manjši vpliv, zato ju lahko poenostavimo s prepustnostjo.

The flow *Q* between two points is proportional to height *h*, distance *l* and hydraulic conductivity *K* of the medium through which the flow flows. Hydraulic permeability is defined with permeability of mass, flow velocity and gravity force. The last two components have smaller influence and can be approximated with permeability.



Sl. 1. *Prikaz definicije Darcyjevega zakona*
Fig. 1. *Presentation of the Darcy law definition*

Oba para vrtin na sliki1 sta enako oddaljena drug od drugega *l*, vendar imata različno hidravlično višino *h*. Zakon tako pravi, da bo tok večji tam, kjer je večja razlika potencialov.

Both wells have the same difference between them *l* but different hydraulic height *h*. The law says that the flow will be larger at higher height potential.

3.2 Zakon o ohranitvi snovi

3.2 Mass conservation law

Naslednji zakon, kateremu je podrejen sistem, je zakon o ohranitvi snovi. Ne glede na časovni korak *dt* je sprememba mase dm_{vol} v vodonosniku enaka razliki mase, ki vstopi, in mase, ki izstopi iz opazovane prostornine:

Furthermore groundwater flow is governed by the law of mass conservation, which is in hydrogeology also called the principle of continuity. Irrespective of the time interval *dt*, the mass change dm_{vol} within the aquifer equals the difference of the masses entering and leaving the observed volume.

$$\frac{m_{in}}{dt} - \frac{m_{out}}{dt} = \frac{dm_{vol}}{dt} \qquad (3).$$

Če postavimo telo v kartezični koordinatni sistem, in zaradi predpostavke o nespremenljivi gostoti tekočine, maso nadomestimo s specifičnim pretokom, dobimo:

Using the geometry of Cartesian co-ordinates and substituting mass flow by changes of the specific flow dq follows:

$$\frac{dq_x}{dx} + \frac{dq_y}{dy} + \frac{dq_z}{dz} = S_s\frac{dh}{dt} \qquad (4).$$

Z vstavitvijo Darcyjevega zakona v enačbo (4), ter dodanim členom vira oziroma ponora tekočine Q_w, dobimo diferencialno enačbo, ki opisuje trirazsežen tok v anizotropnem vodonosniku:

Inserting Darcy's law into equation (4) and adding a source/sink-term Q_w results in a partial differential equation describing a three-dimensional, transient flow in an anisotropic aquifer:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) - Q_w = S_s\frac{\partial h}{\partial t} \qquad (5).$$

Pri praktičnih izračunih splošno enačbo toka podzemne vode (5) po navadi glede na uporabo poenostavimo. Tako na desni strani zanemarimo časovno odvisnost shranjevanja energije in dobimo Laplaceovo enačbo. Nadalje lahko v večini primerov predpostavimo izotropni vodonosnik (K_x=K_y=K_z) ali pa zanemarimo navpični tok.

3.3 Prevod toplote

Analogno hidravličnemu toku popišemo tudi toplotni tok $\dot{Q}_t$. Ta teče, kadar obstaja temperaturni gradient:

This general equation for groundwater flow often can be simplified for practical application. Thus for steady flow the right, time-dependent storage term can be neglected and the Laplace equation results. Furthermore, the assumption of an isotropic aquifer (K_x=K_y=K_z) is possible in most cases, or the omission of vertical flow.

3.3 Conductive heat transfer

Analogous to the hydraulic transport equation a heat flow $\dot{Q}_t$ develops when a temperature gradient exists:

$$j = \frac{\dot{Q}_t}{A} = -\lambda \;\; grad \; \mathrm{T} \qquad (6).$$

Ko uporabimo zakon o ohranitvi energije za opazovano prostornino, lahko izračunamo spremembo temperature (dT) v kartezičnem koordinatnem sistemu:

Applying the law of energy conservation for a body of given volume, a temperature change (dT) can be calculated in Cartesian co-ordinates:

$$\frac{dj_x}{dx} + \frac{dj_y}{dy} + \frac{dj_z}{dz} = c\rho \frac{dT}{dt} \qquad (7).$$

Združitev enačb (6) in (7) da Fourierjevo diferencialno enačbo prenosa toplote, v splošnem to pomeni prevod toplote skozi anizotropno sredstvo:

The combination of Eq. (6) and (7) results in Fourier's differential equation of heat transport, which in general describes the transient conductive heat transport in anisotropic media:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) = c\rho \frac{\partial T}{\partial t} \qquad (8).$$

3.4 Konvektivni prenos toplote

Konvektivni prenos toplote je vedno povezan s prenosom snovi v kapljeviti ali plinasti fazi. Pri tem je bistvena razlika med naravno in prisilno konvekcijo. Pri naravni temperaturi gradient povzroči razliko gostot, kar ima za posledico gibanje tekočine z željo po uravnovešenju stanja. Pri prisilni konvekciji je gibanje tekočine posledica različnih potencialov tlaka oziroma hidravličnih višin, zaradi tega pride še do prenosa toplote. Če tako vzamemo enako tekočino kakor v zgornji enačbi, ima enačba konvektivnega prenosa toplote naslednjo obliko:

3.4 Convective heat transfer

Convective heat transport is always combined with mass transport in fluid or gaseous phase. A distinction can be made between free convection and forced convection. In free convection, temperature gradients cause differences in density. Mass transport tries to equilibrate and thus heat transport occurs. Forced convection is due to pressure differences like differences in hydraulic head leading to groundwater flow and consecutive heat transport. Assuming a flowing fluid has now thermal conductivity, a pure convection heat transport equation has the form:

$$\rho c Q_x \left(\frac{\partial T}{\partial x}\right) + \rho c Q_y \left(\frac{\partial T}{\partial y}\right) + \rho c Q_z \left(\frac{\partial T}{\partial z}\right) = c\rho \frac{\partial T}{\partial t} \qquad (9).$$

Prenos toplote s sevanjem iz Zemljine notranjosti lahko zanemarimo. Do prevoda toplote prihaja v kameninah vodonosnika, s konvekcijo pa se toplota prenaša v podzemni vodi. Trdna in tekoča faza vodonosnika predstavljata dva popolnoma različna sistema prenosa toplote. Pri izračunih predpostavimo, da je tekočina v temperaturnem ravnovesju s kamnino.

Tako ima enačba trenutnega toplotnega toka v poroznih sistemih s tokom tekočine prevodni in konvektivni del:

Convective heat transport in the ground through radiation can be neglected. Conductive heat transport mainly takes place in rock- and soil-matrix, and convective heat transport in groundwater. Solid and liquid phase hence constitute different systems with matching transport equations for each.

Thus the transient heat flow equation for a porous system with fluid flow consists of a conductive and a convective term:

$$\left(\rho_w \phi c_w + \rho_g (1-\phi) c_g\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial tT}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) - \rho_w c_w q_x \frac{\partial T}{\partial x} - \rho_w c_w q_y \frac{\partial T}{\partial y} - \rho_w c_w q_z \frac{\partial T}{\partial z} - \dot{Q}_t \quad (10).$$

4 PROBLEMATIKA VODONOSNIKOV

Shranjevanje toplote v vodonosnikih je tehnološko zelo podobno izkoriščanju pitne vode, izkoriščanju nafte in ogljikovodikov ter termalne energije iz geoloških sestavov, zaradi tega so pri izvedbah projektov shranjevanja toplote v vodonosnikih uporabljene izkušnje s teh področij geotehnike in drugih geoznanosti.

Shranjevanje toplote v vodonosnikih temelji na nalivanju tople vode v vodonosnik in na kasnejšem črpanju te vode iz vodonosnika. Kljub temu, da sta s hidravličnega vidika postopka črpanja in nalivanja v vodonosnik podobna, pa se pri praktični izvedbi zaradi naravnih danosti vodonosnikov pojavljajo številni problemi.

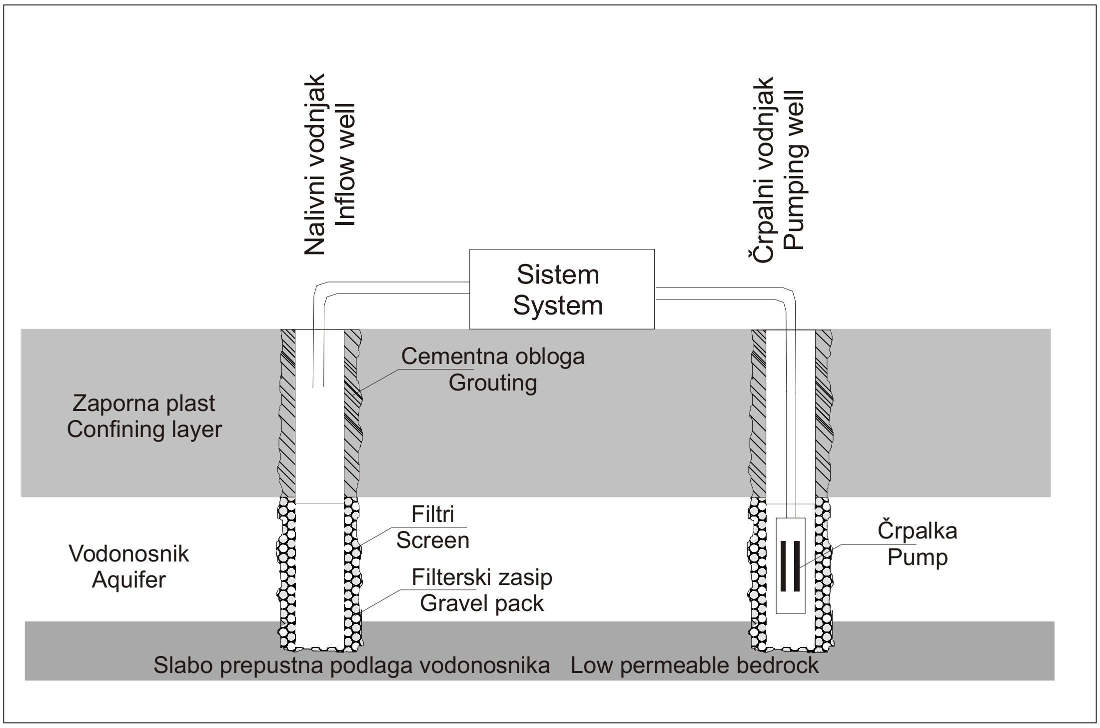
Sistem shranjevanja toplote v vodonosnikih praviloma sestoji iz vrste nalivnih in črpalnih vodnjakov. Po konstrukciji so si nalivni in črpalni vodnjaki podobni. To so lahko vodnjaki različnih premerov, bodisi izkopani, bodisi izvrtani. Konstrukcija vodnjaka sestoji iz trdnih cevi, filtrov in usedalnika. Med zunanjim robom konstrukcije vodnjaka in kamnino ali naplavino je izveden filtrski zasip. Vodnjaki so lahko izvedeni tudi brez filtrskega zasipa, vendar je učinkovito delovanje takšnih vodnjakov krajše od tistih s filtrskim zasipom. Filtri praviloma segajo v celotni zasičeni del vodonosnika, če pa je zasičeni del vodonosnika zajet le deloma, se pojavijo večje tlačne izgube, vodnjak se hitreje postara. V črpalnih vodnjakih je črpalka praviloma vstavljena v tisti del vodnjaka, kjer ni filtrov.

4 PROBLEMS OF AQUIFERS

The storing of heat in aquifers is technologically very similar to the exploitation of drinking water and the extraction of oil, gasses and thermal energy from geological structures, therefore experience from these fields of geotechnics and other geosciences is used in carrying out of such projects.

The storing of heat in aquifers is based on the inflow of warm water into the aquifer and its later withdrawal from the aquifer. Although the processes of pouring and extracting of water are similar from the hydraulic point of view, numerous problems occur in practice because of aquifers' natural properties.

The system of heat storage in aquifers usually consists of a battery of injection and pumping wells. Their construction is similar; they can have different diameters and are either dug or bored. The construction of the well is made of solid pipes, filters and a sediment trap. A gravel pack is placed between the outer edge of the well's construction and the rock or sediment. Wells can also be constructed without the gravel pack, yet such wells have a more short-term effective performance. Filters usually reach into the entire saturated part of the aquifer. Only partial penetration of the saturated zone leads to larger pressure losses and the well ages more rapidly. In pumping wells, the pump is normally installed into the part of the well where there are no filters.



Sl. 2. *Skladiščenje toplote v vodonosniku*
Fig. 2. *Heat storage in aquifer*

Pri shranjevanju toplote v vodonosnik se pojavljajo številni problemi. Do teh problemov pride zaradi mašenja filtrov v vodnjakih. Ta pojav je opazen predvsem v nalivalnih vodnjakih, v manjši meri pa tudi v črpalnih vodnjakih. V praksi ugotavljamo, da je zmogljivost črpalnih vodnjakov do trikrat večja od zmogljivosti nalivalnih vodnjakov. Zaradi mašenja filtrov pride do povečanja tlačnih izgub vodnjaka, s časom se zmanjša izdatnost vodnjaka in tudi zmogljivost celotnega sistema.

Pojave mašenja filtrov vodnjakov razdelimo v naslednje skupine:

a) Kemično mašenje je posledica spremenjenih fizikalno-kemijskih razmer v vodonosniku. Voda, ki jo v vodonosnik vbrizgavamo s površja, je po fizikalno kemijskih karakteristikah drugačna od tiste v vodonosniku. Razlikuje se tako po temperaturi, pH, elektropotencialu in po količini raztopljenih snovi. Ko pride v stik s hladno vodo iz vodonosnika se fizikalno-kemijske razmere na hitro spremenijo, zaradi tega imamo opraviti z obarjanjem mineralov [4], ki se odlagajo na filtre in na filtrski zasip nalivnega vodnjaka. Povišana temperatura vbrizgane vode pa ima tudi določeno prednost, zaradi boljše topnosti mineralov je njihovo odlaganje na filtre vodnjaka počasnejše.

b) Mehansko mašenje filtrov je posledica različno velikih delcev, ki se odlagajo na filtrih vodnjakov. Zamašitve zaradi delcev v vodnjaku so lahko posledica vnosa nečiste vode s površine ali pa posledica konstrukcijskih napak. Zamašitve z delci s površine se pojavljajo predvsem pri nalivnih vodnjakih. Trdni delci prodrejo v filter ali pa celo v filtrski zasip. Pri koloidih pride do kosmičenja. Konstrukcijske napake so lahko posledica slabe izdelave filtrskega zasipa ali pa napačne in nezadostne aktivacije vrtine.

c) Bakterijsko mašenje je posledica delovanja bakterij, ki so v vodonosnik vnesene z vbrizgom ali pa celo nekaterih združb, katerih življenjsko okolje je v vodonosnikih. Problemi z bakterijami se pojavljajo predvsem pri sistemih z nizkimi temperaturami.

d) Kombinirano mašenje je lahko posledica kombinacije vseh treh zgoraj naštetih pojavov. Zaradi spremembe kemijskih razmer v vodonosniku pride do naselitve specifičnih kultur bakterij, ki jih sicer v vodonosniku ne bi zasledili. Delovanje bakterij v vrtinah je v veliki meri odvisno od fizikalno-kemijskih razmer. Od bakterij, ki jih opazimo v vodnjakih, najbolj škodljivo vplivajo na konstrukcije vodnjakov železove bakterije in sulfat reducirajoče bakterije. Zaradi sprememb kemijskih razmer se lahko tudi poveča ali zmanjša gibljivost drobnih delcev v vodonosniku.

Mašenje je z nekaterimi tehničnimi postopki mogoče zmanjšati, ali pa tudi kratkotrajno odpraviti.

In storing heat into the aquifer, several problems can occur, linked mainly to the inflow of water into the aquifer. These problems are caused by the fouling, i.e. the clogging of well filters. Fouling occurs primarily in injection wells, and to a lesser extent also in pumping wells. The capacity of pumping wells is in practice up to three times greater than the capacity of inflow wells. Filter fouling causes increased pressure losses, which with time leads to a decrease in well yield and also to a smaller capacity of the entire system.

Filter fouling processes are divided into the following groups:

a) Chemical fouling. The fouling of filters which is a consequence of changes in physical and chemical conditions in the aquifer is called chemical fouling. Water that is injected into the aquifer from the surface has different physical and chemical characteristics than the water in the aquifer. It has a different temperature, pH, electropotential and a different quantity of dissolved matter. When it comes into contact with water from the aquifer, physical and chemical conditions change rapidly, leading to the precipitation of minerals (4) that are then deposited on filters and on the gravel pack of the inflow well. On the other hand, higher temperature of injected water causes better solubility of minerals and slows down their depositing on well filters.

b) Mechanical fouling. Mechanical fouling is caused by particles of different sizes. Fouling due to particles in the well can be the consequence of inflow of dirty water from the surface or the consequence of construction faults. Fouling with particles from the surface occurs mainly in inflow wells. Solid particles penetrate into the filter or even into the gravel pack. Colloids cause flaking. Construction faults can be the consequence of bad gravel pack or improper and insufficient well activation.

c) Bacterial fouling. Bacterial fouling is caused by the activity of bacteria, introduced into the aquifer with injected water, or even by bacteria that have aquifers as their natural habitat. Problems with bacteria occur mainly with low-temperature systems.

d) Combined fouling. Combined fouling is another possibility. It can be a consequence of all of the above mentioned processes. Because of the changes in chemical conditions, the aquifer becomes populated with specific cultures of bacteria that are not usual for this environment. The activity of bacteria in wells is to a large extent dependent on physical and chemical conditions. Among bacteria that are found in wells, iron bacteria and sulphate-reducing bacteria have the most damaging effect on well construction. Changes in chemical conditions can even lead to the mobility of fine particles in the aquifer.

Fouling processes can be reduced or eliminated for a short period of time with some

Takšni postopki so predvsem čiščenja nalivalnih vodnjakov. Tako poznamo mehanska batiranja vodnjakov, kislinske in klorne obdelave ter obdelave s podhlajenimi inertnimi plini. Vendar pa so ti postopki praviloma zelo dragi in zahtevni, ob nepazljivosti in nenatančni izvedbi pa so lahko tudi neučinkoviti. Tako je pri zmanjšanju izdatnosti vodnjaka pogosto ekonomsko bolj upravičeno izdelati nov vodnjak, še zlasti v primerih, ko vodnjaki ne dosegajo večjih globin. Upočasnitev mašenja lahko dosežemo tudi z ustrezno pripravo vbrizgane vode na površini, toda tudi ti postopki so pogosto pri svoji učinkovitosti omejeni, predvsem zaradi slabega poznavanja interakcij med vbrizgano vodo in vodo iz vodonosnika. Vsi ti postopki so omejeni tudi zaradi tega, ker imamo pri skladiščenju toplote v vodonosnikih opraviti z odprtim obtokom.

Zaradi spremenjenih fizikalno-kemijskih razmer so zelo izpostavljeni tudi materiali, iz katerih so izdelani filtri. Korozija filtrov vodnjakov v podzemni vodi je stalen pojav, v vodi s povišano temperaturo pa je korozija še hitrejša. Korozija se pojavi zaradi različnih energijskih nivojev kovin, ki sestavljajo konstrukcijo vodnjaka in zaradi delovanja vode kot elektrolita. Poznamo štiri tipe korozije vodnjaških konstrukcij:

- zvezno enakomerno tanjšanje elementa; zaradi te korozije pride do zmanjšanja nosilnosti elementov,
- točkovna korozija; ta vrsta korzije se pojavlja v heterogenih kovinah, zaradi česar je korozija na nekaterih mestih mnogo večja kakor na preostali površini,
- medkristalna korozija, ki nastane v sami kovinski zlitini med posameznimi zrni; pojavlja se predvsem v aluminijevih zlitinah z deležem bakra in pri nerjavnih jeklih z deležem ogljika,
- elektrokemična korozija; nastane na stiku dveh kovin z različnim potencialom.

Na korozijo imajo vpliv številni dejavniki. Naj jih opišemo le nekaj:

- *Temperatura*
  Zaradi povišane temperature se obseg korozije poveča predvsem v zaprtih termodinamičnih sistemih, v katerih kisik iz sistema ne more uiti.
- *pH vode*
  Kovine kot so Al, Zn, Pb so močno izpostavljene koroziji kislih in bazičnih raztopin. V nevtralnih raztopinah na površinah teh kovin nastanejo hidroksidi, ki pa ob spremembi pH v kislih ali bazičnih področjih razpadejo. Nasprotno pa nekatere kovine kot so Fe, Mg in Ni v bazičnih in kislih okoljih naredijo zaščitni sloj.
- *Hitrost tekočine*
  Hitrost tekočine ima precejšen vpliv na tip korozije. Tako je pri majhni hitrosti in laminarnem toku opazno le zvezno tanjšanje elementov, pojavlja pa se tudi točkovna korozija. S pojavom turbulentnega toka pride predvsem do nastanka točkovne korozije. Pri nadaljnji povečani hitrosti toka pride do odnašanja snovi, kar še pospeši korozijo. V primeru zelo velikih hitrosti

technical processes. The cleaning of inflow well is the most common solution: mechanical surging of wells, acid and chlorine treatment and treatment with cooled inert gasses. Yet, these procedures are often very expensive and demanding, and may also be ineffective if not carried out properly. In case of well yield drop it is therefore often more economical to build a new well, especially when the well is not very deep. Fouling can also be slowed down with adequate conditioning of injected water on the surface. Also these procedures have a limited efficiency, mainly because of insufficient knowledge of interactions between injected water and water from the aquifer. All these procedures are limited also because heat storage in aquifers is an open circuit.

Changes in physical and chemical conditions also have a negative impact on the materials from which filters are made. The corrosion of filters in groundwater wells is a permanent problem, and the process of corrosion is even faster in the water with higher temperatures. Corrosion is caused by different energy levels of metals of which the well is constructed and because of the water functioning as electrolyte. There are four groups of well construction corrosion:

- continuous proportionate thinning of the element; this corrosion causes decreased bearing strength of the element,
- point corrosion; it occurs in heterogeneous metals and causes some places to corrode far more than the rest of the surface,
- intercrystalline corrosion, which occurs in the metal alloy between individual grains; it is mostly found in aluminium alloys with copper content and in stainless steel with carbon content,
- electrochemical corrosion; it takes place at the contact of two metals with different potentials.

Corrosion is influenced by several factors:

- *Temperature*
  Because of higher temperature, the scope of corrosion is increased above all in closed thermodynamic systems where oxygen cannot exit the system.
- *pH of water*
  Metals such as Al, Zn, Pb are very prone to the corrosion in acid and basic solutions. In neutral solutions, hydroxides are formed on the surface of these metals. They decompose in acid or basic environment. On the other hand, some metals, i.e. Fe, Mg and Ni, form a protective layer in basic and acid environments.
- *Flow rate*
  Flow rate has considerable effect on the type of corrosion. Small velocity and laminar flow only cause a continuing thinning of elements, and point corrosion can also take place. Turbulent flow mainly causes point corrosion. Further increase of flow rate can wash away material, leading to increased corrosion. Very high flow rates can lead

lahko ob stenah nastajajo področja nizkega tlaka in s tem pride do nastajanja mehurčkov. Ti v področjih višjega tlaka implodirajo, kar povzroči kavitacijo.

- *Raztopljene soli*
  V splošnem se z naraščajočo koncentracijo soli povečuje učinek korozije do največje vrednosti, ko se korozija ustali.
- *Raztopljen kisik*
  Raztopljen kisik je dejavnik, ki najbolj vpliva na nastanek korozje. Raziskave so pokazale, da je stopnja korozije sorazmerna deležu kisika v vodi, do 5,5 mg/l. Pri višjih parcialnih tlakih kisika korozija ni več tako intenzivna, saj rabi rja kot zaščitni sloj.
- *Raztopljen ogljikov dioksid (CO_2)*
  Sistem CO_2-H_2O v veliki meri vpliva na pH raztopin. Stopnja korozivnosti se povečuje z večanjem parcialnega tlaka CO_2. Podobno kakor pri kisiku se intenziteta korozivnosti pri določeni vrednosti parcialnega tlaka CO_2 ne povečuje več.
- *Vodikov sulfid*
  Voda, ki vsebuje H_2S, je vedno problematična. Deluje korozivno na železove in kislinsko neodporne zlitine. Pri oksidaciji vode, v kateri je raztopljen H_2S, se zaradi nastanka H_2SO_4 pojavi korozija tudi pri kislinsko odpornih materialih.

Zaradi posledic, ki so nastale pri delovanju prvih sistemov uskladiščenja toplote v vodonosnikih, so bile izdelane smernice za izbiro gradiv. Tako se za izdelavo vrtin priporoča uporaba nerjavnih jekel in nerjavnih zlitin. Ta so bolje odporna proti fizikalno-kemijskim razmeram v vodonosnikih. Zaradi razmer v vodonosnikih pride predvsem do poškodbe zaščitnega sloja gradiv, kar se zgodi zaradi točkovne korozije in kloridov v vodonosnikih.

Poleg tehničnih problemov, ki se pojavljajo pri vbrizgu tople vode v vodonosnik, se, morda še nekoliko bolj izrazito, pojavljajo tudi problemi, ki se navezujejo na onesnaževanje vodonosnikov, saj so vodonosniki praviloma najpomembnejši vir čiste pitne vode. V Sloveniji skoraj vso pitno vodo (95%) pridobivamo iz podzemnih vodnih teles, zaradi česar je velik del države (22%) prekrit z že sprejetimi ali pa predlaganimi vodovarstvenimi pasovi, ki poleg posegov, ki so namenjeni javni vodooskrbi, ne dopuščajo nikakršnih posegov v vodonosnik. Poleg zaščitenih območij vodnih virov in uredb o njihovi določitvi, ki so dopustne v napajalnem zaledju vodnih virov, se je v zadnjem desetletju močno poostrila tudi zakonodaja, ki varuje podzemno vodo kot naravno dobrino, ne glede na to, ali je podzemno vodno telo, v katerem se pojavlja voda, zajeto za javno vodooskrbo ali ne. Na ta način je možnost uporabe vodonosnikov za shranjevanje toplote precej okrnjena. Morebitna izvedba shranjevanja toplote v vodonosnike bi terjala celovito in zahtevno analizo vplivov na kakovost in količino podzemne vode v podzemnem vodnem telesu, v katerega bi shranjevali toploto.

to low-pressure areas along the walls and the formation of bubbles. These bubbles implode in areas with higher pressure, causing cavitation.

- *Dissolved salts*
  Higher salt concentration generally increases the effect of corrosion to a maximum value, when corrosion stops.
- *Dissolved oxygen*
  Dissolved oxygen is the factor which has the most influence upon corrosion. Research showed that the degree of corrosion is proportional to the content of oxygen in water up to 5,5 mg/l. At higher partial pressures of oxygen, corrosion is not so intensive any more, since rust acts as a protective layer.
- *Dissolved carbon dioxide (CO_2)*
  The CO_2-H_2O system has considerable influence on the pH value of solutions. The degree of corrosion increases with the rise in partial pressure of CO_2, similarly as is the case with oxygen, where the intensity of corrosion no longer increases above a certain value of partial pressure of CO_2.
- *Hydrogen sulphide*
  Water with H_2S content is always problematic. It has a corrosive effect upon iron alloys and alloys that are not resistant to acids. Water containing dissolved H_2S is corrosive also for acid-resistant materials because of the H_2SO_4, formed during oxidation.

Because of the consequences observed in the operation of the first heat storage systems in aquifers, guidelines for the selection of materials were set. Therefore the use of stainless steels and alloys is recommended in the construction of wells. These materials are better resistant to the physical and chemical conditions in aquifers, which mainly cause damage to the protective layer of materials due to point corrosion at the presence of chlorides in aquifers.

Beside technical problems that are encountered at the injection of warm water into aquifers, problems linked to the pollution of aquifers are perhaps even more pronounced, since aquifers are as a rule the most important source of pure drinking water. Almost all drinking water in Slovenia (95%) is gained from underground water bodies, therefore a great part of the country (22%) is covered with already defined or proposed groundwater protection zones that allow no intrusions into the aquifer. In addition to protection zones and ordinances which define them and the activities that are allowed in water resource recharge areas, the strictness of legislation protecting groundwater as a natural resource has been intensified over the last decade, irrespective of the fact whether a groundwater body is exploited for public water supply or not. The possibility of aquifer exploitation for heat storage has been substantially reduced in this way. A project of heat storage in aquifers would demand a comprehensive and complex analysis of impacts upon the quality and quantity of water in the groundwater body intended for heat storage.

5 ŠVICARSKI PRIMER

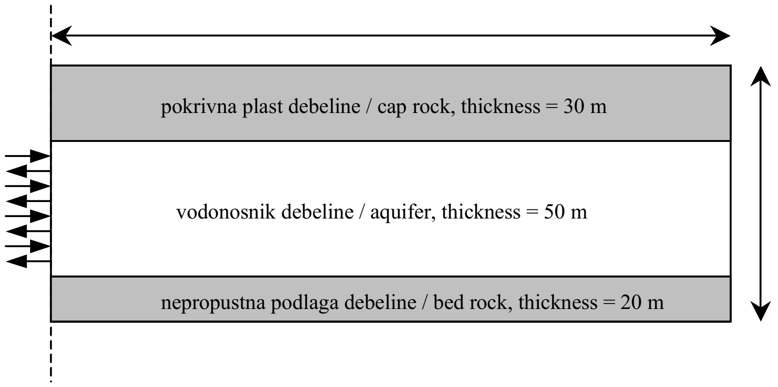
Švicarski laboratorij za geologijo je izvedel simuliranje shranjevanja toplote in nato črpanje te iz vodonosnika prek ene vrtine [5]. Namen je bil primerjava izkoristka vračanja toplote za potrebe ogrevanja.

Simuliranje je bilo izvedeno s programskim paketom FEFLOW, ki temelji na metodi končnih elementov. Modeliran je bil zaprt vodonosnik, v katerem je bil simuliran razvoj temperaturnega polja in tokovi podzemne vode. Simuliranje je bilo dvorazsežno in osnosimetrično, vodonosnik pa je bil razdeljen na trikotne elemente.

5 EXAMPLE FROM SWITZERLAND

Swiss Laboratory for Geology made a simulation of thermal energy storage in an aquifer with one well [5] with the aim to compare the heating efficiency.

The simulation was done by the FEFLOW software, based on the finite element method. Classical aquifer was used where temperature fields and flows of the underground water have been analyzed. The simulation was two-dimensional and axis-symmetrical, and the aquifer was divided into riangular elements.



Sl. 3. *Prikaz zaprtega vodonosnika za dvorazsežen dimenzionalen osnosimetrični model. Mreža je sestavljena iz 50000 trikotnih elementov, katerih stranice so dolge približno 60 cm.*

Fig. 3. *Presentation of the classical aquifer for two dimensional axis-symmetrical model. The net consists of 50000 triangular elements with 60-cm length.*

Preglednica 1. *Prikaz predpostavljenih termohidravličnih parametrov*

Table 1. *The presentation of thermohydraulic parameters*

hidravlični parametri hydraulic parameters		vodonosnik aquifer	podlaga in pokrov bedrock and cap rock
vodoravna hidravlična prevodnost horizontal hydraulic conductivity	K_h m/s	10^{-3} - 10^{-5}	10^{-8}
razmerje hidravličnih prevodnosti hydraulic conductivity anisotropy	$\kappa=K_v/K_h$	1 - 0,1	0,1
poroznost porosity	ϕ	0,2	0,2
stisljivost compressibility	S_o m^{-1}	10^{-4}	10^{-4}
toplotni parametri thermal parameters			
toplotna prevodnost thermal conductivity	λ_s W/mK	3	3
toplotna prevodnost thermal conductivity	λ_l W/mK	0,65	
toplotna prevodnost thermal conductivity	λ_a W/mK	$\Phi\lambda_l+(1-\Phi)\lambda_s=2,53$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_s$ J/m^3K	$2,52\cdot10^6$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_l$ J/m^3K	$4,2\cdot10^6$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_a$ J/m^3K	$\Phi(\rho c)_l+(1-\Phi)(\rho c)_s=2,856\cdot10^6$	
toplotna vzdolžna razpršilnost thermal longitudinal dispersivity	α_l m	5	5
toplotna prečna razpršilnost thermal transverse dispersivity	α_t m	0,5	0,5
začetna temperatura vodonosnika t_0=15 °c reference temperature t_0=15°c			

Predpostavljen je bil vodoraven vodonosnik stalne debeline. Skalnata podlaga in zgornja plast sta prav tako predpostavljeni kot vodoravni. Pri simuliranju je bila uporabljena vrtina s premeri od 0,4 do 1m, odvisno od debeline vodonosnika in vbrizganega toka.

Najmanjša temperatura povratka iz ogrevalnega sistema T_{min}=30 °C. Temperatura polnjenja vodonosnika je nespremenljiva. Pretok vode pri polnjenju Q_{in} in praznjenju Q_{out} je nespremenljiv, velja še $Q_{in} = Q_{out}$. Trajanje polnjenja in praznjenja je enak, in sicer 180 dni, brez dodatnega časa shranjevanja. Izkoristek je definiran kot:

A horizontal aquifer with a constant height was used. Rock basement and upper layer are also horizontal. The diameter of the well is 0.4 to 1 m, depending on aquifer depth and injected flow.

Minimal temperature of backflow from the heating system is T_{min}=30ºC. Temperature of filling the aquifer is constant. Water flow at filling Q_{in} and extracting Q_{out} is constant, it is valid also: $Q_{in} = Q_{out}$. Time for filling and emptying is the same: 180 days without additional time for storing. The efficiency is defined as:

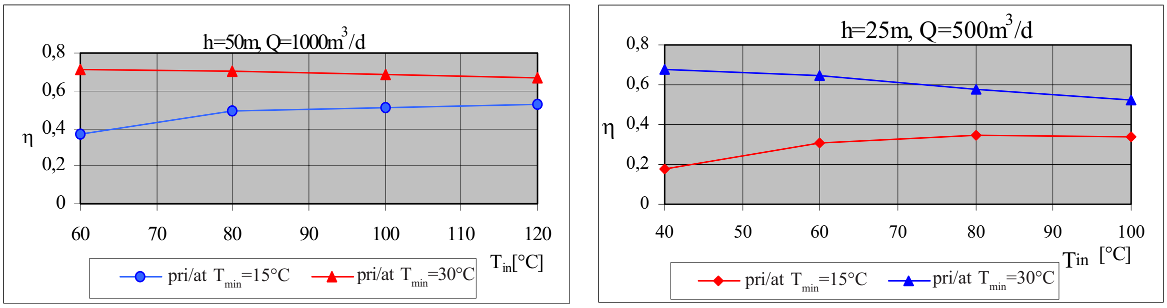
$$\eta = \frac{\text{celotna izčrpana energija pri } T \geq T_{mn}}{\text{celotna shranjena energija}} = \frac{\int_0^{t_{out}} (\rho c)_l Q_{out} (T_{out}(t) - T_{\min}) dt}{\int_0^{t_{in}} (\rho c)_l Q_{in} (T_{in} - T_0) dt} \qquad (11).$$

Za spremenljivki sta bila vzeta debelina vodonosnika h v m in pretok vode pri polnjenju Q_{in} v m^3/d. Rezultati so za drugi krog, to je drugo leto obratovanja sistema.

Pomemben dejavnik je temperatura vode pri polnjenju. Za majhne sisteme (Q_{in}<100m^3/d) in nizko temperaturo polnjenja (T_{in}<60 °C) je izkoristek precej majhen (manj ko 30 %). Drug pomemben dejavnik je naravna konvekcija skozi površino ter podlago vodonosnika. Za določeno debelino vodonosnika obstaja optimalen pretok, tako da preprečimo prevelike izgube. Hidravlična prevodnost K_h, manjša od 10^{-4}m, zmanjša naravno konvekcijo in zato tudi vpliv debeline vodonosnika na izkoristek.

Depth of aquifer h and water flow at injection Q_{in} were taken as variables. The results presented are for the second cycle, which is for the second year of system operation.

The minimum return temperature for the user is an important factor of the thermal efficiency of aquifer thermal energy storage. Small systems (Q_{in}<100m^3/d) and low temperature stock (T_{in}<60ºC) present therefore weak thermal recovery rates (less than 30%). Natural convection is another important and unfavorable factor. For a given injection flow rate Q_{in} an optimum aquifer thickness exists, allowing to avoid buoyancy phenomena and excessive conductive losses through the bedrock and cap rock. Aquifer hydraulic conductivity K_h smaller than 10^{-4} m/s reduces the natural convection cells appearance, and, consequently the importance of aquifer thickness as a factor of efficiency.



Sl. 4. *Izkoristek sistema kot funkcija temperature vode pri polnjenju* T_{in}, T_{min}*=30 °C in* T_{min}*=15 °C*

Fig. 4. *System efficiency as a function of water temperature at injecting* T_{in},

T_{min} = 30 ºC, T_{min} = 15 ºC

Preglednica 2. *Izkoristek sistema v odvisnosti od vodoravne hidravlične prevodnosti* K_h

Table 2. *System efficiency as a function of hydraulic conductivity* K_h *(second cycle* T_{min}*=30 ºC)*

η	Q_{in}=100m^3/d					Q_{in}=500m^3/d					Q_{in}=1000m^3/d			
K_h	10^{-3}	$5\cdot10^{-4}$	10^{-4}	$5\cdot10^{-5}$	10^{-5}	10^{-3}	$5\cdot10^{-4}$	10^{-4}	$5\cdot10^{-5}$	10^{-5}	10^{-3}	$5\cdot10^{-4}$	10^{-4}	10^{-5}
h=5			26,0		29,2			32,3						
h=10	12,6	17,6	29,1		31,2			37,5					40,1	
h=25			15,8	24,6	34,7	5,7	13,3	35,0	41,1	44,0	14,7	23,6	43,1	
h=50			8,7		33,4	1,1	2,7	20,2	32,5	43,9			47,6	
h=100								17,3		42,			21,4	46,1

h [m], K_h [m/s], η [%]

6 MOŽNOST UPORABE VODONOSNIKOV KOT HRANILNIKOV TOPLOTE V SLOVENIJI

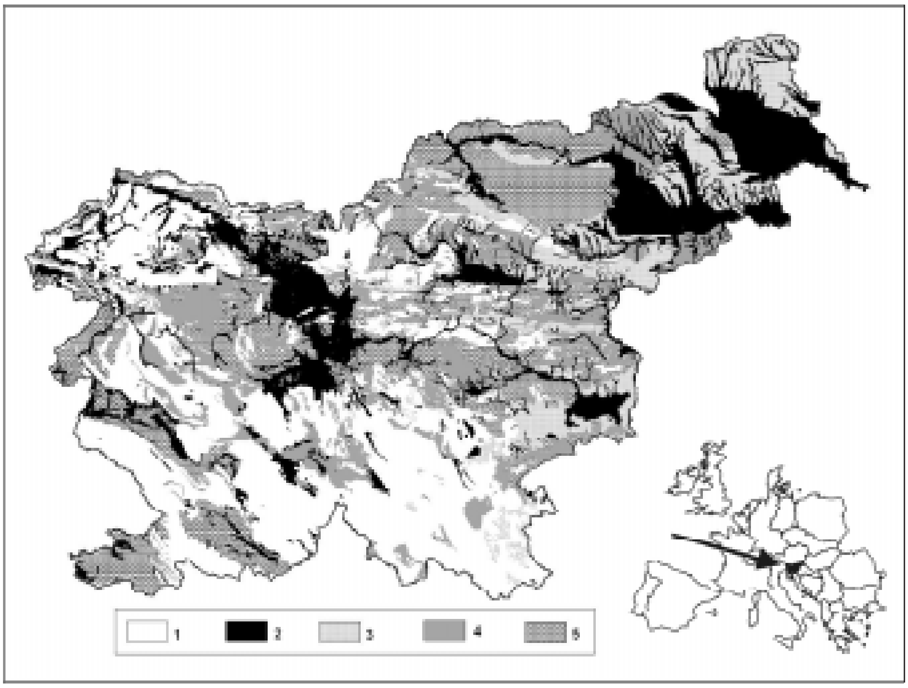
Slovenija je navkljub majhni površini geološko zelo pestra. Prevladujejo kamnine iz srednje zemeljske dobe, navzoče pa so tudi kamnine iz številnih drugih geoloških dob. Za slovensko ozemlje je značilna pestra tektonska dejavnost. Kamnine so prepredene s številnimi prelomi in narivi, zaradi časov so kamnine zelo poškodovane, v njih se pojavljajo številne razpoke, ki pomembno vplivajo na njihove hidrogeološke lastnosti. Tudi na porazdelitev naplavin močno vplivajo tektonske razmere.

Glede na različne tipe poroznosti lahko Slovenijo razdelimo na več hidrogeoloških enot. Takšna razdelitev je dokaj groba, vendar pa v grobem poda hidrogeološke lastnosti slovenskega ozemlja. Medzrnski vodonosniki ležijo predvsem v nižinskih predelih in v dolinah velikih rek. Pokrivajo 22 odstotkov površine države. Medzrnske vodonosnike najdemo v Prekmurju, na Dravskem in Ptujskem polju, v Ljubljanski kotlini in Ljubljanskem barju, Krško-Brežiški kotlini ter v Celjski kotlini. V medzrnskih vodonosnikih praviloma ležejo največja in najizdatnejša črpališča pitne vode.

6 THE POSSIBILITY OF USING AQUIFERS AS THERMAL STORAGE IN SLOVENIA

Despite its small area, Slovenia is geologically very diverse. Mesozoic rocks prevail, and there are also rocks from numerous other geological periods. Intensive tectonic activity is typical of the Slovenian territory. The rocks are cut with faults and thrusts, therefore they are damaged to a large extent, and numerous joints have an important influence on their hydrogeological properties. Tectonic conditions also have a strong impact on the distribution of sediments.

With regard to different types of porosity, Slovenia can be divided into several hydrogeological units. Such division is rather inexact, yet it can roughly define the hydrogeological properties of the Slovenian territory. Intergranular aquifers lie mainly in lowlands and in the valleys of big rivers. They cover 22% of the country's surface. Intergranular aquifers are found in Prekmurje, in the Dravsko and Ptujsko Polje, in the Ljubljana basin and in the Ljubljansko Barje, in the Krško-Brežice basin and in the Celje basin. Intergranular aquifers generally provide the biggest and richest drinking water reservoirs.



Sl. 5. *Pregledna hidrogeološka karta Slovenije (1 – kraški vodonosniki; 2 – medzrnski vodonosniki; 3 – vodonosniki z dvojno poroznostjo; 4 – razpoklinski vodonosniki; 5 – slabo prepustne kamnine)*
Fig. 5. *Hydrogeological map of Slovenia (1 - karst aquifers; 2 - intergranular aquifers; 3 - aquifers with double porosity; 4 - interstitial aquifers; 5 - rocks with low permeability)*

Slovenija je znana po številnih kraških pojavih. Kraški vodonosniki prekrivajo največjo površino Slovenije, njihov delež znaša 32 odstotkov. To so predvsem apnenci, ki jih najdemo na območju Alp in Dinarskega krasa v južni Sloveniji. Kamnine, v katerih se pojavljajo le razpoke, ki pa so lahko zaradi različnih pojavov

Slovenia is known for numerous karst phenomena. Karst aquifers cover the largest part of Slovenia, their share amounting to 32%. These are mostly limestones in the alpine region and in the Dinaric karst in southern Slovenia. Rocks with interstices that can also be somewhat dilated, are tudi nekoliko razširjene, so uvrščene v kategorijo razpoklinskih vodonosnikov, pri tem gre predvsem za različne vrste dolomitov. Ti vodonosniki prekrivajo 15% površine Slovenije. Z dvojno poroznostjo so opredeljeni predvsem peščenjaki terciarne starosti. V teh kamninah se pojavljata tako medzrnska kakor tudi razpoklinska poroznost. Te kamnine pokrivajo 11 odstotkov površine. Kot posebno kategorijo lahko izločimo slabo prepustne kamnine. To so tiste kamnine, pri katerih le stežka govorimo o njihovem potencialu za izkoriščanje podzemne vode, pokrivajo pa le dobro petino države. Sem sodijo različne vrste glinavcev, laporovcev in nekatere magmatske ter metamorfne kamnine.

Za shranjevanje energije so primerni le vodonosniki z majhno hitrostjo podzemne vode. Pomembno pa je tudi, da so v bližini večjih središč, kjer je mogoče to energijo tudi dokaj poceni prenesti do uporabnikov. Na kratko si oglejmo nekaj vodonosnikov. v katerih bi bilo mogoče uskladiščiti energijo. Osnovne lastnosti teh vodonosnikov so zbrane v preglednici 3.

Velenjska kadunja je mlada pliocenska tektonska udorina, ki jo zapolnjujejo rečne in potočne naplavine, predvsem gline in peski. Za tisti del vodonosnika, ki ga tvorijo peščene naplavine, so značilne srednje hidravlične prevodnosti, podzemna voda pa ima nizek gradient.

Krško-Brežiško polje je obsežna kotanja, ki je zasuta s kvartarnimi naplavinami, ki se navzdol nadaljujejo v pliocenske naplavine. Skupna debelina teh sedimentov na nekaterih delih presega 200 m. V zgornjem delu imamo opraviti z dokaj visokimi hidravličnimi prevodnostmi, v spodnjem pliocenskem delu pa se te hidravlične prevodnosti močno zmanjšajo, zaradi česar se močno upočasni tudi tok podzemne vode.

Kamniško-Mengeško polje je tektonska udorina, zapolnjena z mladimi kvartarnimi naplavinami, ki so po svojem izvoru predvsem ledeniškega nastanka. Debelina kvartarnih naplavin se od Kamnika proti Domžalam veča in doseže debelino več ko 70 m. Zaradi strmo nagnjene predkvartarne podlage so tudi hidravlični gradienti razmeroma visoki.

Na območju Prekmurskega in Murskega polja imamo opraviti z obsežnim vodonosnikom kvartarne starosti, ki se navzdol nadaljuje v pliocenske, nekoliko slabše prepustne naplavine. V kvartarnem delu vodonosnika imamo opraviti z relativno hitrim tokom podzemne vode, v pliocenskem vodonosniku, pa je tok podzemne vode počasnejši in zaradi tega primernejši za skladiščenje toplote.

Gričevje Goričkega je sestavljeno iz pleistocenskih in pliocenskih rečnih naplavin v katerih je razmerje med peščeno - prodnato in glinasto - meljasto frakcijo 1 : 2. Za te peske in prode so značilne dobre do srednje hidravlične prevodnosti. Glede na geološko sestavo, ki tone v smeri severozahod – jugovzhod, te naplavine v Moravskih toplicah segajo že do globine 1000 m. V tej globini pa se pojavlja podzemna voda s temperaturo prek 60 °C. Ti peski na

classified as interstitial aquifers, and are mainly different types of dolomites. These aquifers cover 15% of Slovenia. Aquifers with double porosity are mainly found in sandstones of Tertiary age. These rocks have intergranular as well interstitial porosity and have an 11% share. Rocks with low permeability are classified as a separate category. These are rocks that can hardly be considered to have any groundwater exploitation potential, and they cover only a good fifth of the country. Different types of clays, marls and some volcanic and metamorphic rocks belong into this group.

Only aquifers with slow groundwater flow are suitable for heat storage. It is also very important that they are in the vicinity of larger centres where the energy can also be relatively cheaply transported to consumers. The following is a short list of some aquifers where energy could be stored. The basic properties of these aquifers are summarized in Table 1.

The Velenje valley is a young Pleistocene tectonic depression filled with fluvial deposits, mainly clays and sands. The sandy part of the aquifer has medium porosity, while groundwater has a low gradient.

The Krško-Brežice field is an extensive basin, filled with Quaternary sediments that are downwards followed by Pliocene sediments. Total thickness of these deposits exceeds 200 m in some parts. The upper zone has relatively high permeability which is reduced to a large extent in the lower, Pliocene part, causing also the groundwater flow to slow down.

The Kamnik-Mengeš field is a tectonic depression filled with young Quaternary sediments of mostly alluvial origin. The thickness of Quaternary sediments increases from Kamnik towards Domžale and reaches more than 70 m. Because of the steep Pre-Quaternary bedrock also hydraulic gradients are relatively high.

The Prekmurje and Mura field has an extensive aquifer of Quaternary age that is downwards followed by Pliocene sediments of somewhat lower permeability. Groundwater flow is relatively fast in the Quaternary part of the aquifer and slower in the Pliocene aquifer, which is consequently more suitable for heat storage.

The hills of Goričko are composed of Pleistocene and Pliocene fluvial deposits with a 1:2 ratio between sand-gravel and clay-silt fractions. High to medium porosities are typical of sand and gravel. Because of the geological structure that declines in the NW-SE direction, these sediments reach already a depth of 1000 m in Moravske toplice. At this depth groundwater temperature is over 60^{0}C. The thickness of the saturated zone in these sands in Goričko is sufficient for storing energy, however it has to be

Goričkem sicer nudijo dovolj debelo omočeno plast, ki omogoča skladiščenje energije.

Ljubljansko barje je mlada tektonska udorina, v kateri se dobro prepustne plasti izmenjujejo s slabše prepustni. Opraviti imamo z dvema obsežnima vodonosnikoma. V zgornjem delu imamo opraviti z odprtim vodonosnikom, v spodnjem delu pa z obsežnim zaprtim vodonosnikom, ki bi bil primeren za skladiščenje energije.

pointed out that there is no source of surplus industrial heat in this area.

The Ljubljansko barje is a young tectonic depression in which layers with high porosity alternate with those with lower porosity. There are two large aquifers: an open aquifer in the upper part and a closed aquifer in the lower part, which would be suitable for energy storage.

Preglednica 3. *Ocenjeni parametri nekaterih vodonosnikov v Sloveniji, ki so primerni za skladiščenje toplote*
Table 1. *Estimated parameters of some aquifers in Slovenia that are suitable for heat storage*

lokacija in sestava location and composition	globina do depth up to	debelina thickness	hidravlična prevodnost porosity	gradient	poroznost porosity	hitrost flow rate
	m	m	m/s			m/dan m/day
Pomurje						
kvartarni prodi (odprt) quaternary gravels (open)	3 do 5	5 do 50	10^{-4}-10^{-6}	$1*10^{-3}$	0,25	3,5e-02
pliocenski peski (zaprt) pliocene sands (closed)	8 – 55	50 – 200	10^{-6}	$1*10^{-3}$	0,2	4,3e-04
Goričko						
pliocenski peski (zaprt) pliocene sands (closed)	0 - 50	50 – 200	10^{-6}	$1*10^{-3}$	0,2	4,3E-04
Velenje						
pliocenski peski (zaprt) pliocene sands (closed)	100	10	10^{-6}	$<1*10^{-3}$	0,2	4,3E-04
Krško						
pliokvartarni zaglinjeni prodi (zaprt) plio-quaternary clayey gravels (closed)	50	5	10^{-6}	$0,5 - 1*10^{-3}$	0,15	2,8E-04
Kamnik - Mengeš						
kvartarni prodi (odprt) quaternary gravels (open)	5 - 20	10 - 50	10^{-4}	$0,5 – 1*10^{-2}$	0,25	1,7E-01
Lj. barje						
kvartarni prodi in peski (zaprt) quaternary gravels and sands (closed)	50	15	10^{-4}	$<1*10^{-3}$	0,2	4,3E-04

V Sloveniji so glede na hidrogeološke lastnosti številni vodonosniki primerni za skladiščenje toplote, vendar pa so to praviloma tudi vodonosniki, ki pomenijo pomemben vir pitne vode. Zaradi tega je pri nadaljnjih raziskavah izkoriščanja vodonosnikov za potrebe uskladiščenja toplote v Sloveniji veliko pozornosti treba posvetiti morebitnim vplivom na kakovost in količino podzemne vode.

Skladiščenje toplote v vodonosnike je smiselno tam, kjer obstaja vir odvečne industrijske toplote. Za vsako možno lokacijo je treba pripraviti podrobne hidrogeološke in tehnološke osnove, s katerimi se oceni bistvene parametre podzemnega skladiščenja toplote, ki so v zvezi z naravnimi pogoji skladiščenja (hitrost razširjanja toplote v vodonosniku), s tehnološkimi pogoji skladiščenja (razporeditev nalivalnih in črpalnih vodnjakov in

With regard to hydrogeological properties, several aquifers in Slovenia are suitable for heat storage, yet these are as a rule also the aquifers providing an important drinking water resource. Because of this fact, further investigations of aquifer exploitation for heat storage will have to pay much attention to possible impacts upon the quality and quantity of groundwater.

The storing of heat in aquifers is reasonable where there is a resource of excessive industrial heat. For each potential location, detailed hydrogeological and technological bases have to be prepared in order to estimate essential parameters of underground heat storage that are in connection with natural storage conditions (how fast heat spreads in the aquifer), with technological conditions of storage (the distribution of injection and pumping wells and their njihova konstrukcija, interakcija tople vode s podzemno vodo v vrtinah) ter z zakonodajnimi pogoji, povezanimi s toplotnim onesnaževanjem v vodonosnikih in vplivi na vire pitne vode.

7 SKLEP

Možnost za uporabo vodonosnikov kot hranilnikov toplote se v svetu izraziteje raziskuje zadnjih petindvajset let. Po posameznih državah gredo raziskave v različne smeri, pač glede na to, kaj je lokalno pomembno. Na Japonskem iščejo rešitev v smeri le ene vrtine, medtem ko primer iz Kanade kaže rezultate raziskave o uporabi še dodatne odpadne vrtine. Posamezne države imajo različno geološko sestavo. Povsem različni sta Nizozemska in Švica. Prvo skoraj v celoti pokrivajo medzrnski vodonosniki, medtem ko so ti v Švici, katere primer je prikazan v prispevku, le v ledeniških dolinah in na redkih ravninskih delih.

Za popis shranjevanja termalne energije v vodonosniku je potrebno zelo natančno poznavanje geoloških razmer. Poznati moramo hitrosti in pretoke podzemne vode. Ti se lahko po globini zelo razlikujejo, kar dodatno oteži računalniška simuliranja. Spregledati ne smemo niti naravnega vzgona. Zaradi tega je treba namestiti odvzem tople vode na manjši globini kakor je izvedeno vbrizganje.

V Sloveniji delujočega sistema, kjer bi iz vodonosnika črpali in nato vračali vodo, še ni. Izvedenih je le nekaj primerov z vkopanimi cevmi. Glede na to, da večino vodonosnikov v Sloveniji uporabljamo za črpanje pitne vode, je shranjevanje toplote v njih dokaj tvegano, ker vsako vbrizganje v vodonosnik pomeni nevarnost onesnaženja.

construction, the interaction of warm water with groundwater in wells) and with legislative conditions pertaining to the heat pollution of aquifers and influences on drinking water resources.

7 CONCLUSION

The possibility of aquifer utilization has been investigated in the world for the last 25 years. In different countries the research is directed towards different objectives, depending on the specific conditions in each country. The solution in Japan is directed towards one well only, whereas the example form Canada shows the utilization of one pumping well and one refuse well. Netherlands and Swiss are different. The first is almost entirely covered by intergranular aquifers whereas in Swiss aquifers are usually in glacial valleys and rare flat areas.

For the description of thermal energy storage in aquifers, a detailed knowledge of the aquifer’s structure is necessary, together with the speed and flows of underground water. Those can vary considerably with the depth, presenting difficulties at computer simulations. Natural convection cannot be neglected. This is the reason why the pumping of warm water has to be performed at smaller depths than the injection of cold water.

Systems that would pump warm water from the earth and inject cold water back are not known in Slovenia. The fact that most aquifers in Slovenia are used for drinking water, makes thermal energy storage in aquifers very risky.

8 SIMBOLI
8 SYMBOLS

koordinate kartezičnega koordinatnega sistema	x,y,z		coordinates of the Cartesian system
specifičen tok	q	m/s	specific flow
prostorninski tok	Q	m^3/s	volumetric flow
površina	A	m^2	area
hidravlična prevodnost	K	m/s	hydraulic conductivity
hidravlična višina	h	h	hydraulic height
gostota toplotnega toka	j	W/m^2	heat flux density
toplotni tok	$\dot{Q}_t$	W	heat flux
toplotna prevodnost	λ	W/mK	thermal conductivity
temperatura	T	K	temperature
čas	t	s	time
specifična toplota tekočine	c_w	J/kgK	specific heat of fluid
specifična toplota kamenine	c_g	J/kgK	specific heat of rock
gostota tekočine	ρ_w	kg/m^3	fluid density
gostota kamnine	ρ_g	kg/m^3	rock density
poroznost	ϕ	%	porosity
stisljivost	S_o	m^{-1}	compressibility
polmer	r	m	radius
transmisivnost vodonosnika	τ_a	m^2/d	transmisivity of aquifer
hitrost tekočine	$\vec{v}$	m/s	fluid velocity

komponente hitrosti tekočine	u,v,w	m/s	components of fluid velocity
gravitacijski pospešek	g	m/s^2	gravitational acceleration

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Analiza porazdelitve toplote pri brušenju titanove zlitine VT 9 in njena povezava do zaostalih napetosti

Analysis of the Heat Distribution when Grinding of a VT 9 Titanium Alloy and its Relation to Residual Stresses

Miroslav Neslušan - Andrej Czán - Uroš Župerl

Porazdelitev toplote pri strojni obdelavi je ena od fenomenoloških značilnosti tega postopka, ker pomembno vpliva na funkcionalne lastnosti obdelanih površin. Prispevek obravnava porazdelitev toplote pri brušenju titanove zlitine VT 9 in njeno razmerje do kakovosti brušenih delov, ki jo predstavljajo zaostale napetosti. Analiza porazdelitve toplote temelji na merjenju temperature na stiku brusa in obdelovanca ter obodne komponente rezalne sile. Porazdelitev toplote pri brušenju titanove zlitine VT 9 se razlikuje od porazdelitve toplote pri brušenju običajnega jekla za kotalne ležaje (14 209.4), kot tipičnega predstavnika brušenih kaljenih jekel in sicer predvsem zaradi majhne toplotne prevodnosti titanijevih zlitin. Nadalje, uporaba CBN in diamantnih brusov znatno zmanjša izpostavljenost brušenih delov toploti, predvsem kadar se uporablja hladilno-mazalna tekočina. To dejstvo pomembno vpliva na zaostale napetosti po brušenju. Rezultati analize kažejo, da obstaja močna povezava med porazdelitvijo energije in zaostalimi napetostmi.

(Ključne besede: brušenje, zlitine titana, porazdelitve toplote, zaostale napetosti)

Heat distribution during machining is one of the phenomenological characteristics of this process because it significantly influences the functional properties of machined surfaces. This paper deals with heat distribution during the grinding of a VT 9 titanium alloy and its relationship to the quality of ground parts in terms of residual stresses. The analysis of the heat distribution is based on a measurement of the temperature in the contact of the grinding wheel and workpiece, and the tangential component of the cutting force. The heat distribution when grinding a VT 9 titanium alloy differs from the heat distribution when grinding a conventional (14 209.4) roll-bearing steel (a typical representative of ground-hardened steels) mainly because of the low heat conductivity of titanium alloys. Also the application of CBN and diamond grinding wheels significantly reduces the thermal exposition of the ground parts, primarily when applying cutting fluid. This fact significantly influences the residual stresses after grinding. The results of the analysis show that there is a strong correlation between energy partitioning and residual stresses.

(Keywords: grinding, titanium alloys, heat distributions, residual stresses)

0 UVOD

Titan in njegove zlitine so priljubljeni materiali zaradi njihovega edinstvenega velikega razmerja med trdnostjo in težo, ki se ohranja pri zvišanih temperaturah ter zaradi njihove izjemne odpornosti proti koroziji. Titanove zlitine se uvrščajo med težko obdelovane materiale. Strojno obdelani deli iz titanovih zlitin so običajno izpostavljeni utrujanju, kajti najpogosteje se titan uporablja v letalski in vesoljski industriji za ogrodja letal in komponente motorjev. Fine operacije strojne obdelave imajo običajno za posledico nihajno utrujenostno trdnost, ki je mnogo večja (do približno 5-krat) kakor pri ustreznih neugodnih rezalnih razmerah [1]. Kahles idr. [2] trdijo, da se površina titanovih zlitin zlahka

0 INTRODUCTION

Titanium and its alloys are attractive materials due to their very high strength-to-weight ratio, which is maintained at elevated temperatures. and their exceptional corrosion resistance. Titanium alloys are classified as difficult-to-machine materials. The machined parts made from titanium alloys are usually exposed to the fatigue load because the major applications of titanium have been in the aerospace industry, where titanium is used in airframes and engine components. Gentle machining operations usually result in a high cyclic fatigue strength that is much higher (as much as five times) than that of the corresponding unfavourable cutting conditions [1]. Kahles et al. [2] claim that the surface of titanium poškoduje med postopki strojne obdelave, zlasti med brušenjem. Celo ustrezna praksa brušenja z uporabo običajnih parametrov ima za posledico znatno nižjo utrujenostno trdnost zaradi poškodb površine.

Poškodbe obdelovanca pri brušenju so običajno termično povzročene, in sicer ne samo zaradi toplote, nastale v coni rezanja, ampak tudi zaradi temperature na površini brušenega dela, njenega gradienta in koeficienta R_w- razmerja porazdelitve (razmerje med toploto, ki vstopi v obdelovanec in celotno toploto). Zaostale natezne napetosti, ki so termičnega izvora, so lahko nesprejemljive. Pri raziskavah je bilo ugotovljeno, da se ugodne tlačne napetosti bolj verjetno dosežejo z brusi CBN in diamantnimi brusi. Rezultati raziskav [3] kažejo, da je ugodneje uporabiti bruse CBN in diamantne bruse, pri katerih je vstop energije v obdelovanec manjši. Razmerje porazdelitve je zato koristen pokazatelj učinkovitosti brusa glede na verjetnost nateznih napetosti.

Pri brušenju običajnih jekel za kotalne ležaje in pri uporabi brusa iz korunda večina energije vstopa v obdelovanec (90%) ([3] in [4]). To je podano s kinematičnimi pogoji in z dejstvom, da je toplotna prevodnost običajnih ležajnih jekel (46 W/mK) večja kot toplotna prevodnost brusa iz korunda (6÷30 W/mK, veliko področje podanih vrednosti). Porazdelitev toplote pri brušenju titanove zlitine VT 9 se razlikuje od porazdelitve toplote pri brušenju običajnih jekel za kotalne ležaje, zaradi slabih termičnih lastnosti titanovih zlitin (toplotna prevodnost titanovih zlitin je 7,5 W/mK) in zato ta prispevek obravnava analizo toplotne porazdelitve in njeno razmerje do kakovosti brušenih delov, ki je odvisno od zaostalih napetosti.

1 EKSPERIMENTALNA METODA

Eksperimentalna analiza porazdelitve toplote temelji na ‘’teoriji pomičnega vira toplote” [5]. Vir toplote s stalnim tokom toplote na enoto površine q, dolžino $2l$, se premika vzdolž površine polneskončnega mirujočega telesa z nespremenljivo hitrostjo v_w. Izhodišče koordinatnih osi x, z je v središču izvora toplote. Dobimo dvorazsežno, ustaljeno porazdelitev toplote:

alloys is easily damaged during machining operations, especially during grinding. Even proper grinding practice using conventional parameters results in an appreciably lower fatigue strength due to surface damage.

The damage to a workpiece when grinding is usually thermally induced and comes not just from the heat generated in the cutting zone, but also by the temperature on the surface of a ground part, its gradient and R_w coefficient (the partition ratio: the ratio of the heat entering the workpiece to the total heat). Residual tensile stresses, which are primarily thermal in origin, may be unacceptable. Investigations have found that preferred compressive stresses are more likely to be achieved with CBN and diamond grinding wheels. Results of investigations [3] indicate an advantage of CBN and diamond grinding is a smaller proportion of the energy entering the workpiece. The partition ratio is therefore a useful indicator of grinding-wheel performance relevant to the likelihood of tensile stresses.

Most of the energy enters the workpiece (90%) when grinding conventional roll-bearing steels using an alumina grinding wheel ([3] and [4]). This is given by kinematics conditions and the fact that the thermal conductivity of conventional roll-bearing steels (46 W/mK) is higher than that the alumina grinding wheel (6÷30 W/mK, wide range of the presented values). The heat distribution when grinding a VT 9 titanium alloy differs from the heat distribution when grinding conventional roll-bearing steels because of the poor thermal properties of titanium alloys (the thermal conductivity of titanium alloys is 7.5 W/mK) and so this paper deals with its analysis and the relation to quality of the ground parts in terms of residual stresses.

1 EXPERIMENTAL METHOD

The experimental analysis of the heat distribution is based on the “Moving Heat Source Theory” [5]. The heat source of constant heat flux per unit area q, length $2l$, moves along the surface of a semi-infinite stationary body at a constant velocity v_w. The origin of the coordinate axes x, z is at the centre of the heat source. The two-dimensional, steady-state temperature distribution for this model is:

$$\theta \frac{\pi k v_w}{2q\alpha} = \int_{X-L}^{X+L} e^{-u} K_0\{(Z^2+u^2)^{0,5}\}du \qquad (1),$$

kjer pomenijo:

θ – dvig temperature nad temperaturo okolice v C°,
α – termično difuzivnost v m^2/s,
k – toplotno prevodnost v W/mK,
q – toplotni tok v m^{2}kg/s,
l – polovično dolžino območja izvora v m,
K_0 – modificirano Bessel-ovo funkcijo,
u – specifično energijo brušenja v J/m^3,
X, Z, L – brezrazsežne vrednosti ($X=v_w \cdot x/2\alpha$, $Z=v_w \cdot z/2\alpha$, $L=v_w \cdot l/2\alpha$).

where:

θ – temperature rise above ambient temperature (^{o}C),
α – thermal diffusivity (m^2/s),
k – thermal conductivity (W/mK),
q – heat flux (m^{2}kg/s),
l – half length of the band source (m),
K_0 – the modified Bessel function,
u – specific grinding energy (J/m^3),
X, Z, L – dimensionless quantities ($X=v_w \cdot x/2\alpha$, $Z=v_w \cdot z/2\alpha$, $L=v_w \cdot l/2\alpha$).

Takazawa je dobil rešitev za enačbo (1) z numerično integracijo. Njena poenostavljena oblika je:

Takazawa obtained a solution for equation (1) by using numerical integration. Its simplified form is:

$$\theta \frac{\pi k v_w}{2 R_w q \alpha} = 3.1 L^{0.53} \exp(-0,69 L^{-0,37} Z) \qquad (2)$$

in enačba za največji dvig temperature θ_d (z=0) je:

and the equation for a maximum temperature rise θ_d $(z=0)$ is:

$$\theta_d = 0,947 \alpha^{0,47} k^{-1} F_c R_w v_c {v_w}^{-0,47} l_c^{-0,47} \qquad (3),$$

kjer pomenijo:
F_c – obodno komponento sile v N,
v_c – hitrost brusa v m/s,
l_c – dolžino dotika v m.

$F_c \cdot v_c$ je skupna energija, ustvarjena v področju rezanja Q. Porazdelitev energije R_w se lahko izračuna tako, da vstavimo največji dvig temperature θ_d in obodno silo brušenja F_c v enačbo (3).

Meritev vrednosti F_c je bila izvedena s piezoelektričnim merilnikom sile KISTLER skupaj z meritvijo temperature. Temperatura je bila izmerjena z metodo termoelementa (sl. 1), ki jo je uvedel Peklenik [6] in ki sta jo izboljšala Gu in Wager [7] (obe vrednosti sta bili merjeni z uporabo kartice A/D na osebnem računalniku).

Rezalne razmere: v_c = 25 m/s, v_w = 4 m/min, brus A99 60LVS, profilno brušenje, s hladilno mazalno tekočino in brez nje (Emulzin z 2 % koncentracijo).

Strojno obdelani materiali:
1. titanova zlitina VT 9 – termična difuzivnost 2,87·10^{-6} m^2/s, meja plastičnosti R_m = 900 MPa po žarjenju. Sestava zlitine VT 9 je iz faze α in β. Njena kemična sestava je podana v preglednici 1.
2. Kaljeno jeklo za kotalne ležaje (14 209.4) – termična difuzivnost 12,4·10^{-6} m^2/s. Kemična sestava je podana v preglednici 2.

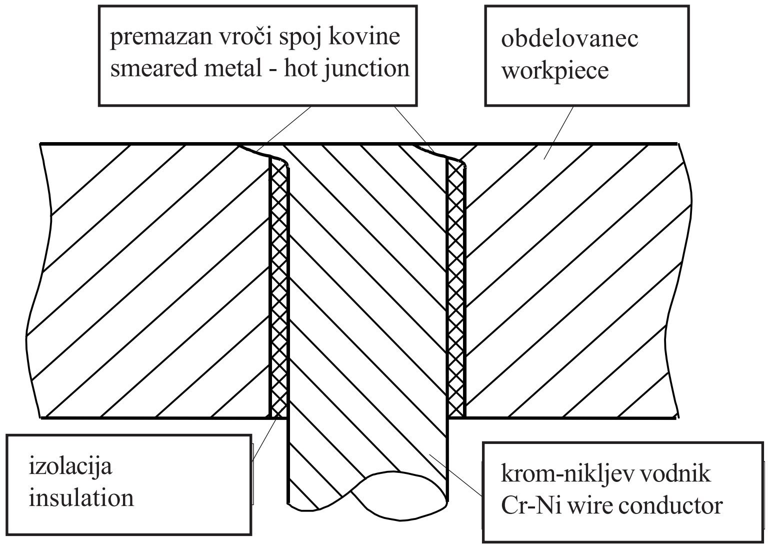
where:
F_c – tangential force component (N),
v_c – wheel speed (m/s),
l_c – contact length (m).

$F_c \cdot v_c$ is the total energy created in the cutting zone Q. The energy partition R_w can be calculated by entering the maximum temperature rise θ_d and the tangential grinding force F_c into equation (3).

The measurement of F_c was made with a piezoelectric KISTLER dynamometer together with the measurement of temperature. The temperature was measured with the thermocouple technique (Fig.1) introduced by Peklenik [6] and improved by Gu and Wager [7] (both quantities measured through an A/D card to a PC).

Cutting conditions: v_c = 25 m/s, v_w = 4 m/min, grinding wheel A99 60LVS, plane plunge grinding, with and without cutting fluid (Emulzín 2 % concentration).

Machined materials:
1. VT 9 titanium alloy - thermal diffusivity 2.87·10^{-6} m^2/s, yield strength R_m = 900 MPa, after annealing. The structure of VT9 consists of α and β phase. Its chemical composition is given in Table 1.
2. hardened roll-bearing (14 209.4) steel - thermal diffusivity 12,4·10^{-6} m^2/s. Its chemical composition is given in Table 2.



Sl. 1. *Peklenikova metoda za merjenje temperature na stiku brusa in obdelovanca*
Fig.1 *Peklenik method for the measurement of the temperature in the contact of the grinding wheel and the workpiece*

Preglednica 1. *Kemična sestava titanove zlitine VT 9*
Table 1. *Chemical composition of the VT 9 titanium alloy*

element	Al	Mn	Si	Zr	O_2	N_2	H_2	C	Fe
%	5,8-7	2,8-3,8	0,2-0,3	0,8-2,5	$\leq 0{,}15$	$\leq 0{,}05$	$\leq 0{,}015$	$\leq 0{,}1$	$\leq 0{,}25$

Preglednica 2. *Kemična sestava jekla za kotalne ležaje (14 209.4)*
Table 2. *Chemical composition of the hardened roll-bearing (14 209.4) steel*

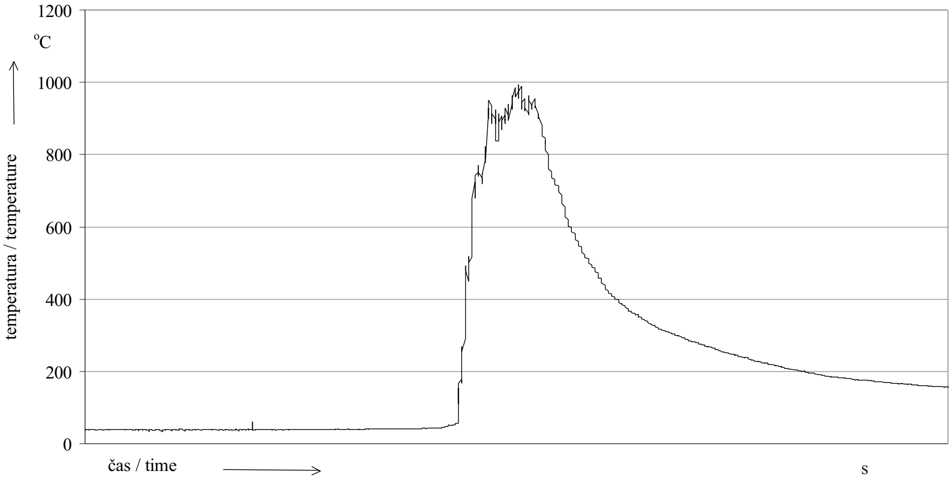
element	Cr	Mn	Si	Cu	S	P	Ni	C
%	1,3-1,6	0,9-1,2	0,3-0,6	$\leq 0{,}\ 25$	$\leq 0{,}\ 03$	$\leq 0{,}\ 03$	$\leq 0{,}\ 3$	1

2 EKSPERIMENTALNI REZULTATI

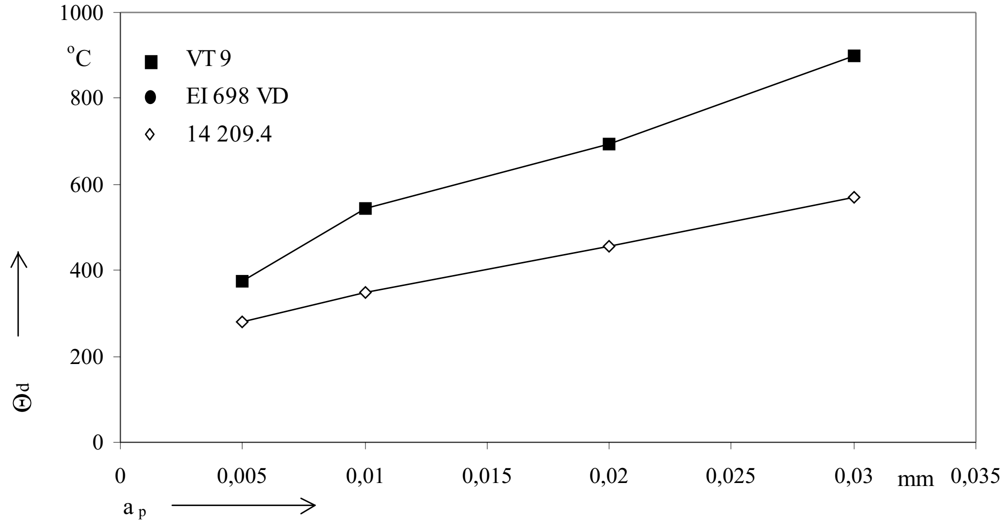
Temperaturo na površini θ_d smo dobili tako, da smo dali gladko krivuljo skozi merjeno območje. Slika 3 kaže odnos med temperaturo površine in globino rezanja. Skupna toplota je ugotovljena tako, da smo izmerili obodno silo in hitrost koluta (sl. 4).

2 EXPERIMENTAL RESULTS

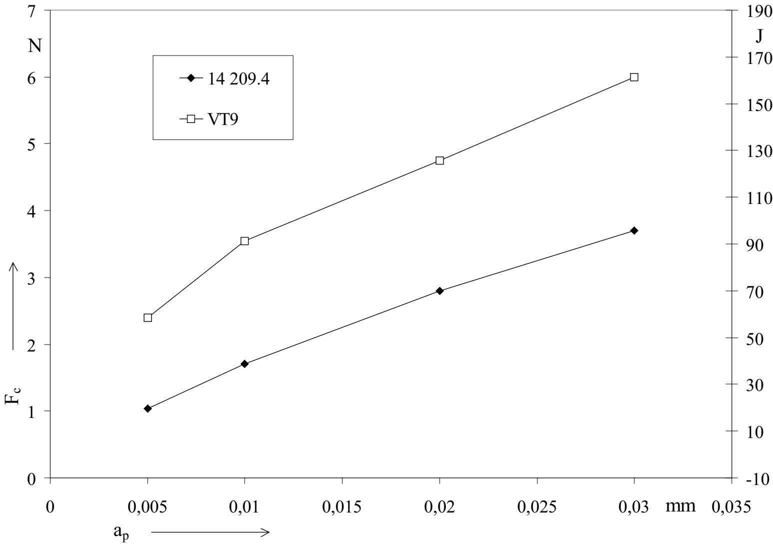
The temperature on the surface, θ_d, was obtained by putting a smooth curve through the measured trace. Figure 3 presents the relation between the surface temperature and the cutting depth. The total heat was determined by measuring the tangential force and the wheel speed (Figure 4).



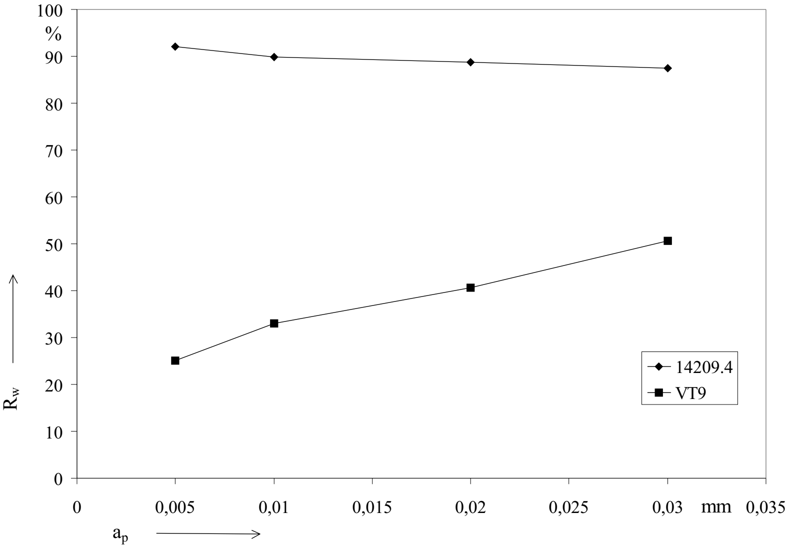
Sl. 2. *Tipični izmerjeni dvig temperature pri brušenju titanove zlitine VT 9 (a_p = 0,03 mm)*
Fig.2. *Typical measured temperature rise when grinding the VT 9 titanium alloy (a_p = 0.03 mm)*



Sl. 3. *Temperatura površine kaljenega jekla za kotalne ležaje 14 209.4 in titanove zlitine VT 9*
Fig. 3. *Surface temperature for the hardened roll-bearing 14 209.4 steel and the VT 9 titanium alloy*



Sl. 4. *Skupna toplota Q in obodna komponenta brusne sile F_c na 1 mm širine brušenja*
Fig. 4. *Total heat, Q, and tangential component of grinding force, F_c, per 1mm of grinding width*



Sl. 5. *Razmerje porazdelitve R_w*
Fig. 5. *Partition Ratio R_w*

Razmerje porazdelitve R_w (sl. 5) je delež toplote, ki vstopi v obdelovanec, proti celotni toploti, ki jo izračunamo tako, da vstavimo največji dvig temperature θ_d s slike 3 in obodno silo brušenja F_c s slike 4 v enačbo (3).

Pri postopku brušenja se skoraj vsa energija brušenja spremeni v toploto na majhnem območju brušenja. Pri suhem brušenju so trije pomembni toplotni ponori: obdelovanec, brus in odrezki. Največja mogoča toplota, ki vstopi v odrezke, se lahko izrazi z specifično odstranitvijo kovine, gostoto, specifično toplotno kapaciteto in razliko med temperaturo taljenja in temperaturo okolice [8]. Na temelju te predpostavke je največja toplota, ki vstopi v odrezke, približno 8 % pri 14 209.4 in približno 4,5 % pri titanovi zlitini. Velik del nastale toplote preide v obdelovanec, kar ima

The partitioning ratio R_w (Figure 5) is the ratio of the heat entering the workpiece to the total heat, calculated by entering the maximum temperature rise, θ_d, from Figure 3 and the tangential grinding force, F_c, from Figure 4 into equation (3).

In a grinding operation almost all the grinding energy is converted into heat within a small grinding zone. There are three significant heat sinks in dry grinding: the workpiece, the grinding wheel and the grinding chips. The maximum possible heat entering the grinding chips can be expressed in terms of the specific metal removal, the density, the specific heat capacity and the difference between the melting temperature and the ambient temperature [8]. On the basis of this assumption the maximum heat entering the grinding chips is about 8% for 14 209.4 and about 4.5% for the titanium alloy. A large part of the generated heat flows into the workpiece, which za posledico skrajno visoke temperature na stiku med brusom in obdelovancem.

Na podlagi eksperimentalnih rezultatov je mogoče trditi, da majhen delež energije vstopi v brus pri brušenju kaljenega jekla. Pri brušenju titanove zlitine v brus vstopi približni 65 % toplote. Velika mehanska in termična obremenitev zrn pri brušenju titanove zlitine vodi do velike obrabe zrn in močne adhezije med obdelovanim materialom in rezalnim zrnom [9]. Največji dvig temperature pri titanovi zlitini je mnogo večji kakor pri ležajnem jeklu, čeprav je čisti vnos energije pri titanovi zlitini manjši kakor pri kaljenem jeklu. To je zato, ker je toplotna prevodnost titanove zlitine mnogo manjša kakor pri kaljenem jeklu (koncentracija toplote na stiku brusa in obdelovanca pri brušenju titanove zlitine).

Rezultati naslednjih preskusov kažejo, da uporaba diamantnih brusov in brusov CBN omogoča, da zmanjšamo nagnjenje k termičnim poškodbam brušenih površin na delih iz titanove zlitine VT 9. Temperature površine pri brusih CBN in diamantnih brusih, izmerjene z isto metodo, so znatno nižje od temperature površine, izmerjene pri Al_2O_3, in sicer predvsem pri uporabi hladilno mazalne tekočine (Emulzin H z 2-odstotno koncentracijo), pregl. 3. Nadalje, vrednosti porazdelitvenih razmerij so mnogo nižje pri brusih CBN in diamantnih brusih ter pri uporabi hladilno mazalne tekočine, pregl. 4. Titanova zlitina se oprime brusnih zrn in tako ustvari močno oviro za prenos toplote (predvsem pri uporabi brusov CBN in diamantnih brusov, zaradi njihove mnogo večje termične prevodnosti v primerjavi z brusom iz Al_2O_3). Hladilno mazalna tekočina ustvari film na brusnih zrnih in tako prepreči močno adhezijo titanove zlitine.

results in extremely high temperatures at the interface between the wheel and the workpiece.

On the basis of the experimental results it is possible to say that a small portion of energy enters the grinding wheel when grinding hardened steel. On the other hand, about 65% of the heat is entering the grinding wheel when grinding the titanium alloy. The high mechanical and thermal load of the grains when grinding the titanium alloy leads to a high grain-wear rate and strong adhesion between the machined material and the cutting grain [9]. The maximum temperature rise for the titanium alloy is much higher than that of the roll-bearing steel, although the net energy input for the titanium alloy is lower than for the hardened steel. This is because the thermal conductivity of the titanium alloy is much smaller than that of the hardened steel (the concentration of heat in the contact of the grinding wheel and the workpiece when grinding the titanium alloy).

The results of the next experiments show that the use of diamond and CBN grinding wheels reduces the tendency to induce thermal damage to the ground surfaces of parts made from the VT 9 titanium alloy. The surface temperatures for the CBN and diamond grinding wheels, measured with the same technique, are significantly lower than those measured for Al_2O_3, primarily when applying cutting fluid (Emulzin H 2 % concentration), Table 3. Next, the values of the partitioning ratios are much lower with CBN and diamond grinding and the use of cutting fluid, Table 4. Titanium alloy adheres to the grinding grains and so creates a strong barrier against heat transfer (mainly when using CBN and diamond grinding wheels, because of their much higher thermal conductivity in comparison with an Al_2O_3 grinding wheel). The cutting fluid creates a film on the grinding grains and so eliminates the strong adhesion of titanium alloy.

Preglednica 3. *Vpliv hladilno mazalne tekočine (Emulzin H - 2 % koncentracijo) na temperaturo na stiku brusa in obdelovanca,* $v_c = 25$ *m/s,* $v_w = 4$ *m/min,* $a_p = 0{,}02$ *mm*

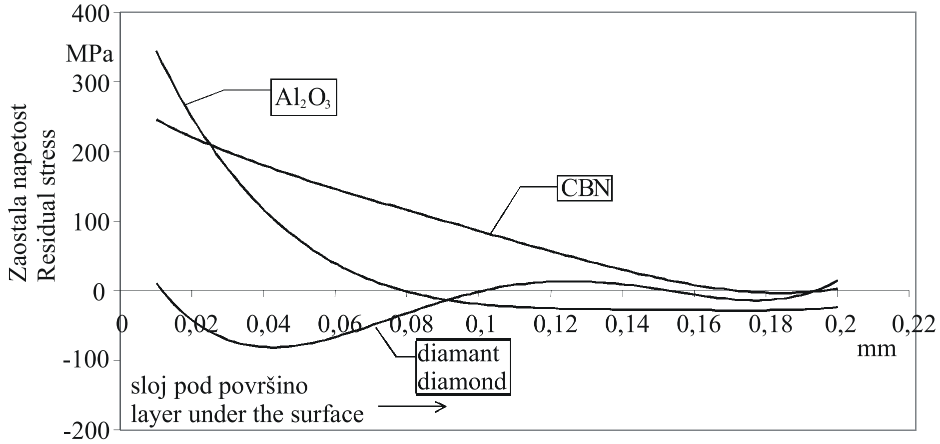
Table 3. *The influence of cutting fluid (Emulzin H – 2 % concentration) on the temperature in the contact of the grinding wheel and the workpiece,* $v_c = 25$ *m/s,* $v_w = 4$ *m/min,* $a_p = 0.02$ *mm*

	Al_2O_3 °C		CBN °C		Diamant / Diamond °C	
	suho / dry	Emulzin H	suho / dry	Emulzin H	suho / dry	Emulzin H
14 209.4	455	275	300	180	222	167
VT 9	695	580	610	235	340	180

Preglednica 4. *Vpliv hladilno-mazalne tekočine (Emulzin H - 2 % koncentracijo) na razmerje porazdelitve* R_w, $v_c = 25$ *m/s,* $v_w = 4$ *m/min,* $a_p = 0{,}02$ *mm*

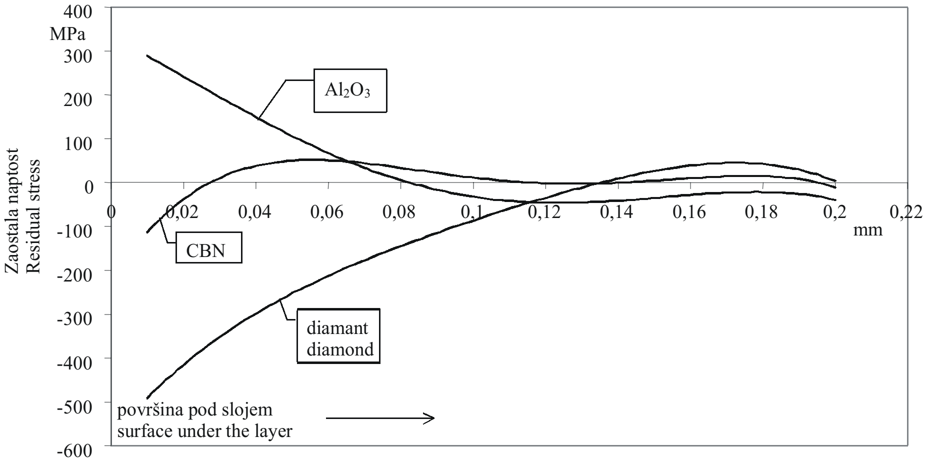
Table 4. *Influence of cutting fluid (Emulzin H – 2 % concentration) on the partitioning ratio* R_w, $v_c = 25$ *m/s,* $v_w = 4$ *m/min,* $a_p = 0.02$ *mm*

	Al_2O_3 %		CBN %		Diamant / Diamond %	
	suho / dry	Emulzin H	suho / dry	Emulzin H	suho / dry	Emulzin H
14 209.4	88	68	77	48	64	48
VT 9	40	38	33	12	29	19



Sl. 6. *Zaostale napetosti po brušenju titanove zlitine VT 9 brez uporabe hladilno mazalne tekočine,* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0,02 mm*

Fig. 6. *Residual stresses after grinding the VT 9 titanium alloy without cutting fluid,* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0.02 mm*



Sl. 7. *Zaostale napetosti po brušenju titanove zlitine VT 9 z uporabo hladilno mazalne tekočine (Emulzin H - 2 % koncentracijo),* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0,02 mm*

Fig. 7. *Residual stresses after grinding the VT 9 titanium alloy with cutting fluid (Emulzin H – 2 % concentration),* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0.02 mm*

Zmanjšanje termične obremenitve brušenega dela znatno vpliva na njegovo kakovost, ki jo predstavljajo zaostale napetosti (sl. 6 in 7).

Rezultati merjenja zaostalih napetosti kažejo, da obstaja močna zveza med razmerjem porazdelitve R_w in zaostalimi napetostmi. Tlačne zaostale napetosti so postale bolj verjetne pri nižjih vrednostih razmerja porazdelitve R_w (manjši delež energije vstopi v obdelovanec). Tako brušenje titanove zlitine VT 9 z brusi CBN in diamantnimi brusi ter z uporabo hladilno-mazalne tekočine omogoča, da dosežemo sprejemljive zaostale napetosti. Po drugi strani pa visoki stroški brusov CBN in diamantnih brusov omejujejo njihovo uporabo. Čeprav temperatura površine ne sme presegati delovne temperature, pri delih iz titanovih zlitin, lahko imajo natezne zaostale napetosti, ki jih povzroči ta temperatura, za posledico znatno nižjo utrujenostno trdnost zaradi poškodb površine.

Reducing the thermal load on the ground part significantly influences their quality, represented by residual stresses, Fig. 6 and Fig. 7.

Results of the measurement of residual stresses show that there is a strong correlation between the partition ratio, R_w, and the residual stresses. Compressive residual stresses become more likely with lower values of partition ratio (smaller proportion of the energy entering the workpiece). And so CBN and diamond grinding of the VT 9 titanium alloy with cutting fluid enables us to achieve acceptable residual stresses. On the other hand, the high costs of CBN and diamond grinding wheels limit their application. Even though the surface temperature must not exceed the working temperature for the parts made of titanium alloys, the tensile residual stresses induced at this temperature can result in an appreciably lower fatigue strength due to the surface damage.

Zaradi tega se dandanes nagibamo k temu, da se vključi dodaten postopek mehanskega utrjevanja brušenih površin pri vseh delih v letalski in vesoljski industriji.

For these reasons there is a current tendency to include an additional operation of mechanically hardening the ground surfaces of all the parts made for the aerospace and space industries.

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Osebne vesti

Personal Events

Zoisova nagrada

Zoisovo nagrado za vrhunske znanstvene dosežke na področju strojništva je prejel

Prof.dr. Jože Vižintin

Jože Vižintin, redni profesor na Fakulteti za strojništvo Univerze v Ljubljani, je vodilni slovenski strokovnjak na področju tribologije. Z dolgoletnim znanstveno-raziskovalnim, razvojnim in strokovnim delom si je pridobil velik ugled doma in v tujini. Njegove raziskave so posvečene predvsem vprašanjem utrujanja materiala pri majhnih amplitudah in velikih frekvencah ter vprašanjem uporabe trdih prevlek za strojne elemente. Na teh področjih je profesor Vižintin skupaj s sodelavci v zadnjih sedmih letih objavil 51 izvirnih znanstvenih del, od tega 31 v revijah, ki jih citira SCI, in 20 v drugih revijah, ki jih priznava stroka kot pomembne. O mednarodni odmevnosti njegovih del pričajo citati v bazi SCI.

Najodmevnejše rezultate je profesor Vižintin s sodelavci dosegel pri določanju trenutne temperature v tornem stiku. Dokazal je, da te temperature dosegajo 1000 stopinj Celzija in več in so določujoče za nastanek poškodb. Pravilnost te ugotovitve, ki je bila v nasprotju s splošnim prepričanjem, da trenutna temperatura v tornih stikih ne presega 100 stopinj Celzija, so potrdili zadnji citati tujih raziskovalcev.

Značilno za profesorja Vižintina je, da skrbi tudi za prenos svojih temeljnih in uporabnih raziskav v prakso, predvsem z razvojem novih izdelkov za industrijo. V zadnjih sedmih letih ima dva patenta v Sloveniji in dve patentni prijavi v ZDA. V raziskovalno delo vključuje mlade raziskovalce in sodelavce iz drugih ustanov ter s sodelovanjem s tujimi ustanovami uveljavlja slovensko znanje. Med drugim je ustanovil prvi Tribološki laboratorij v Sloveniji, ki je pozneje prerasel v Center za tribologijo in tehnično diagnostiko. Pomemben je bil njegov prispevek pri ustanovitvi Evropskega virtualnega tribološkega inštituta.

Profesor Vižintin je celovita osebnost, ki je z izvirnimi raziskovalnimi dosežki prispeval k razvoju tribologije v svetovnem merilu, obenem pa je s svojim razvojnim in strokovnim delom odločilno vplival na razvoj te stroke v Sloveniji.

Doktorati, magisteriji, specializacije, diplome

DOKTORATI

Na Fakulteti za strojništvo Univerze v Ljubljani sta z uspehom zagovarjala svoji doktorski disertaciji,:

dne 29. oktobra 2002: **mag. Simon Strgar**, z naslovom “Optodinamski opis in novi načini laserskega označevanja” in **mag. Marjan Gantar**, z naslovom “Tokovne razmere v stranskih prostorih rotorjev pri hidravličnih turbostrojih in njihov vpliv na aksialne obremenitve”.

S tem sta navedena kandidata dosegla akademsko stopnjo doktorja tehničnih znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Mariboru je *dne 10. oktobra 2002* **Zvonko Kremljak** z uspehom zagovarjal svoje magistrsko delo z naslovom: “Povezava livarskega in obdelovalnega sistema s povečanimi sinergijskimi učinki”.

S tem je navedeni kandidat dosegel akademsko stopnjo magistra tehničnih znanosti.

SPECIALIZACIJE

Na Fakulteti za strojništvo Univerze v Mariboru sta z uspehom zagovarjala svoji specialistični deli:

dne 11. oktobra 2002: **Jernej Tahirović**, z naslovom “Načrtovanje in vodenje zagotavljanja nemotene proizvodnje” in **Rolando Koren**, z naslovom “Humanizacija dela na liniji sestave vrat hladilnih naprav”.

S tem sta navedena kandidata dosegla akademsko stopnjo specialista.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne 1. oktobra 2002: Martin DEŽELAK, Mihael DOBNIKAR, Boštjan GUŠTIN, Andrej PUNGERČIČ in Primož ŽAGAR.

*

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv diplomirani inženir strojništva:

dne 10. oktobra 2002: Roman KIRN, Breda LUKANEC, Boštjan PERDAN, Jurij REPIČ in Blaž WEBER;

dne 11. oktobra 2002: Štefan ANČIMER, Damjan GLINŠEK, Gregor ISTENIČ, Andrej JEJČIČ, Tomaž MEDVED, Alojzij PRAH, Sebastjan STERNAD in Marjan ŽULIČ;

dne 14. oktobra 2002: Gregor ANDROJNA, Iztok ČUFER, Primož GOSTINČAR, Tomaž MUNIH, Andreja PENKO, Janez ZUPAN in Samo ŽVEGLA.

Na Fakulteti za strojništvo Univerze v Mariboru je pridobil naziv diplomirani inženir strojništva:

dne 24. oktobra 2002: Igor SVEČKO.

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Navodila avtorjem

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Instructions for Authors

Navodila avtorjem

Instructions for Authors

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.

Vsebina članka

Članek naj bo napisan v naslednji obliki:

- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- 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].

Oblika članka

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

Enote in okrajšave

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

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

Papers submitted for publication should comprise:

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

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

The format of the paper

The paper should be written in the following format:

- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a miniversion of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

The layout of the text

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

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

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

Units and abbreviations

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

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

Slike

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

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

Vse označbe na slikah morajo biti dvojezične.

Za vse slike po fotografskih posnetkih je treba priložiti izvirne fotografije ali kakovostno narejen posnetek. V izjemnih primerih so lahko slike tudi barvne.

Preglednice

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

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

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

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

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

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

Podatki o avtorjih

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

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Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

Rokopisi člankov ostanejo v arhivu SV.

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Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Figures may be saved in any common format, e.g. BMP, GIF, JPG. However, the use of CDR format (CorelDraw) is recommended for graphs and line drawings, since vector images can be easily reduced or enlarged during final processing of the paper.

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

All figure captions must be bilingual.

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

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in Italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

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

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

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

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

Author information

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

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The Editorial Committee of the Journal of Mechanical Engineering reserves the right to decide whether a paper is acceptable for publication, obtain professional reviews for submitted papers, and if necessary, require changes to the content, length or language.

Authors must also enclose a written statement that the paper is original unpublished work, and not under consideration for publication elsewhere. On publication, copyright for the paper shall pass to the Journal of Mechanical Engineering. The JME must be stated as a source in all later publications.

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