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Analiza prenosa toplote v postopku sintranja feritov

A Heat-Transfer Analysis of the Ferrite Sintering Process

Zlatko Rek - Matjaž Perpar - Iztok Žun

Obravnavana je analiza prenosa toplote v postopku sintranja feritov v komorni peči. Izvedeni sta bili meritev in numerično simuliranje časovnega razvoja temperaturnega polja. Zaradi zahtevnosti problema je simuliranje potekalo v dveh delih. V prvem delu je obravnavana celotna peč, v drugem delu pa je analiziran samo pladenj s feriti. V prispevku je opisan postopek meritve temperature, numerični model (enačbe prenosa toplote) in generacija mrežastega modela peči za izbrano računsko območje, t.j. notranjost peči z grelniki, pladnji, feriti, nosilci in podstavki. Narejena je analiza rezultatov numerične simulacije in njihova primerjava z izmerjenimi vrednostmi. Ujemanje numerične rešitve in izmerjenih vrednosti je dobro.

(Ključne besede: sintranje feritov, prenos toplote, simuliranje numerično, modeli sevanja)

The paper deals with a heat-transfer analysis of the process of sintering ferrites in a furnace. Experimental measurements and a numerical simulation of the time development of the temperature field were performed. Due to the complexity of the problem the simulation had to be performed in two steps. The first step takes into consideration the whole furnace, while in the second step only a single ferrite plate is analyzed. The experiment, the numerical model (the heat-transfer equations) and the generation of the discretized model of the furnace for the chosen computational domain, e.g. furnaces with heaters, plates, ferrites, bearers and supports, are described. The results of the numerical simulation are analyzed and compared with experimental data. The agreement between the numerical results and the experimental data was good.

(Keywords: ferrite sintering, heat transfer, numerical simulations, radiation models)

0 UVOD

Prispevek predstavlja opravljeno delo v okviru raziskovalnega projekta L2-0784: Izboljšave postopkov pri sintranju feritov v peči, pri katerem sta sodelovala Fakulteta za strojništvo - Laboratorij za dinamiko fluidov in termodinamiko, Ljubljana in Iskra Feriti, Podjetje za proizvodnjo feritov in navitih komponent, d.o.o., Ljubljana.

V postopku sintranja feritov je natančen časovni potek temperature, poleg drugih parametrov, ključnega pomena za kakovost izdelka, to je njegove elektromagnetne in reološke lastnosti. Da bi bolje razumeli dogajanje pri prenosu toplote v postopku sintranja, skušamo narediti numerični model peči ([1] in [2]). Tako lahko proučujemo vpliv posameznih parametrov na kakovost izdelka.

Ker je treba numerični model preveriti, smo v prvi fazi izvedli meritve temperatur [3]. Namen je bil dvojen:

0 INTRODUCTION

This paper presents work done in the framework of research project L2-0784 – Improvement of ferrite sintering in furnaces – in collaboration of the Faculty of Mechanical Engineering, Laboratory for Fluid Dynamics and Thermodynamics, Ljubljana with Iskra Feriti, Company of ferrite materials and wound components production Ltd., Ljubljana.

In the process of ferrite sintering, an accurate time-dependent temperature distribution (among other parameters) is of key importance for achieving a high-quality product, i.e. a material with good electromagnetic and rheological properties. To understand better the heat transfer during the sintering process a numerical model of the furnace has to be made ([1] and [2]). In this way the influence of the process parameters on the quality of the product can be studied.

Because the numerical model has to be verified, in the first step the temperature measurements [3] are performed. The purpose is twofold:

1. Izmeriti časovni potek temperatur na notranji steni peči in na grelnikih, ki jih potrebujemo za robne pogoje pri numeričnem simuliranju.
2. Izmeriti časovni potek temperatur ob feritih, v feritih na robu pladnja in v feritih na sredini pladnja. Te izmerjene vrednosti so namenjene za primerjavo oz. overitev numeričnega modela.

1 MERITEV TEMPERATUR

V komornih pečeh je sintranje pod nadzorom računalnika, ki vodi postopek glede na vstavljen program obratovalnih parametrov. Za (iz)gradnjo ter testiranje modela prenosa toplote je poleg vstopnih parametrov potrebno poznavanje temperatur znotraj peči, še posebej ob samem sintrancu. Izmerjen je bil časovni potek temperatur na različnih mestih v peči, na zunanji steni peči in v okolici. Temperature v snovi so bile izmerjene s termopari tipa S in K, na zunanji steni peči pa z merilnikom temperature na infrardeče zaznavalo.

1.1 Izvedba meritev

Za merjenje temperatur v peči so bili uporabljeni termopari tipa S (Pt-10%Rh/Pt) in K (Ni-Cr/Ni-Al). Tip S so bili iz neoplaščenih žic debeline 0,5 mm, vodenih skozi keramične cevi, tip K pa so bili iz žic debeline 0,8 mm, oplaščenih s temperaturno odporno tkanino. Termopar S je omogočal meritve temperatur do 1700 °C, termopar K pa meritve do 1200 °C stalno ter do 1400 °C kratkotrajno. Pripravljena je bila merska veriga termopar - podaljševalni vod - referenčna točka hladnega spoja (0 °C) - priključni kabel - preklopno stikalo - digitalni voltmeter. Temperatura zunanje stene peči je bila izmerjena z infrardečim digitalnim merilnikom.

Temperatura ob zunanji steni (25 mm od stene) in temperatura okolice sta bili izmerjeni z digitalnima termometroma z zaznavali tipa K. Izmerjene vrednosti so bile zapisane v računalnik. Merska veriga je bila umerjena za vsak tip termoparov. Termopar tipa S je bil umerjen v območju 170,0 °C do 1123,2 °C, največja vrednost poprave je bila -2,6 °C. Termopar tipa K je bil umerjen v območju 170,0 °C do 1086,0 °C, največja vrednost poprave je bila -2,4 °C. Relativna napaka kazanja merila (razmerje med vsoto absolutnih vrednosti poprave in merilne negotovosti ter dogovorno pravo vrednostjo temperature) za temperature, večje od 170 °C ni presegla 0,5%. Ocenjeno je bilo, da je bila točnost merske verige zadostna, torej poprava izmerjenih temperatur ni bila potrebna. Vrednosti temperatur, ki so bile izmerjene z digitalnim voltmetrom, so bile izračunane z znižanima polinomoma po ameriškem standardu NBS (9. stopnje za tip S in 8. stopnje za tip K). Za testiranje izračuna so bili uporabljeni rezultati kalibracijske meritve. Razlike med

1. To determine the time-dependent temperature of the furnace's internal wall, which is used as a boundary condition for the numerical simulation.
2. To measure the time-dependent temperature profile near the ferrites, in the ferrites at the edge, and in the plate centre.

1 TEMPERATURE MEASUREMENTS

The process of sintering in the furnace is controlled by computer with an operation schedule. Besides input parameters, the development and testing of the heat-transfer model requires temperatures inside the furnace, especially near the ferrite. A time history of the temperatures at different locations in the furnace, on the outer wall, and in the surroundings was measured. Thermocouples (types S and K) and an infrared (IR) thermometer were used for the medium and outer-wall temperatures, respectively.

1.1 Obtaining the measurements

The temperatures in the furnace were measured by types S (Pt-10%Rh/Pt) and K (Ni-Cr/Ni-Al) thermocouples. The S type thermocouple was made of uncoated 0.5-mm-thick wire led through a ceramic tube. The type K wire was 0.8-mm thick and shielded with a high-temperature-resistant textile. Thermocouple S was suitable for measurements up to 1700 °C, while thermocouple K was suitable for permanent measurements up to 1200 °C, and for a short duration up to 1400 °C. The composition of the measuring chain was: thermocouple – extension wire – cold reference point (0 °C) – connecting cable – switch contact – digital voltmeter. The temperature of the outer furnace wall was measured with a IR digital thermometer.

The temperature near the outer wall (25 mm from the wall) and the temperature of the surroundings were measured by digital thermometers with type K sensors. The measured values were recorded with a computer. The measuring range was calibrated for each thermocouple. The type S thermocouple was calibrated in the range 170.0 °C to 1123.2 °C, the highest correction was -2.6 °C. The type K thermocouple was calibrated in the range 170.0 °C to 1086.0 °C, the highest correction was -2.4 °C. The relative error of the instrument readouts (the proportion between the sum of the absolute correction values and of the measurement uncertainty and the conventional true value of the temperature) for temperatures higher than 170 °C did not exceed 0.5%. The accuracy of the measuring chain was estimated to be sufficient, therefore, a correction of the measured temperatures was not necessary. Temperature values measured with a digital voltmeter were calculated using polynomial regression following the NBS standard (9th order for type S and 8th order for type K). The results of the calibration measurement dogovornimi pravimi in izračunanimi vrednostmi so bile istega reda velikosti kot vrednosti poprav pri kalibraciji, zato smo menili, da so bile temperature ustrezno izračunane.

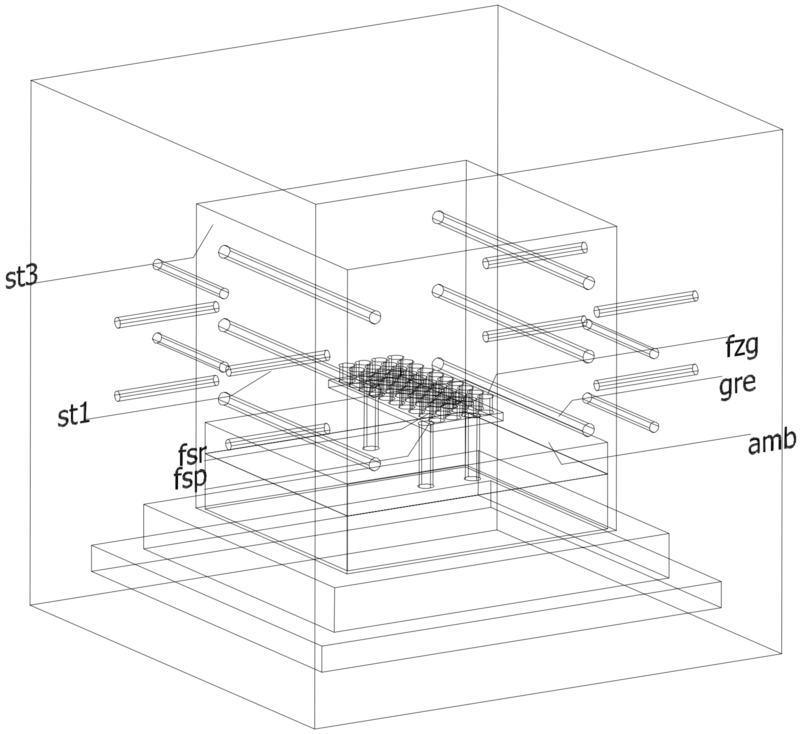
1.2 Potek meritev

Termopari so bili v peč vstavljeni skozi obstoječe odprtine. Za postavitev zaznaval pri sintrancih je bil uporabljen endoskop, ker se zapiranje peči izvaja z dvigom pladnjev v komoro. Na sliki 1 je shematsko prikazana namestitev zaznaval v peči. Temperaturni zaznavali na steni (st1 in st3) sta bili nameščeni na izolacijo. Feriti so bili razvrščeni na treh pladnjih. V vsaki plasti je bilo nameščeno po eno zaznavalo 10 mm od sintranca (fsp, fsr, fzg). Eno zaznavalo je bilo položeno na grelnik (gre), eno pa je bilo nameščeno pod grelnikom (amb). Termopar “st3” je bil tip K, vsi drugi pa tip S.

were used to test the calculation. The differences between the conventional true and the calculated values were within the range of correction, therefore, we considered the calculated values suitable.

1.2 Measuring procedure

The thermocouples were inserted into the furnace through existing holes. An endoscope was used to position the sensors near the ferrites because the furnace is closed by lifting the ferrite trays into the chamber. The locations of the sensors in the furnace are shown schematically in Fig.1. The thermocouples on the wall (st1 and st3) were placed onto the insulation. The ferrites were arranged on three trays. In each level the sensor was placed 10 mm from the ferrite (fsp, fsr, fzg). One sensor was put on the heater (gre) and one was placed in the area under the heater (amb). The thermocouple “st3” was type K, the others were type S.



Sl. 1. *Shema eksperimentalne komorne peči za sintranje feritov in merilna mesta v komorni peči*
Fig. 1. *Schematic of the experimental furnace for sintering of ferrites and measuring locations in the furnace*

2 NUMERIČNO SIMULIRANJE

2.1 Prenosna enačba energije

Temperaturno polje v komorni peči za sintranje feritov je opisano z enačbo ohranitve energije [4]:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + S \qquad (1),$$

pri čemer so: c_p specifična toplota pri nespremenljivem tlaku, ρ gostota, λ toplotna prevodnost in S viri toplote. Za temperaturno odvisnost toplotne

2 NUMERICAL SIMULATION

2.1 Energy transport equation

Temperature field in the furnace for ferrites sintering is governed by the equation for energy conservation [4]:

where c_p denotes the specific heat at constant pressure, ρ is the density, λ is the heat conductivity and S are the heat sources. The dependence of the temperature on prevodnosti je uporabljen Sutherlandov zakon [5]:

heat conduction is described by Sutherland's law [5]:

$$\lambda = \frac{2.502 \cdot 10^{-3} T^{1.5}}{T + 194.4} \qquad (2).$$

Natančnost približka je 2% na temperaturnem območju med 160 K in 1000 K.

Ker imamo v našem primeru več različnih materialov (zrak, feriti, keramika), morajo na stiku veljati združljivostni pogoji:

The accuracy of the approximation is 2%, in the range between 160 K in 1000 K.

Because there are different materials air, ferrites, ceramics – the compatibility conditions have to be satisfied:

$$T^1 = T^2 \qquad (3),$$

$$\lambda_1 \frac{\partial T^1}{\partial n} = -\lambda_2 \frac{\partial T^2}{\partial n} \qquad (4),$$

torej enakost temperatur in nasprotna enakost gostote toplotnih tokov.

i.e. equality of the temperatures and the heat fluxes.

2.2 Difuzijski model sevanja

2.2 Diffusion model for radiation

Sevalna temperatura T_r je določena z integralom intenzivnosti sevanja *i* po prostorskem kotu ([6] do [8]):

The radiation temperature T_r is defined with the integral of the radiant intensity *i* over all directions ([6] to [8]):

$$\frac{1}{4\pi} \int_{4\pi} i \, d\Omega = \frac{\sigma T_r^4}{\pi} \qquad (5).$$

Po analogiji za gostoto sevalnega toplotnega toka pri difuzijski meji je gostota sevalnega energijskega toka definirana kot:

By analogy with the radiant heat flux in the diffusion limit, the radiant energy flux is defined as:

$$\vec{q}_r = -\frac{4\sigma}{3K_e} \nabla T_r^4 \qquad (6).$$

Difuzijska meja obstaja, če je dejanska absorpcija $K_{(}$ velika, in je po Gibbu definirana kot:

A diffusion limit exists if the effective absorption $K_{(}$ is large, and was defined by Gibb to be:

$$K_e = K_a + K_p'(\bar{\epsilon}_p + \bar{\sigma}_p(1-f)) \qquad (7).$$

V našem primeru je $K'_p=0$, ker v zraku ni trdnih delcev. Ko enačbo (6) vstavimo v prenosno enačbo sevanja in integriramo po vsem območju valovnih dolžin, dobimo:

In our case $K'_p=0$, because there are no particles in the air. When equation (6) is substituted into the radiation transport equation and integrated over all wavelengths we obtain:

$$-\nabla \cdot \left(\frac{1}{3K_e} \nabla T_r^4 \right) = K_a (T_f^4 - T_r^4) \qquad (8),$$

kjer je T_f temperatura zraka. Celoten energijski tok iz zraka na sevalno fazo je:

where T_f is the air temperature. The net energy transfer from the air to the radiant phase is:

$$\dot{Q}_f = 4\sigma K_a (T_f^4 - T_r^4) \qquad (9).$$

Ta člen je treba v prenosni enačbi toplotne energije (1) odšteti.

This term is subtracted from the thermal energy equation (1).

Robni pogoj

Ob predpostavki, da na steni sevanje prihaja in jo zapušča neodvisno od smeri, za robni pogoj na steni velja:

Boundary conditions

From the assumption that the radiant intensity arriving at and leaving from the wall are directionally independent, the boundary conditions at the walls are:

$$\vec{n} \cdot \vec{q}_r = -\frac{4\sigma}{3K_e} \frac{\partial T_r^4}{\partial n} = \frac{2\sigma\epsilon_w}{2-\epsilon_w} \left(T_w^4 - T_r^4 \right) \qquad (10),$$

kjer je ***n*** enotska normala, T_w je temperatura stene in Σ_w sevalnost stene.

Začetni pogoj

Po naravi je porazdelitev T_r po območju veliko bolj enakomerna kakor T_f, zato lahko izberemo nespremenljivo začetno vrednost. Določimo jo z integracijo enačbe (9) po vsem območju Ω:

where ***n*** is the unit vector outward normal to the wall, T_w is the wall temperature and Σ_w is the wall emissivity.

Initial condition

By its nature, T_r is more uniform throughout the domain than T_f, therefore a constant value can be set for the initial value. It is determined by integrating equation (9) over the entire domain Ω:

$$4\sigma \int_{\Omega} K_a (T_f^4 - T_r^4)\, dV = \int_{\partial\Omega} \frac{2\sigma\epsilon_w}{2-\epsilon_w} \left(T_w^4 - T_r^4\right) dA \qquad (11).$$

Če zanemarimo prispevek robnega integrala, je začetna vrednost:

Without taking into account the contribution from the boundary integral, the initial value is

$$\overline{T_r^4} = \frac{1}{V} \int_{\Omega} T_f^4\, dV \qquad (12).$$

2.3 Robni pogoji

Če želimo rešiti sitem ločenih enačb, moramo predpisati smiselne robne pogoje. V našem primeru predpišemo temperaturo na notranji steni peči in na grelnikih. Vrednosti so dobljene z meritvami.

2.4 Mrežasti model

2.4.1 Komorna peč

Ker je geometrijska oblika peči zelo zapletena, saj so v notranjosti grelniki, kjer predpišemo robni pogoj, moramo računsko območje razdeliti na tri dele. Za vsak del posebej naredimo mrežo, ki jih na koncu združimo v eno celotno - strukturirano mrežo, ki ima 32422 vozlišč.

Določitev mreže pri delu 2 je zelo zahtevna, ker so v računskem območju telesa, ki prevajajo toploto: nosilci, podstavki, pladnji in feriti. Vsa ta notranja telesa je treba upoštevati in tudi ločiti, pri tem pa paziti, da mreža ni preveč spačena, saj se lahko pri reševanju enačb pojavijo problemi s konvergenco.

2.4.2 Pladenj s feriti

Mrežasti model pladnja s feriti je sestavljen iz treh delov: pladenj, feritna podlaga in feriti. Za vsak del posebej naredimo mrežo, ki poteka v naslednjih fazah:

1. geometrijski opis problema (koordinate točk, krivulje),
2. določitev vozlišč na robovih računskega območja,
3. določitev vozlišč v notranjosti računskega območja,
4. sprememba 2D mreže v 3D mrežo.

Ko imamo za vsak del narejeno strukturirano računsko mrežo, jih združimo v eno celotno - strukturirano mrežo, ki ima 101077 vozlišč.

Čeprav je geometrijska oblika peči simetrična, tega pri izračunu ne moremo uporabiti ker je: 1. mrežasti model zasnovan tako, da lahko z najmanjšimi spremembami obravnavamo različne oblike feritov in različne nalagalne sheme; 2. robni

2.3 Boundary conditions

To solve the system of discrete equations, consistent boundary conditions have to be prescribed. In our case the temperature at the inside wall of the furnace is known. Values are obtained by measurements.

2.4 Discrete model

2.4.1 Furnace

Because the geometry of the furnace is very complex, i.e. there are heaters where the boundary conditions are set, we have to split our domain into three segments. A mesh is generated for each segment. At the end all meshes are joined into one block-structured mesh which has 32422 nodes.

Mesh generation for segment 2 is very difficult due to the conjugate heat transfer (CHT) objects in the domain: bearers, supports, plates and ferrites. All these CHT objects have to be discretized as well. The mesh must not be too deformed because convergence problems could appear.

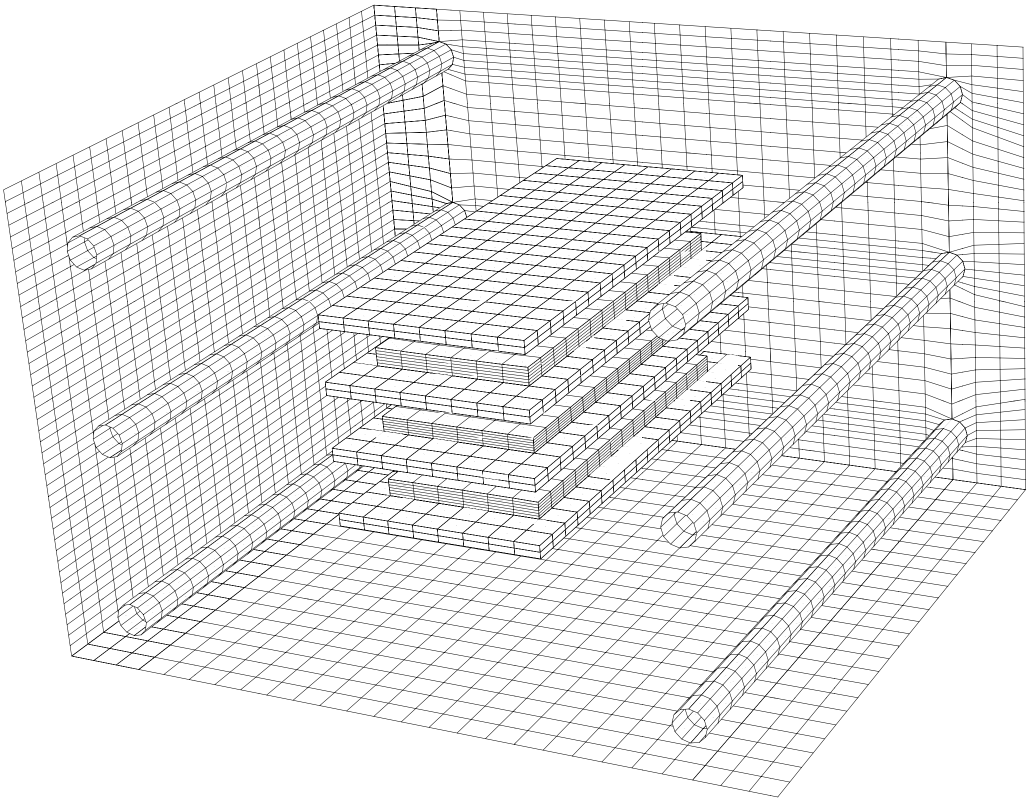
2.4.2 Ferrite plate

The discrete model of the ferrite plate is composed of three segments: plate, ceramic ferrite base and ferrites. A mesh is generated for each segment according to the following steps:

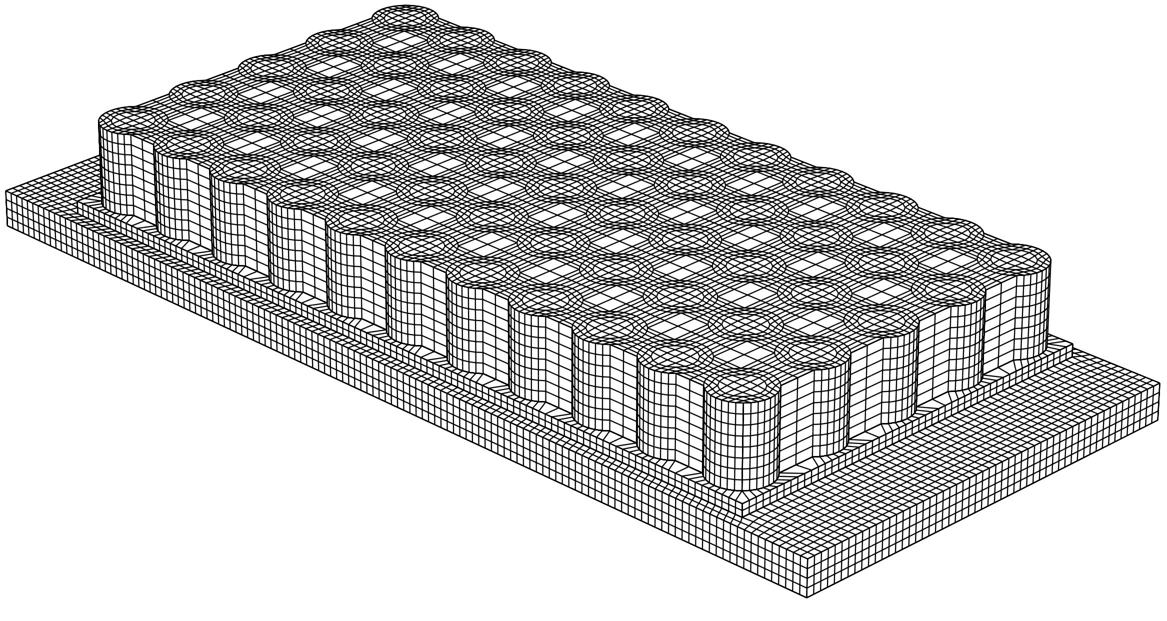
1. Geometric description (point coordinates, curves)
2. Generation of nodes at the edges of the domain boundary
3. Generation of nodes on the inside of the domain
4. Transformation of 2D mesh into 3D mesh

The meshes of all three segments are joined into one block-structured mesh with 101077 nodes.

Although the geometry of the furnace is symmetrical, this cannot be taken into account in the simulation because: 1. the discrete model is designed in such way that various types of ferrites and different load schemes can be studied with minimal changes; 2.) the



Sl. 2. *Računska mreža komorne peči*
Fig. 2. *Computational mesh for furnace.*



Sl. 3. *Računska mreža pladnja s feriti*
Fig. 3. *Computational mesh for ferrite plate.*

pogoj za temperaturo ni nujno simetričen (meritve).

Za simuliranje prenosa toplote je bil uporabljen poslovni programski paket TASCflow, ki za reševanje prenosnih enačb uporablja metodo nadzornih prostornin.

boundary conditions for the temperature are not necessarily symmetrical (measurements).

The simulation of the heat-transport equation is performed with a commercial package called TASCflow, where the transport equations are solved using the control volume method.

2.5 Analiza rezultatov

2.5.1 Temperatura v peči

Na sliki 4 je prikazana razlika med izračunano in izmerjeno temperaturo v peči v opazovani točki (fsp). Točka je tik ob feritih na spodnjem pladnju. Ujemanje numerične rešitve in izmerjenih vrednosti je dobro. Največja relativna napaka se pojavi v izgonski fazi in ne presega 20%. Nekaj večje je odstopanje tudi v fazi segrevanja, kjer je največja napaka 12%. To je tudi razumljivo, saj je hitrost spremembe temperature zelo velika. V fazi sintranja so razlike majhne, relativna napaka je <0,1%. Tudi to je smiselno, saj so razmere ustaljene (*dT/dt*=0). V fazi ohlajanja se razlika zopet povečuje na 12%).

2.5.2 Temperatura v feritih

Sliki 5 in 6 prikazujeta temperaturno polje vodoravni ravnini skozi središče feritov v prvi plasti, tj. feriti na podlagi, med fazo segrevanja (*dT/dt*>0) in fazo ohlajanja (*dT/dt*<0). S slik se jasno vidi, da so največji temperaturni gradienti v feritih na robu pladnja. To je tudi razumljivo, saj zunanji deli feritov prejmejo največ sevalne energije zaradi neposredne izpostavljenosti grelnikom. Temperaturno polje v notranjih feritih je bolj homogeno.

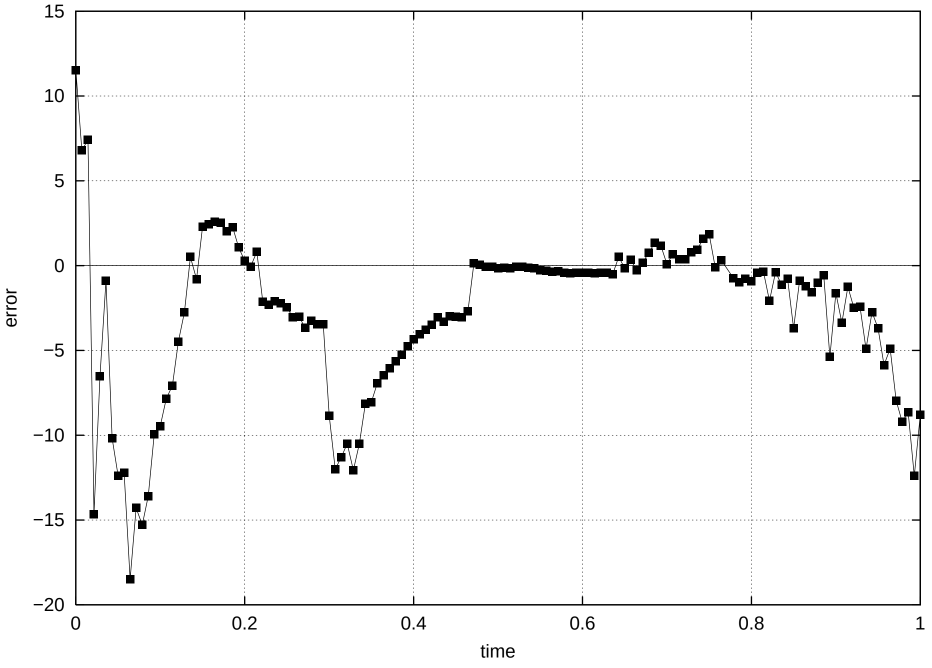
2.5 Analysis of the results

2.5.1 Temperature in the furnace

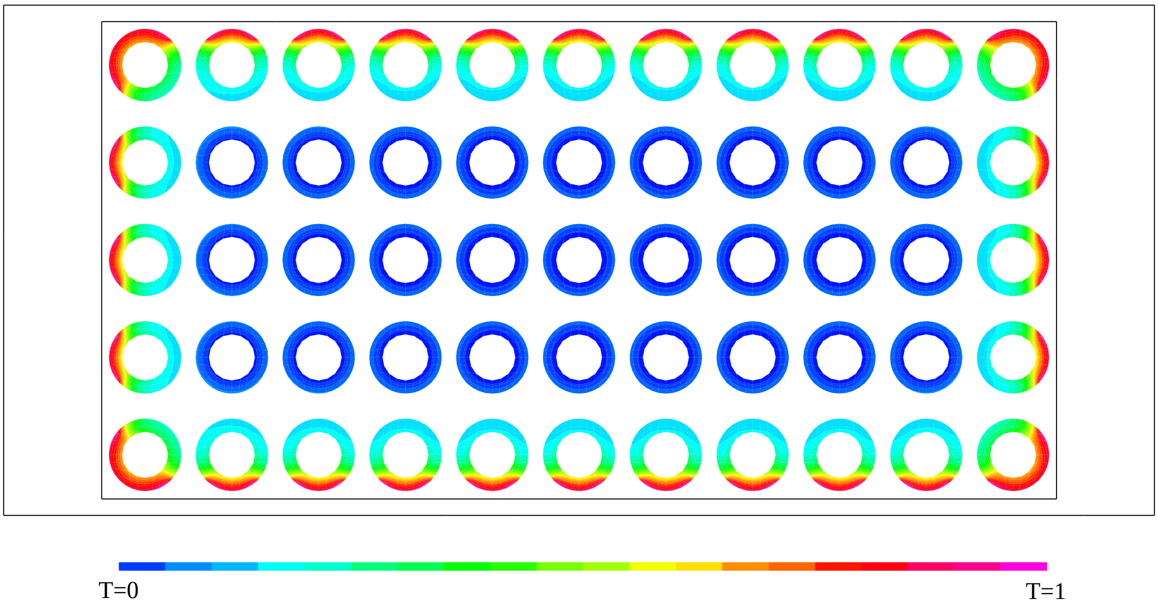
Figure 4 shows the difference between the computed and measured temperatures in the furnace at the monitoring point (fsp). The location of the monitoring point is close to the ferrites on the bottom plate. Agreement between the numerical results and the measured values is good. The largest relative error appears at the expulsion phase, and does not exceed 20%. A somewhat worse deviation also appears at the heating phase, where the maximum error is 12%. This is understandable, because the rate of change in temperature is very high. The differences in the sintering phase are minimal, the relative error is <0.1%. This also make sense because the conditions are steady (*dT/dt*=0). In the cooling phase the error again increases up to 12%.

2.5.2 Temperature in the ferrites

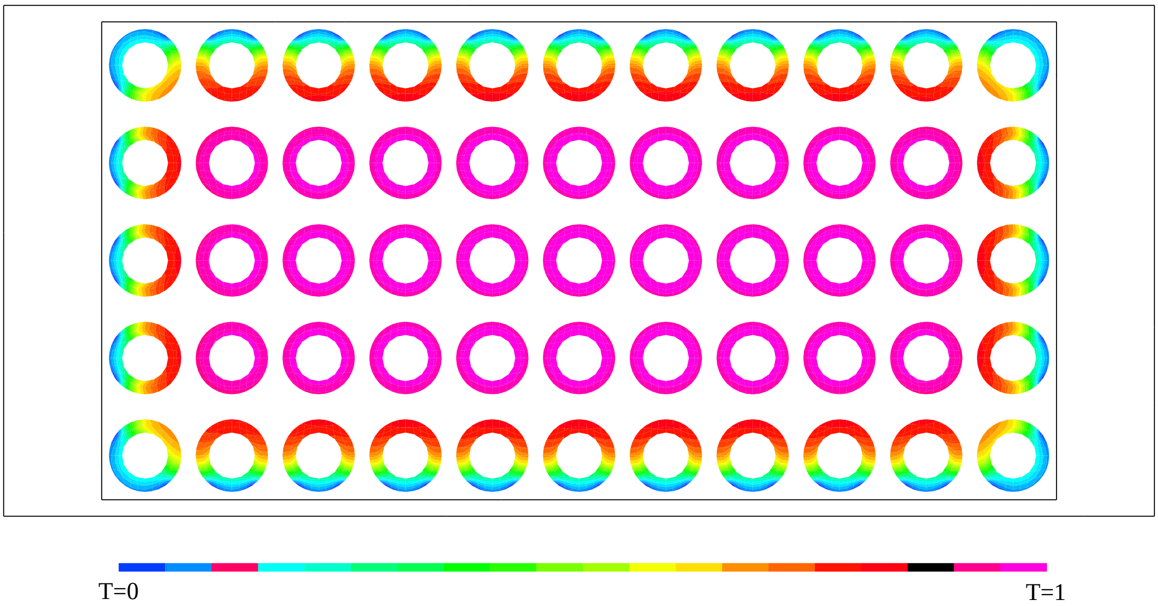
Figures 5 and 6 show the temperature field on the horizontal plane through the centre of the ferrites in the first layer, e.g. the ferrites near the ceramic ferrite base, during the heating phase (*dT/dt*>0) and during the cooling phase (*dT/dt*<0). It can be clearly seen that the largest temperature gradients appear in the ferrites at the plate edge. This is understandable because the outer parts of the ferrites receive the majority of the radiation heat due to direct exposure to the heaters. The temperature field in the other ferrites is more homogeneous.



Sl. 4. *Razlika med izmerjeno in izračunano temperaturo*
Fig. 4. *Difference between computed and measured temperatures*



Sl. 5. *Temperaturno polje v feritih v fazi segrevanja*
Fig. 5. *Temperature field in the ferrites during the heating phase*



Sl. 6. *Temperaturno polje v feritih v fazi ohlajanja*
Fig. 6. *Temperature field in the ferrites during the cooling phase*

3 SKLEPI

V prispevku je prikazan postopek numeričnega simuliranja temperaturnega polja v laboratorijski komorni peči za sintranje feritov in temperaturnega polja v feritih. Narejena sta bila dva mrežasta modela: peč z notranjimi telesi (feriti, pladnji, nosilci, podstavki) in pladenj s feriti za dve numerični simuliranji.

Za preverbo numeričnega modela je bilo treba izvesti meritve temperatur. Za merjenje temperatur znotraj peči so bili uporabljeni umerjeni termopari tipa S in tipa K. Temperature zunaj peči so bile izmerjene z digitalnimi termometri.

3 CONCLUSIONS

This article shows a numerical simulation of the development of the temperature field in a laboratory furnace for sintering ferrites. Two discrete models were made, the furnace with CHT objects (ferrites, plates, bearers, supports) and a single ferrite plate, for two numerical simulations.

Testing of the numerical model required temperature measurements. The temperatures inside the furnace were measured with calibrated type S and type K thermocouples. The temperatures outside the furnace were measured with digital thermometers.

Ker postopek sintranja poteka pri visokih temperaturah, je glavni mehanizem prenosa toplote iz grelnikov na ferite sevanje. Za reševanje sistema diferencialnih enačb v razliški obliki je bila uporabljena metoda nadzornih prostornin. Časovno odvisni robni pogoji, ki so potrebni za rešitev tega sistema, so bili dobljeni z meritvami.

Zaradi zahtevnosti problema je bilo narejenih nekaj poenostavitev. Ker so feriti zelo majhni v primerjavi s preostalimi telesi, jih ni mogoče razbiti na dele. V prvi fazi so bili obravnavani kot enoten del. Ker se med seboj ne dotikajo, med postopkom sintranja pa se še skrčijo, je bilo treba zračne reže upoštevati pri izračunu koeficienta prevodnosti feritnega dela. V drugi fazi je bilo izvedeno numerično simuliranje časovno spremenljivega temperaturnega polja v feritih med postopkom sintranja. Obravnavan je bil keramičen pladenj, 220 svitkov feritov, naloženih po štiri v stolpec in feritne ploščice za podlago feritom. Porazdelitev temperature v feritih je pričakovana. V fazah izgona in segrevanja je temperatura višja v feritih, ki so na robu pladnja, na sredini pa nižja. Po fazi sintranja, tj. je v fazi ohlajanja, pa je slika obrnjena. Na sredini je temperatura višja kakor na robu. Zaradi geometrijske simetrije in simetrije robnih pogojev je tudi temperaturno polje simetrično.

Iz primerjave meritev in rezultatov numeričnega simuliranja lahko sklenemo, da je numerični model ustrezen in da z njim dovolj natančno opišemo dogajanje v komorni peči.

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Due to the high temperatures of the sintering process the main heat-transfer mechanism from the heaters to the ferrites is radiation. The system of differential equations in a discrete form is solved by the control volume method (CVM). The time-dependent boundary conditions, which are needed to solve the system, are obtained by measurement.

A few simplifications are used because of the complexity of the problem. Because the ferrites are very small when compared to the other objects they could not be discretized. In the first step they are treated as a single block. Because they are not touching each other, and because they shrink during the sintering process, the air gap must be taken into account when computing the heat conduction coefficient of the ferrite block. In the second step a numerical analysis of the time-dependent temperature field in the ferrites during the sintering process was performed. It deals with a ceramic plate with 220 toroidal ferrites stacked in columns of four on a ceramic base. The temperature distribution is as expected. In the expulsion and heating phase the temperature is higher in the ferrites at the edge of the plate and lower at the plate's centre. After the sintering phase, i.e. during the cooling phase, the picture is reversed. The temperature is higher at the centre and lower at the edge. Due to the geometry, and the symmetry of the boundary conditions, the temperature field is also symmetrical.

From a comparison of the measurements and the numerical simulation results we can conclude that the numerical model is appropriate and that the process in the furnace is well described.

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4 LITERATURA
4 REFERENCES

[1] Rek, Z., I. Žun (1998) Numerična simulacija temperaturnega polja v komorni peči. Poročilo FERITI 02 - 97/98. *Poročilo o raziskovalni nalogi*. Fakulteta za strojništvo, Ljubljana.

[2] Rek, Z., I. Žun (2000) Numerična simulacija temperaturnega polja v feritih Poročilo FERITI 03 - 00. *Poročilo o raziskovalni nalogi*. Fakulteta za strojništvo, Ljubljana.

[3] Perpar, M., I. Žun, D. Petrič (1998) Meritve temperatur in deleža kisika v komorni peči. Poročilo FERITI 01 - 97. *Poročilo o raziskovalni nalogi*. Fakulteta za strojništvo, Ljubljana.

[4] Isachenko, V.P., V.A. Osipova, A.S. Sukomel (1977) Heat transfer. *Mir Publishers*, Moskva.

[5] TASCflow (1996) Version 2.5 Documentation: User documentation. *Advanced Scientific Computing Ltd.*, Waterlo, Ontario, Canada.

[6] TASCflow (1996) Version 2.5 Documentation: Theory documentation – diffusion model for radiation. *Advanced Scientific Computing Ltd.,* Waterlo, Ontario, Canada.

[7] Siegel, R. and J.R. Howell (1972) Thermal radiation heat transfer . *Mc Graw-Hill Book Company*, New York.

[8] Edwards, D.K. (1981) Radiation heat transfer notes. *Hemisphere Publishing Corporation*, New York.

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