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Preprečevanje izločanja vodnega kamna na površinah prenosnikov toplote z uporabo naprave za magnetno obdelavo vode

The Preventation of Surface Precipitation on Heat Exchangers Using a Magnetic Water-Treatment Device

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V nalogi predstavljamo metodo za nadzor vodnega kamna na temelju magnetne obdelave vode (MOV) v prenosnikih toplote.

Podali smo teoretičen pregled tvorbe kotlovca pri industrijskih prenosnikih toplote s poudarkom na obarjanju kalcijevega karbonata ($CaCO_3$) in kalcijevega sulfata ($CaSO_4$) ter osnovne izračune za uspešno uporabo naprav MOV pri preprečevanju nastajanja vodnega kamna.

(Ključne besede: prenosniki toplote, zaščita proti kotlovcu, magnetna obdelava vode, magnetohidrodinamika)

Magnetic water treatment (MWT), a water-conditioning method for scale control in heat exchangers (HEs), is discussed.

The theoretical possibilities of scale formation in industrial processes with the emphasis on the precipitation of $CaCO_3$ and $CaSO_4$ as the main scale components, are reviewed. Some preliminary calculations for a theoretical understanding of the scale problem in HEs and its prevention using MWTs are contributed.

(Keywords: heat exchangers, scale control, magnetic water treatment, magnetohydrodynamic)

0 UVOD

Problem izločanja vodnega kamna se pojavlja pri vseh tehnoloških procesih, ki uporabljajo naravno vodo. To pa še posebej velja v primeru uporabe prenosnika toplote, pri katerem pride do povišanja temperature in posledično do prenasičenja soli, ki tvorijo vodni kamen (predvsem $CaCO_3$ in $CaSO_4$). Obstaja več dobro znanih in uporabnih metod za preprečevanje nastajanja vodnega kamna. Uporaba nekaterih pomeni velik finančni strošek, druge pa onesnažujejo okolje. V zadnjih letih se kot alternativa kemičnim metodam vedno bolj uveljavlja t.i. magnetna obdelava vode (MOV).

Čeprav je metoda znana že petdeset let in z ekonomskega in okoljevarstvenega vidika zelo sprejemljiva, prav procesna industrija še naprej dvomi o njeni učinkovitosti in uporabi ([1] do [4]).

1 NASTANEK VODNEGA KAMNA

Naravna voda je dejansko bogata raztopina/disperzija mnogih ionov: Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-} in Cl^-. Ioni Na^+, K^+ in Cl^- so inertni, preostali pa so vključeni v t.i. medfazno ravnotežje. Zaradi

0 INTRODUCTION

The build-up of scale deposits is a common and costly problem in many industrial processes which use natural water supplies, especially in heat-exchange processes, where a high oversaturation of scale-forming components (i.e. $CaCO_3$ and $CaSO_4$) is established. There are many well-known scale-prevention methods, but they are costly and environmentally unfriendly. MWT is being used more and more as an alternative method for scale control.

The process industry remains skeptical about this non-chemical method despite its long history and examples of favorable economic benefits ([1] to [4]).

1 SCALE FORMATION

Natural waters are rich solution/dispersion systems which contain the ions: Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-} and Cl^-. The Na^+, K^+ and Cl^- ions are inert, while the others are incorporated into an intersprememb obratovalnih razmer (sprememba tlaka, temperature, vrednosti pH) pride do prenasičenja in soli se v obliki vodnega kamna izločajo na stene cevi, prenosnikov toplote in drugih naprav, ki so v stiku z vodo.

phase equilibrium. Due to the natural supersaturation of the supplied water or supersaturating due to changed operating conditions (such as a pressure drop, temperature or pH increase) hard scale precipitates in pipelines and on the walls of equipment.

Najpomembnejši parameter za nadzor vodnega kamna je delež kalcijevih ionov Ca^{2+}. Določimo ga s pomočjo t.i. karbonatnega ravnotežja ((1) do (4)). Parametra (c) in (K) pomenita koncentracijo in konstanto ravnotežja.

The most important parameter in scale control is the concentration of Ca^{2+} ions, determined by carbonate equilibrium ((1) to (4)), where the parameter c is the concentration and parameters K is the equilibrium constant.

$$CO_{2(g)} + H_2O \leftrightarrow H_2CO_3, \qquad K_g = \frac{c_{H_2CO_3}}{p_{CO_2}} \tag{1}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-, \qquad K_1 = \frac{c_{HCO_3^-} \cdot c_{H^+}}{c_{H_2CO_3}} \tag{2}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}, \qquad K_2 = \frac{c_{H^+} \cdot c_{CO_3^{2-}}}{c_{HCO_3^-}} \tag{3}$$

$$CaCO_{3(s)} \leftrightarrow Ca^{2+} + CO_3^{2-}, \qquad K_s = \mathrm{c}_{Ca^{2+}} \cdot \mathrm{c}_{CO_3^{2-}} \qquad (4).$$

Iz pogoja o električni nevtralnosti (5) in z upoštevanjem ionskega produkta vode (6) lahko izpeljemo odvisnost koncentracije kalcijevih (Ca^{2+}) ionov kot funkcije vrednosti pH in temperature.

From the condition of the solution's electric neutrality (5) and the water dissociation equilibrium (6), the concentration of Ca^{2+} ions can be derived as a function of pH and temperature.

$$2c_{Ca^{2+}} + c_{H^+} = 2c_{CO_3^{2-}} + c_{HCO_3^-} + c_{OH^-} \tag{5}$$

$$H_2O \leftrightarrow H^+ + OH^- \qquad K_w = c_{H^+} \cdot c_{OH^-} \tag{6}$$

$$c_{Ca^{2+}} = \frac{K_W - c_{H^+}^2 + \left[\left(c_{H^+}^2 - K_W\right)^2 + 8c_{H^+}^2 \cdot K_s\left(2 + \frac{c_{H^+}}{K_2}\right)\right]^{1/2}}{4c_{H^+}} \qquad (7).$$

Konstante ravnotežja so odvisne od temperature (7). V naravnih vodah (pH < 7) vodi zvišanje temperature in vrednosti pH do znižanja ravnotežne koncentracije Ca^{2+} ionov (7). Pri znižanju tlaka pride do znižanja koncentracije H_2CO_3 (1) in posledično s povečevanjem vrednosti pH pospešeno obarjanje $CaCO_3$ ((2) do (4) in (7)).

The equilibrium constants in equation (7) are temperature dependent. In natural waters (with a pH less than 7), a rise in temperature and pH leads to a reduction of the Ca^{2+} equilibrium concentration according to equation (7). The pressure drop leads to a lower concentration of H_2CO_3 according to equation (1) and causes $CaCO_3$ precipitation with a pH increase according to eqs. ((2) to (4) and (7)).

S temperaturo (do 40 °C) se zvečuje topnost $CaSO_4$, pri višjih temperaturah (okoli 100 °C) pa naglo zmanjšuje. Iz opisanega je razvidno, da se bo v nizkotemperaturnih sistemih v glavnem izločal kalcijev karbonat ($CaCO_3$) in v visokotemperaturnih sistemih (toplovodi, uparjalniki, prenosniki toplote) pa kalcijev sulfat ($CaSO_4$).

The solubility of $CaSO_4$ increases as the temperature increases to approximately 40°C and then rapidly decreases at higher temperatures around 100°C. As a result, $CaCO_3$ is the main scale component in low-temperature water systems, while in high-temperature water systems (especially in high-pressure heat exchangers and boilers) $CaSO_4$ prevails.

2 ZMANJŠANJE UČINKOVITOSTI PRENOSA TOPLOTE

2 HEAT EXCHANGE REDUCTION

Obloge vodnega kamna, ki nastanejo na površinah prenosov toplote, zmanjšujejo pretočne zmogljivosti in predvsem učinkovitost prenosnikov toplote ter s tem zvišujejo investicijske, obratovalne in vzdrževalne stroške. Brez primerne obdelave napajalne

The scale formed on heated surfaces reduces the flow capacity and heat exchange efficiency which leads to higher investment, operation and maintenance costs. Hard scale can be a severe industrial problem without properly supplied water condition-vode so tako nastale trdovratne obloge težak industrijski problem; terjajo periodično čiščenje z mehanskimi postopki in jedkanjem s solno kislino.

Naslednja ocena bo pokazala, kako vodni kamen izrazito znižuje prenos toplote.

Moč toplotnega toka P_1 skozi kovinsko steno površine S_{stene} pri temperaturni razliki ΔT je za nov prenosnik (sl. 1.a) določena z enačbo (8). Prestopnostni koeficient α_1 je tu praktično enak konvekcijskemu koeficientu plasti vode na obeh straneh stene. Konvekcijski koeficient kovine je namreč bistveno višji kakor za vodo

ing. It demands periodic cleaning using mechanical methods and HCl etching.

The following preliminary calculations show how scale drastically reduces the exchange of heat.

With a new wall of a HE (Fig. 1/a), the heat-flow intensity (P_1) through the metallic wall of area S at a temperature difference ΔT is determined by equation (8), where the heat transition coefficient (α_1) is practically equal to the convection coefficient of the water layer on both sides of the wall due to the much higher value of the heat-conduction coefficient of the metal

$$P_1 = \alpha_1 \cdot S \cdot \Delta T \qquad (8).$$

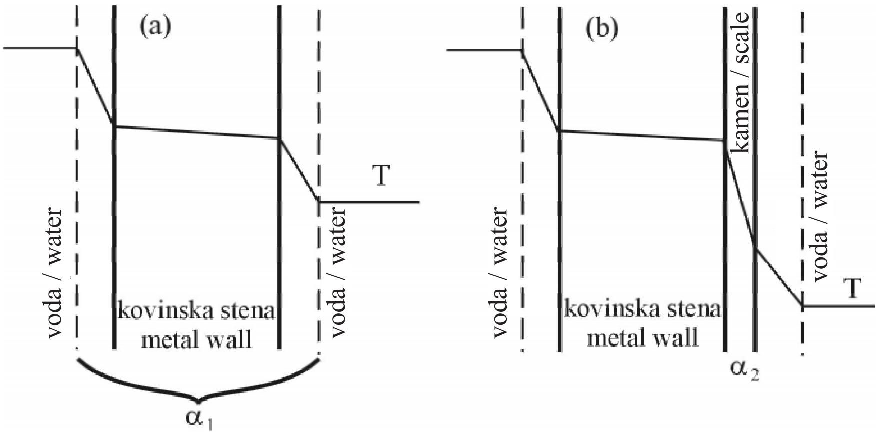
Obloge vodnega kamna (sl. 1.b) znižujejo moč toplotnega toka P' in je ta določen z enačbo (9). Tukaj se lahko celokupni prestopnostni koeficient α' izračuna iz α_1 nove stene in α_2 nastalih oblog po enačbi (10). Velja za postavko iste temperaturne razlike med ogrevano in hladilno vodo $\Delta T = \Delta T_1 + \Delta T_2$. Koeficient α_2 je odvisen od celotne debeline oblog Δy_2 po zvezi (11), kjer je λ_2 toplotna prevodnost vodnega kamna.

The formation of scale (Fig. 1/b) reduces the heat flow intensity (P') according to equation (9), where the total heat-transition coefficient (α') can be calculated using α_1 of the new wall and α_2 of the formed scale according to equation (10) at the same temperature difference $\Delta T = \Delta T_1 + \Delta T_2$. The coefficient α_2 depends on the total scale lining thickness (Δy_2) according to equation (11), where λ_2 is the heat conductivity of the scale.

$$P' = \alpha' \cdot S \cdot \Delta T = \alpha_1 \cdot S \cdot \Delta T_1 = \alpha_2 \cdot S \cdot \Delta T_2 \qquad (9)$$

$$\alpha' = \frac{1}{1/\alpha_1 + 1/\alpha_2} \qquad (10)$$

$$\alpha_2 = \frac{\lambda_2}{\Delta y_2} \qquad (11).$$



Sl. 1. *Temperaturni krivulji skozi: (a) novo kovinsko steno in (b) skozi kovinsko steno z oblogo vodnega kamna*

Fig. 1. *The temperature curve through a new metallic wall (a) and through a metallic wall covered with scale (b)*

Preglednica 1 prikazuje nekaj vrednotenj relativnega zmanjšanja učinkovitosti prenosa toplote ξ, ki je definirana z enačbo:

Table 1 represents some estimations for the relative drop of the heat-exchange efficiency (ζ) defined by equation:

$$\zeta = \frac{P_1 - P'}{P_1} = 1 - \frac{\alpha'}{\alpha_1} = 1 - \frac{1}{1 + \alpha_1 \Delta y_2 / \lambda_2} \qquad (12)$$

Preglednica 1. *Relativna zmanjšanja učinkovitosti prenosa toplote (pri izbrani praktični vrednosti* $\alpha_1 = 500$ *W/m^{2}K za kovinsko steno) zaradi oblog* $CaCO_3$ ($\lambda_2 = 1{,}75$ *W/mK) oziroma* $CaSO_4$ ($\lambda_2 = 0{,}50$ *W/mK)*
Table 1. *Relative drops of heat-exchange efficiency at chosen practical values* $\alpha_1 = 500$ *W/m^{2}K due to* $CaCO_3$ *lining* ($\lambda_2 = 1.75$ *W/mK) and* $CaSO_4$ *lining* ($\lambda_2 = 0.50$ *W/mK), respectively*

Δy_2	1,5 mm	5,5 mm	20 mm
$\zeta(CaCO_3)$	30%	60%	85%
$\zeta(CaSO_4)$	60%	85%	95%

Rezultati potrjujejo praktične izkušnje, da zaradi nizke toplotne prevodnosti $CaCO_3$ in $CaSO_4$, celo tanke obloge vodnega kamna izrazito zmanjšujejo učinkovitost prenosa toplote. V visokotlačnih grelnih napravah je ta problem še posebej močno izražen, saj se v večinskem deležu izloča kalcijev sulfat, ki ima manjšo toplotno prevodnost od kalcijevega karbonata.

V mnogih primerih se je izkazalo, da omogočajo naprave za magnetno obdelavo vode razmeroma učinkovit sistem za nadzor vodnega kamna. Eden od uspešnih preskusov naprav MOV domačega proizvajalca Panorama Ptuj [6] pomeni vgradnja le-teh v prenosnik toplote Toplotne oskrbe Maribor (TOM) [5].

Naprave so bile instalirane na ceveh s hladno napajalno vodo in so učinkovito preprečile nastanek vodnega kamna. V preglednici 2 sta predstavljena rezultata vgradnje naprav za magnetno obdelavo v prenosnika toplote.

Results prove that even thin scale linings drastically reduce the heat-exchange efficiency because of the low heat of conductivity of the scale components $CaCO_3$ and $CaSO_4$. In high-pressure boilers the problem will be even greater due to the main scale component, $CaSO_4$, which has a lower heat of conductivity than $CaCO_3$.

These theoretical predictions are in accordance with many practical results, where scale formation on HE surfaces demanded a preliminary treatment of the supplied water. In many cases MWT turned out to be a very efficient method for scale control. The installation of MWT devices to prevent hard scale in the HEs in the TOM town heating station [5] was one of the successful domestic tests of the Panorama Ptuj magnetic device [6].

These devices were installed on the cold water pipeline entrance of the HE and efficiently solved any problems with hard scale. Table 2 represents some observations on the scale in the two HEs which were supplied with magnetic ally treated water.

Preglednica 2. *Rezultati naprave za magnetno obdelavo proizvajalca Panorama Ptuj v toplotni postaji TOM-a*
Table 2. *Results of Panorama Ptuj devices in the TOM station*

Prenosnik toplote HE	star cevni register U old U-pipe register	nov spiralni register new spiral register
obloge ob vgradnji scale at MWT installation	da yes	ne none
prvi pregled time of the first control	8 mesecev po vgradnji 8 months after installation	11 mesecev po vgradnji 11 months after installation
stanje po prvem pregledu state after the first control	obloge, odstranitev z vodnim visokotlačnim curkom present scale was removable with high-pressure water jet	tanke plastne obloge, odstranitev z vodnim visokotlačnim curkom thin powder scale was removed with jet
drugi pregled time of the second control	16 mesecev po vgradnji 16 months after installation	17 mesecev po vgradnji 17 months after installation
stanje ob drugem pregledu state after the second control	oblog ni bilo,površina je bila veliko bolj čista kakor pred samo vgradnjo without a new scale, surfaces were cleaner than before the installation time	enako kakor pri prvem pregledu the same as at the first control

3 NADZOR VODNEGA KAMNA V PRENOSNIKIH TOPLOTE

V naravni vodi, bogati z raztopljenimi/dispergiranimi snovmi, delujejo naprave za magnetno obdelavo vode neposredno na samo stabilnost in

3 THEORETICAL PRINCIPLES OF MWT SCALE PREVENTION ON HE SURFACES

The nature of MWT devices acting on supplied water as a rich solution/dispersion system is to alter its crystallization habits and dispersion stability to form kristalizacijo dispergiranih delcev. Kristali, ki se izločajo po obdelavi, so večji in modificirani. Prav na teh kristalih se neposredno iz vode izloči večji del soli, tako da se na stenah naprav nabere neprimerno manj vodnega kamna.

Ob pretakanju vode skozi napravo za magnetno obdelavo prihaja do sprememb, ki pa se izražajo (najverjetneje) v spremenjeni ionski hidrataciji prek magnetohidrodinamičnega premika ionov in koncentracijskega vpliva na dispergirane delce v sami napravi MOV [7].

Izračuni kažejo, da se med magnetno obdelavo vode agregatne tvorbe, sestavljene iz $CaCO_3$ in $CaSO_4$ trdno sprimejo. Iz samega načela staranja kristalov namreč kosmiči, v katerih so delci med seboj šibko povezani, niso tako zaželeni kakor goste agregatne tvorbe [8].

Po teoriji DLVO (Deryagin, Landau, Verwey, Overbeck) ([9] in [10]) smo opravili numerično analizo koagulacije in kosmičenja nemagnetnih delcev vodnega kamna in prišli do sklepa, da v naravnih vodah prevladuje koagulacija, ki je odvisna od same naprave MWT, medtem ko je zaradi nizke vrednosti Hamakerjeve konstante in nizke magnetne susceptibilnosti pri večjih delcih ($a > 0,1$ μm) mogoča le kosmičenje.

Po drugi strani pa se bodo magnetohidrodinamično nastali kosmiči pod vplivom turbulentne pulzacije razbile. Do pulzacije prihaja v večini naprav MOV, kjer je priporočena pretočna hitrost od 0,5 do 2 m/s.

Ob preseženi vrednost Reynoldsovega števila (10^4) imamo opraviti s turbulentnim tokom

bigger modified crystals, which in suspended form offer surfaces for scale precipitation and in that way hard scale formation indirectly prevails on equipment walls.

The change in the water's behaviour when the water flows through the magnetic field is most probably a result of altered ion hydration, by magnetohydrodynamic shifts of ions and concentration effects on the dispersed particles in the working channel of the MWT device [7].

Some calculations have been made showing that all aggregates, formed from scale components ($CaCO_3$ and $CaSO_4$) during MWT, are compact-strongly adhered. In other words, the flocks in which constituent particles are weakly bonded are not as favorable for scale prevention as the compact aggregates according to the principles of crystal aging [8].

A numerical analysis of the coagulation and flocculation of the nonmagnetic scale components, based on the Deryagin, Landau, Verwey, Overbeck theory ([9] and [10]), has been made. It offered an estimation that in natural waters only flocculation from big particles (with radius $a > 0,1$ μm) is possible due to the low Hamaker constant and low magnetic susceptibility of these components, while a coagulation prevails and depends on the MWT working conditions.

On the other hand, the magnetohydrodynamically formed big flocks will be shattered by turbulent pulsations which appear in the majority of practical MWT devices, where the recommended values of water flow velocity are in range from 0.5 to 2 m/s for efficient anti-scale treatment.

The Reynolds number Re, defined by equation (13), characterizes turbulent flow, if it is greater than 10^4

$$\mathrm{Re} = \frac{\rho \cdot v \cdot d}{\eta} \tag{13}$$

Parametra η in ρ pomenita viskoznost in gostoto vode. Pri pretočni hitrosti 0,5 m/s je kritična velikost delovnega preseka znotraj naprave MOV 2 cm in pri 2 m/s pa 0,5 cm.

Iz pulzacijske teorije [11] smo za izračun pulzacijske dolžine (b) in pulzacije delcev(v_b) s polmerom (a) izpeljali sistem enačb:

The parameter η is the viscosity and ρ is the mass density of water. For a water flow of velocity 0.5 m/s, the critical thickness of the working channel (d) is 2 cm, and for 2 m/s, the critical thickness is 0.5 cm.

From the turbulent pulsations theory [11], the equation system was obtained for the evaluation of the pulsation length (b) and the pulsation for a particle with radius a (v_b).

$$b = 207d\,\frac{\log \mathrm{Re}/7}{\mathrm{Re}^{7/4}} \tag{14}$$

$$v_{\mathrm{b}} = 0,17v\left(\frac{\mathrm{b}}{\mathrm{a}}\right)^{1/3}\mathrm{Re}^{1/4} \tag{15}$$

Stabilni kosmič z $10\mathrm{k_B}T$ vezno energijo med delci ($\mathrm{k_B}$ je Boltzmannova konstanta) lahko razbijemo s turbulentno pulzacijo samo, če je gostota kinetične energije $\rho v_b^2/2$ večja od gostote vezne energije $10\mathrm{k_B}T/(4\pi a^3/3)$. Določimo lahko t.i. kritični polmer kristalnega delca (a^*):

A stable flock with a $10\mathrm{k_B}T$ bonding energy between constituent particles ($\mathrm{k_B}$ is the Boltzmann constant) would be shattered by turbulent pulsation, if the kinetic energy density $\rho v_b^2/2$ were greater than the bonding energy density $10\mathrm{k_B}T/(4\pi a^3/3)$. A crystal particle radius is therefore:

$$a^{*} = \sqrt[3]{15\mathrm{k_B}T / \pi\rho v_{\mathrm{b}}^{2}} \qquad (16).$$

Tako je pri $v = 0{,}5$ m/s kritični polmer 0,25 μm in 0,13 μm pri $v = 2$ m/s. Povzamemo lahko, da bo za priporočene pretočne hitrosti proizvajalcev naprav MOV turbulenca razbila $CaCO_3$ in $CaSO_4$ kosmiče. V suspendirani obliki bodo ostali le najbolj močno vezani agregati.

V primerjavi s kemijskimi metodami priprave vode za nadzor vodnega kamna je magnetna obdelava še najbolj podobna suspendiranju kristalnega prahu.

Naslednji izračuni določajo potrebno količino prahu za preprečevanje izločanja $CaCO_3$ na stenah prenosnikov toplote z relativno površino $S_{\mathrm{HE}} = S_{\mathrm{stene}}/V_{\mathrm{vode}}$, kjer sta S_{stene} površina sten in V_{vode} prostornina vode.

Da bi se zagotovil hiter prenos toplote, so v skladu z enačbo (17) [12] priporočane visoke vrednosti S_{HE}, in sicer med 100 in 1000 /m.

The critical radius a^* is 0.25 μm for a water flow of velocity $v = 0.5$ m/s and a^* is 0.13 μm for $v = 2$ m/s. A theoretical conclusion could be made for all recommended ranges of water flow velocity that turbulence will deaggregate $CaCO_3$ and $CaSO_4$ flocks. Only highly adhered aggregates will remain in a suspended form.

In a comparison with chemical scale-prevention methods, the suspending of crystal powder is the most similar to the MWT method.

The following calculation estimates that the necessary amount of powder for the prevention of $CaCO_3$ precipitation on the walls of a HE with a relative surface: $S_{\mathrm{HE}} = S_{\mathrm{wall}}/V_{\mathrm{water}}$, where S_{wall} is the area and V_{water} is the water volume.

To ensure a quick heat exchange, high values of S_{SE} from 100 to 1000 /m are recommended according to equation (17) [12].

$$\frac{dT}{dt} = \frac{\alpha}{c_{\mathrm{p}}\rho}\Delta T S_{\mathrm{HE}} \qquad (17).$$

V enačbi (18) je iz kvocienta ξ oborjene mase v jedru vode (dm_{v}) in mase na stenah (dm_{s}) razvidno, da se bo vodni kamen nalagal v tanjših oblogah pri nižjih vrednostih S_{HE}.

In this relationship for the heating rate dT/dt, the parameter c_{p} is the heat capacity of water. A thinner scale lining will be formed at lower values S_{HE}, as can be predicted from the ξ-quotient (of precipitated mass in the bulk of water-dm_{v} and precipitated mass on the walls - dm_{s}) in equation (18). So, the optimal value S_{HE} in HE designing should be found.

$$\xi = \frac{dm_{\mathrm{v}}}{dm_{\mathrm{s}}} = \frac{r_{\mathrm{v}}V_{\mathrm{water}}}{r_{\mathrm{s}}S_{\mathrm{wall}}} = \frac{r_{\mathrm{v}}}{r_{\mathrm{s}}S_{\mathrm{HE}}} \qquad (18).$$

V modificirani obliki sta enačbe za hitrost kristalne rasti (r) določila Nancollas in Reddy [13], in sicer na podlagi obarjanja iz jedra raztopine s temperaturo T_1 na površino naprav s temperaturo T_2 ((19) in (20)). Pri tem velja, da je parameter k določen empirično, $M_{\mathrm{CaCO_3}}$ je relativna molska masa kalcijevega karbonata in R splošna plinska konstanta.

The relationship of crystal growth rate r has been determined by Nancollas and Reddy [13] and is represented by equations (19) and (20) in a modified form for precipitation in the bulk of a solution with temperature T_1 and on the equipment walls with temperature T_2, where k is an empirical parameter, $M_{\mathrm{CaCO_3}}$ is the relative molecular mass of $CaCO_3$ and R is the universal gas constant.

$$r_{\mathrm{v}} = kM_{\mathrm{CaCO_3}}\exp\left(\frac{-\Delta G_1}{\mathrm{R}T_1}\right)S_{\mathrm{powder}}\beta_1 \qquad (19)$$

$$r_{\mathrm{s}}S_{\mathrm{HE}} = kM_{\mathrm{CaCO_3}}\exp\left(\frac{-\Delta G_2}{\mathrm{R}T_2}\right)S_{\mathrm{wall}}\beta_2 \qquad (20)$$

$$\beta = c_{\mathrm{Ca^{2+}}}\cdot c_{\mathrm{CO_3^{2-}}} - K_{\mathrm{s}} \qquad (21)$$

Kristalna rast je odvisna od sestave raztopine in trdnine:

- stopnje prenasičenja β, ki je ob stenah prenosnikov toplote (β_2) višje kakor v jedru raztopine (β_1), in od
- aktivacijske energije ΔG, ki je odvisna od kristalne faze.

V primeru obarjanja $CaCO_3$ sta kristalni fazi kalcit in aragonit. V suspendiranem prahu, nastalem z magnetno obdelavo, je opažen povečan delež

The crystal growth rate depends on solution and solid phase composition by:

- β supersaturation degree (defined by 21), which is higher at the HE walls (β_2) than in the bulk of solution (β_1);
- ΔG activation energy depending on crystal phase.

In the case of $CaCO_3$ precipitation, crystal phases aragonite and calcite are formed. A powder, formed from magnetically treated water, has an increased aragonita. Za hipotetični primer vzamemo vrednost ΔG_1 za aragonit in vrednost ΔG_2 za kalcit.

Z zamenjavo r_v in $r_s S_{HE}$ v enačbi (18) z izrazoma (19) in (20) dobimo zvezo (22) za količino prahu, ki je potrebna za učinkovit nadzor $CaCO_3$ oblog:

fraction of aragonite. In an ideal case a ΔG_1 value could be taken for aragonite and a ΔG_2 for calcite.

With the substitution r_v and $r_s S_{HE}$ in (18) by (19) and (20), equation (22) is obtained and a necessary powder surface is estimated:

$$\frac{S_{\mathrm{powder}}}{S_{\mathrm{wall}}} = \xi\left(\frac{\beta_1}{\beta_2}\right)\exp\left(\frac{\Delta G_1}{\mathrm{R}T_1} - \frac{\Delta G_2}{\mathrm{R}T_2}\right) \tag{22}$$

Da bi se učinkovito preprečile obloge trdega vodnega kamna za temperaturno območje 40 do 100°C in za zahtevano učinkovitost, je potrebna količina prahu S_{prah} istega reda, kakor je površina sten prenosnikov toplote S_{stene}

For efficiency request $\xi \approx \beta_1/\beta_2$ and operational temperatures between 40°C and 100°C, the necessary powder surface S_{powder} should be of the same order as the surfaces of the heat exchanger walls S_{wall} to effectively prevent hard scale.

4 SKLEP

Za nadzor vodnega kamna na stenah prenosnikov toplote je potrebna optimizacija velikosti površine za prenos toplote glede na obratovalne razmere. Zraven kemičnih postopkov za zmanjšanje koncentracije Ca^{2+} ionov se priporoča uporaba naprav MOV.

Dobro načrtovana naprava MOV, ki zagotavlja zadostno količino suspendiranih delcev v obliki praška, lahko učinkovito prepreči nastanek kotlovca. Problem učinkovitega načrtovanja naprav MOV je nezadostno poznavanje samega mehanizma delovanja teh naprav. Mehanizem je zapleten in je neposredno odvisen tudi od obratovalnih razmer in sestave napajalne vode. Na srečo so na temelju empiričnih izkušenj izdelali lepo število učinkovitih naprav MOV. S tem zadovoljujejo veliko povpraševanje po tej preprosti in cenovno ugodni rešitvi za preprečevanje nastanka vodnega kamna.

4 CONCLUSION

For scale control in HEs an optimization of the heat-exchange surface area is recommended for simultaneous high heat transition and scale prevention. In addition, besides chemical methods for the reduction of the Ca^{2+} concentration, the alternative method of MWT is recommended.

A well-designed MWT device which assures the formation of a suspended scale powder with a surface area comparable to the exchange surface area can effectively prevent hard-scale formation. The problem with designing MWT devices is an insufficient theoretical understanding of the MWT mechanism. The mechanism is complex and depends directly on operational conditions and the composition of the supplied water as a solution/dispersion system. Fortunately, numerous MWT devices of different constructions have been designed on an empirical basis resulting from several decades of testing and are available to satisfy a large demand for such easy and cheap solutions to industrial scale problems.

5 OZNAKE
5 SYMBOLS

premer delca	a	m	particle radius
dolžina pulza	b	m	pulsation length
koncentracija	c	mol/L	concentration
specifična toplota	c_p	J/kgK	heat capacity
premer cevi	d	m	thickness of working channel
aktivacijska energija	ΔG	J/mol	activation energy
prva konstanta ravnotežja pri disociaciji H_2CO_3	K_1	ml/L	equilibrium constant of the first step of H_2CO_3 dissociation
druga konstanta ravnotežja pri disociaciji H_2CO_3	K_2	ml/L	equilibrium constant of the second step of H_2CO_3 dissociation
plinska konstanta ravnotežja	K_g	mol m^2/NL	gas equilibrium constant
topnostni produkt	K_s	mol^2/L^2	soluble product
ionski produkt vode	K_w	mol^2/L^2	dissociation product of water
empirična konstanta hitrosti kristalne rasti	k	1/mol m^{3}s	empirical constant of crystal growth rate
Boltzmannova konstanta	k_B	J/K	Boltzman constant
molska masa	M	kg/mol	molar mass
masa	m	kg	mass
moč toplotnega toka	P	J/s	heat flow intensity
tlak	p	N/m^2	gas pressure

splošna plinska konstanta	R	J/molK	universal gas constant
Reynoldsovo število	Re	-	Reynolds number
hitrost kristalne rasti s raztopini	r_v	kg/m^{3}s	crystal growth rate in bulk of water
hitrost kristalne rasti na kovinskih stenah	r_s	kg/m^{2}s	crystal growth rate on walls
površina	S	m^2	surface area
absolutna temperatura	T	K	temperature
čas	t	s	time
hitrost pretoka	v	m/s	flow velocity
hitrost turbulentne pulzacije	v_b	m/s	turbulent pulsation velocity
debelina sloja vodnega kamna	Δy	m	scale thickness
koeficient toplotne prehodnosti	α	J/m^{2}sK	heat transition coefficient
stopnja prenasičenja	β	mol^2/L^2	supersaturation degree
viskoznost	η	Ns/m^2	water viscosity
koeficient toplotne prevodnosti	λ	J/msK	heat conductivity
gostota snovi	ρ	kg/m^3	mass density
učinkovitost nadzora vodnega kamna	ξ	-	scale control efficiency
učinkovitost prenosa toplote	ζ	-	heat exchange efficiency

6 LITERATURA
6 REFERENCES

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