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Numerična simulacija toka delovne tekočine v razpoki stene cevi uparjalnikove membrane parnega kotla

Numerical Simulation of Working-Fluid Flow Cut in a Tube of a Steam-Boiler Membrane-Wall Evaporator

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Prispevek prikazuje problem neustaljenega prenosa toplote in napetosti v cevi stene uparjalnikove membrane parnega kotla s predpostavko nenadne zaustavitve toka delovne tekočine skozi eno od njegovih cevi. Gre za skrajen primer, v katerem je konvektiven prenos toplote s stene cevi na delovno tekočino nenadno ustavljen. Opravljena je dvorazsežna analiza z metodo končnih prostornin ob predpostavki, da je material termoelastično zvezno telo. Analiza je pokazala razmeroma hitro dosego kritične vrednosti napetosti.

(Ključne besede: kotli parni, uparjalniki, prenos toplote, metode numerične)

This paper presents the problem of transient heat transfer and the stress in the tube of a steam-boiler membrane-wall evaporator, assuming a sudden cut of the working-fluid flow through one of its tubes. Thus, an extreme case was considered in which the convective heat transfer from the tube wall to the working fluid was suddenly cut. The 2D analysis was carried out using a finite-volume method and with the assumption that the material is a thermo-elastic continuum. The analysis showed that the critical stress values were achieved relatively quickly.

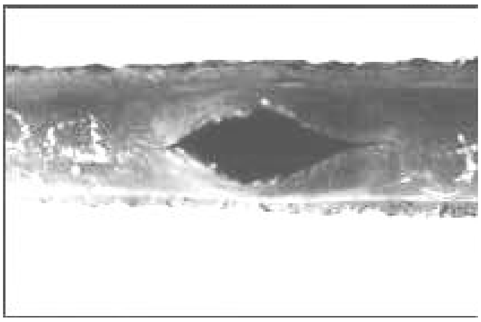
(Keywords: steam boilers, evaporators, heat transfer, numerical methods)

0 UVOD

Obravnavan je dejanski dogodek v termoelektrarni Kakanj, in sicer v njegovi enoti 7 z močjo 230 MW. V decembru leta 2000 je tam nastala okvara na cevi uparjalnika parnega kotla, ki je bila več ali manj usmerjena vzdolžno. Deformacija je bila največja na višini cevi 17 in 18 metrov [1]. Inženirji v elektrarni so mnenja, da se je zgodila kot posledica zastoja delovnega medija v poškodovani cevi. Zares je bil tu ob demontaži poškodovane cevi najden material, ki je zapiral šobo na izhodu uparjalnikove cevi. Material je bil tam puščen po napaki med remontom sistema šob. V nadaljevanju je bil opazen stalen problem zagotovitve uravnovešenega pretoka delovne tekočine skozi cevi uparjalnika v kotlu, potrjen z merjenjem z ultrazvočnim inštrumentom. Rezultati kažejo odstopanja v toku delovne tekočine v območju ± 60 % od imenske vrednosti [1]. Poleg težav zagotovitve ustaljenega pretoka delovne tekočine so se slabšali pogoji delovanja uparjalnika zaradi razpoke v toplotno zaščitnem materialu v delu uparjalnika, posebno na stropu zgorevalne komore.

0 INTRODUCTION

A real event that occurred in the thermal power plant Kakanj, i.e., in its thermal unit 7, with a power of 230 MW, was analysed. In December 2000, there was a breakdown of the steam boiler's evaporator tube, which was more or less deformed lengthways. The deformation was the largest at tube heights of 17 and 18 meters [1]. Engineers in the plant assumed that it happened due to a cut in the working-medium flow in a damaged tube. Indeed, while disassembling the damaged tube, a material was found, which blocked a nozzle at the inlet of the evaporator tube. The material was left behind by mistake during an overhaul of the nozzle system. In addition, there was a constant problem regarding provision of a balanced working-fluid flow through the evaporator tubes in this boiler, which was confirmed by measurements using ultrasonic instrument. The results showed certain deviations in the working-fluid flow reaching ± 60 % of the nominal value [1]. Besides the problem with the provision of a balanced working-fluid flow, the evaporator working conditions were worsened due to a lack of heat-protection material in some parts of the evaporator, especially at the ceiling of the flame



Sl. 1. *Poškodovana cev*
Fig. 1. *Damaged tube*

Slika 1 prikazuje poškodbo cevi, nastalo v območju najvišjih temperatur zaradi zaustavitve pretoka delovne tekočine. Delovna tekočina je demineralizirana voda, ki vstopa v uparjalnik v stanju nasičene kapljevine. Vzdolž cevi se stanje tekočine nadalje spreminja prek stanja mokre pare v nasičeno paro.

Postopek uparjanja vode v uparjalniku parnega kotla je urejen tako, da je nasičena voda gnana iz rezervoarja uparjalnika skozi cevi uparjalnika v uravnovešenem toku. Nadaljnje gretje v uparjalniku vodi v postopno uparjanje nasičene vode, dokler se v celoti ne upari v nasičeno paro. Točka celotne preobrazbe iz kapljevite v parno fazo se imenuje kritična točka in je za ta uparjalnik približno 18 metrov. Tipično za to območje je nenadno povišanje temperature stene, kateremu sledi postopno povišanje temperature v smeri toka pare. Hkrati pade vrednost koeficienta prenosa toplote na strani delovne tekočine. Območje intenzivnega uparjanja nasičene vode, to je območje mokre pare, ima značilno visoko vrednost koeficienta prenosa toplote na strani delovne tekočine, to je 10 kW/m^{2}K [2].

Teoretično (v ustaljenem stanju) kritična točka vedno zavzame isto vrednost. V resničnih razmerah v elektrarni se kritična točka premika. Če pomični gradient ni prevelik, je pričakovati, da toplotne napetosti, povzročene s tem pomikanjem, niso nad dovoljeno mejo.

Premik kritične točke navzgor ali navzdol lahko povzročijo različni razlogi. Za primer: upočasnitev pare delovne tekočine skozi cevi uparjalnika vodijo k znižanju kritične točke proti dnu kurišča kotla. Do izredne situacije pride v primeru celotne in trenutne ustavitve toka pare delovne tekočine v cevi, ko kapljevina delovne tekočine uparja zelo hitro. To je napovedano stanje v numerični simulaciji.

chamber. Figure 1 illustrates the tube damage that occurred in the maximum temperature zone as a consequence of a cut in working-fluid flow. The working fluid is a decarbonized water, which enters the evaporator in the state of a saturated liquid. Along the tube this state is subsequently followed by the states of wet and then saturated steam.

The process of water evaporation in the steam-boiler evaporator is thus organized so that saturated water is forced from the steam drum through the tubes in a balanced flow. Further heating in the evaporator leads to gradual evaporation of the saturated water until it completely evaporates into saturated steam. The point of complete transformation from the liquid phase to the gas phase is the so-called critical point, and for this boiler it is above 18 meters. Typical for this area is a sudden increase in tube-wall temperature, which is then followed by a gradual temperature increase in the steam flow direction. At the same time, the heat-transfer coefficient decreases on the working-fluid side. The area of intensive evaporation of saturated water, i.e., the wet steam zone, has a significantly high heat transfer coefficient on the working fluid side e.g., 10 kW/m^{2}K [2].

Theoretically (in the steady state), the critical point always takes the same position. However, in real plant conditions the critical point is movable. If the moving gradient is not too large, it can be expected that the thermal stresses caused by this movement are not above the allowed limit.

Different reasons can lead to displacement of the critical point upwards or downwards. For example, a slow down of the working-fluid stream through the evaporator pipes leads to a lowering of the critical point towards the boiler flame chamber bottom. An extreme situation occurrs in the case of a complete and immediate interuption of the working-fluid stream in the pipe when the total liquid working fluid evaporates very quickly. This is an anticipated situation in the numerical simulation.

1 MATEMATIČNI MODEL

1.1 Vodilne enačbe

Glede na zgoraj navedeno je uporabljen dvorazsežni napetostni postopek. V vodilnih enačbah

1 MATHEMATICAL MODEL

1.1 Governing equations

Based on the above, the 2D strain concept was adopted. In the governing equations of linear gibalne količine in ohranitve energije so zanemarjene prostorninske sile in deformacijsko delo. Tako imajo enačbe v dvorazsežnem kartezijevem koordinatnem sistemu obliko:

momentum and energy conservation the volume forces and the deformation work were neglected. Thus, in the Cartesian 2D coordinate system the equations are:

$$\frac{\partial}{\partial \tau}\int_V \rho \frac{\partial u}{\partial \tau} dV = \int_S \left\{ \left[2\mu \frac{\partial u}{\partial x} + \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) - 3\, K\, \beta\, \Delta T \right] n_x + \mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) n_y \right\} dS \tag{1}$$

$$\frac{\partial}{\partial \tau}\int_V \rho \frac{\partial v}{\partial \tau} dV = \int_S \left\{ \mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) n_x + \left[2\mu \frac{\partial v}{\partial y} + \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) - 3\, K\, \beta\, \Delta T \right] n_y \right\} dS \tag{2}$$

$$\frac{\partial}{\partial \tau}\int_V \rho \; c_p \; T \; dV = \int_S \left(k \frac{\partial T}{\partial x} n_x + k \frac{\partial T}{\partial y} n_y\right) \; dS \tag{3},$$

kjer so: V – prostornina, S – robna površina, n_x in n_y – normalni vektorji katezijevih komponent, λ in μ - Lamejevi konstanti, K - elastični modul (λ, μ in K so definirani v viru [3]), c_p – specifična toplota, k – toplotna prevodnost in β - prostorska toplotna razteznost. Prostorski koordinati x in y, kakor tudi čas t so neodvisne spremenljivke, medtem ko so u, v in T odvisne spremenljivke, ki pomenijo kartezijeve komponente pomika (u, v) in temperaturo (T).

where V is volume, S is the system boundary area, n_x and n_y are the Cartesian normal vector components, λ and μ are Lame's constants, K is the elasticity module (λ, μ and K are defined in reference [3]), c_p is the specific heat, k is the thermal conductivity and β is the coefficient of linear thermal expansion. The space coordinates, x and y, as well as the time τ are independent variables, whereas u, v and T are dependent variables representing Cartesian displacement components (u, v) and temperature (T) respectively.

1.2 Robni pogoji

Z namenom podaje popolne matematične razlage problema, so podani Neumannovi robni pogoji za enačbo gibalne količine na robnem območju, podane so sile, kakor je prikazano spodaj:

1.2 Boundary conditions

In order to give a full mathematical explanation of the problem, boundary conditions of the Neumann type were given to the linear momentum equation at the boundary domain, i.e., the forces were given as shown below:

$$\int_S \mathbf{N} \cdot \mathbf{n} \quad dS = \int_S \mathbf{f} \quad dS \tag{4},$$

kjer so: $\mathbf{N}$ – napetostni tenzor, $\mathbf{n}$ – vektor v smeri normale, $\mathbf{f}$ – podan vektor sil na robu S.

Robni pogoji druge in tretje vrste so prav tako uporabljeni v primeru energijske enačbe:

where $\mathbf{N}$ is the stress tensor, $\mathbf{n}$ is the normal vector, and $\mathbf{f}$ is the given force vector on the boundary S.

Boundary conditions of the second and third kind were also used in the case of the energy equation

$$q = -k \frac{\partial T}{\partial n} \quad \text{na/on} \quad S_1 \tag{5}$$

$$k \frac{\partial T}{\partial n} = -\alpha \left(T - T_f \right) \quad \text{na/on} \quad S_2 \tag{6},$$

kjer je q znana vrednost toplotnega toka na delu roba S_1 medtem, ko so na delu roba S_2 podane vrednosti: α – toplotna prestopnost na strani delovne tekočine, T – temperatura stene, T_f – povprečna temperatura delovne tekočine, ki pomeni temperaturo nasičene vode. Prav tako je treba navesti, da je $S=S_1 \cup S_2$.

where q is the heat flux value known in the part of the S_1 boundary, whereas the values known in the part of the S_2 boundary are as follows: α is the average convection heat-transfer coefficient on the side of the working fluid, T is the wall temperature, T_f is the the working-fluid average temperature, which, in fact, represents the temperature of the saturated water. Also, it is necessary to note that $S=S_1 \cup S_2$.

2 NUMERIČNI IZRAČUNI

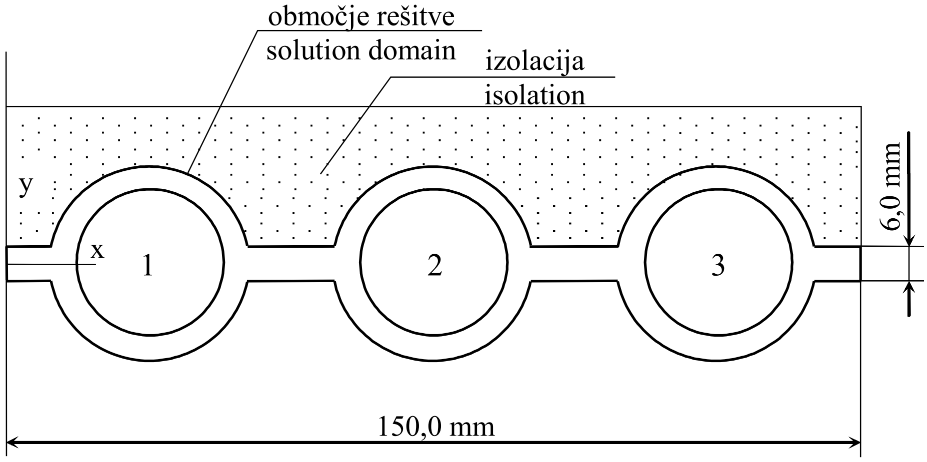
2.1 Definiranje računskega območja

Računsko območje (sl. 2) je razdeljeno na 3976 nadzornih prostornin. Za diskretizacijo območja

2 NUMERICAL CALCULATIONS

2.1 Definition of the calculation domain

The calculation domain (shown in Figure 2) was divided in 3976 control volumes. An unstructured



Sl. 2. *Geometrijska oblika računskega območja (notranji premer cevi je 25 mm)*
Fig. 2. *Calculation domain geometry (inner diameter of the tube is 25 mm)*

Preglednica 1. *Snovske lastnosti materiala (15Mo3)*
Table 1. *Physical characteristics of material (15Mo3)*

ρ [kg/m^3]	c_p [J/kgK]	k [W/mK]	β [1/K]	ν -	E [Pa]	σ_g [Pa]
7749	574	40,697	$1{,}3469\cdot10^{-5}$	0,3	$1{,}7163\cdot10^{11}$	$1{,}7163\cdot10^{8}$

je uporabljena nestrukturirana mreža. Opravljena je vozliščna analiza, katere rezultati so prikazani v viru [6]. Izračun je izpeljan na mreži, ki je nekoliko ustreznejša za zagotovitev zahtevane natančnosti spremenljivk u, v in T. Fizikalne lastnosti materiala 15Mo3 (podane v preglednici 1) so vzete za temperaturo 673 K in so štete kot nespremenljive med izračunom. Vrednosti ν, E , σ_g so Poissonov koeficient, Youngov modul elastičnosti, meja elastičnosti.

Za obravnavani problem je uporabljena metoda nadzornih prostornin. Poleg klasičnega numeričnega postopka s programskim orodjem COMET [4] je uporabljena večmrežna tehnika za pospešitev konvergence in za ta namen je ustvarjena preprosta mreža.

2.2 Opis robnih pogojev

Tlak v cevi je bil 18,8 MPa, medtem ko preostali robovi območja niso bili obremenjeni s silo. Tu so različni referenčni podatki za koeficient prenosa toplote za uparjanje vode v navpičnih ceveh, kjer so vrednosti v območju 5 do 29 kW/m^{2}K. Za obravnavani parni kotel je koeficient v mejah od 5 do 10 kW/m^{2}K. V tem delu je vzet koeficient prenosa toplote 7 kW/m^{2}K, z ustrezno temperaturo nasičenosti vode 633 K. Na strani dimnih plinov je podan konstanten toplotni tok 211 kW/m^2, katerega vrednost je dobljena s preizkusom v območju uparjanja vode [5]. Zunanja stena stenskega uparjalnika je obravnavana kot idealno

grid was used for the space discretisation. A grid-independence test was carried out and shown in reference [6]. This calculation used a grid that was somewhat more than necessary for the requested accurateness of the variables u, v and T. The physical properties of the 15Mo3 material (given in Table 1) are determined for 673 K and considered constant during the calculation. The values ν, E and σ_g are Poisson's coefficient, Young's module of elasticity and elasticity limit stress, respectively.

The finite-volume method was applied to the considered problem. Besides a standard numerical proceeding integrated in the COMET software [4], there was also a multigrid technique of accelerating convergence and, for that purpose, two coarse grids were generated.

1.2 Description of boundary conditions

The pressure within the tube was 18.8 MPa, whereas the other boundaries of the domain were free of forces. There are various reference data for the heat-transfer coefficient of water evaporation in vertical tubes, the values of which range from 5 to 29 kW/m^2·K. For this particular steam boiler the coefficient ranges from 5 to 10 kW/m^2·K. In this paper, the adopted heat-transfer coefficient is 7 kW/m^2·K, with a corresponding water-saturation temperature of 633 K. On the flue-gas side a constant heat flux of 211 kW/m^2 was given, and its value was found by an experiment in the water-evaporation zone [5]. The external wall of the wall evaporator is considered as izolirana. Začetno polje odvisnih spremenljivk *u, v* in *T* je računano za ustaljeno stanje in prej omenjene robne pogoje [6].

V začetnem trenutku $\tau_0 = 0$ sekund je podan robni pogoj $q = 0$ kW/m^2 na notranji strani cevi 2 računskega območja, prikazanega na sliki 2. Preostali robni pogoji se niso spreminjali med izračunom. Testni izračun je pokazal, da se pomembni dogodki pojavijo med prvimi desetimi sekundami, medtem ko je dosežen ustaljen koeficient prenosa toplote po 600 sekundah.

Upoštevajoč navedeno dejstvo je izbran časovni korak $\delta\tau$ =1 sekund za prvih deset sekund izračuna. Za nadaljnjih petdeset sekund je uporabljen časovni korak $\delta\tau$ =5 s. Koraki $\delta\tau$ =10 sekund in $\delta\tau$ =20 sekund so uporabljeni do poteka opazovanega časovnega obdobja. Izračun prenosa toplote je opravljen do poteka opazovanega časa ob predpostavki, da območje ne dopušča deformacij, ki bi lahko privedle do spremembe oblike ali celo do razpoke. Napetost je računana oziroma obravnavana samo do trenutka, ko je najvišja ustrezna napetost v območju višja od napetosti materialove meje elastičnosti.

2.3 Rezultati izračunov

Iz rezultatov izračuna je mogoče dobiti veliko pomembnih informacij. Najzanimivejši so: temperatura v območju v posameznih časih, čas za dosego ustaljenega stanja prenosa toplote in čas za dosego elastične meje napetosti. Kot primer je na sliki 3 prikazano temperaturno polje v območju v začetnem času, po 6 sekundah in po 600 sekundah.

Očitno je (sl. 3), da po 600 sekundah začetni robni pogoj $q = 0$ kW/m^2 privede začetno ustaljeno polje v novo ustaljeno stanje. To ima za posledico postopek prenosa toplote na sosednje cevi skozi povezujoče membranske plošče. Najvišja temperatura v materialu cevi po 600 sekundah je 1593 K, kar je pod tališčem (1809 K). Potrebna hitrost lokalnega gretja materiala je lahko ponazorjena s temperaturno spremembo v odvisnosti od časa v robnem vozlišču, ležečem na zunanjem premeru cevi 2 (sl. 4a). Razvidno je, da je ustaljeno stanje skoraj doseženo po 600 sekundah.

Po drugi strani je dejanska napetost računana na temelju Misesove hipoteze ob uporabi vrednosti prej izračunanih glavnih napetosti. Časovna sprememba dejanske napetosti je prikazana na sliki 4b. Ta sprememba se prav tako nanaša na robno vozlišče, ležeče na zunanjem premeru cevi 2. Preglednica v diagramu podaja računane dejanske napetosti v MPa in kaže, da je elastična meja napetosti dosežena po 6 sekundah.

Slika 5 prikazuje porazdelitev normalnih napetosti v ceveh (po šestih sekundah), ki s strižnimi napetostmi določajo napetostno stanje v območju.

ideally insulated. The initial field of dependent variables *u, v* and *T* was calculated for the stationary state and the previously mentioned boundary conditions [6].

In the initial moment $\tau_0 = 0$ sec., a boundary condition $q = 0$ kW/m^2 was set within the tube No.2 of the calculation domain, shown in Figure 2. The other boundary conditions remained unchanged during the calculation. The testing calculations showed that important events occur in the first 10 sec., whereas stationary heat transfer is achieved after 600 sec.

Based on this fact, the time interval $\delta\tau$ =1 sec. was chosen in the first 10 sec. In the next 50 sec. the interval was $\delta\tau$ =5 sec. Intervals $\delta\tau$ =10 sec. and $\delta\tau$ =20 sec. were used until the end of the observed time interval. The heat-transfer calculation was carried out until the end of the observed time interval, providing the domain has not suffered deformations that would cause a change of shape – or even cracking. The stresses were only calculated or considered until the moment when a maximum equivalent stress appearing in the domain is somewhat above the stress on the material elasticity limit.

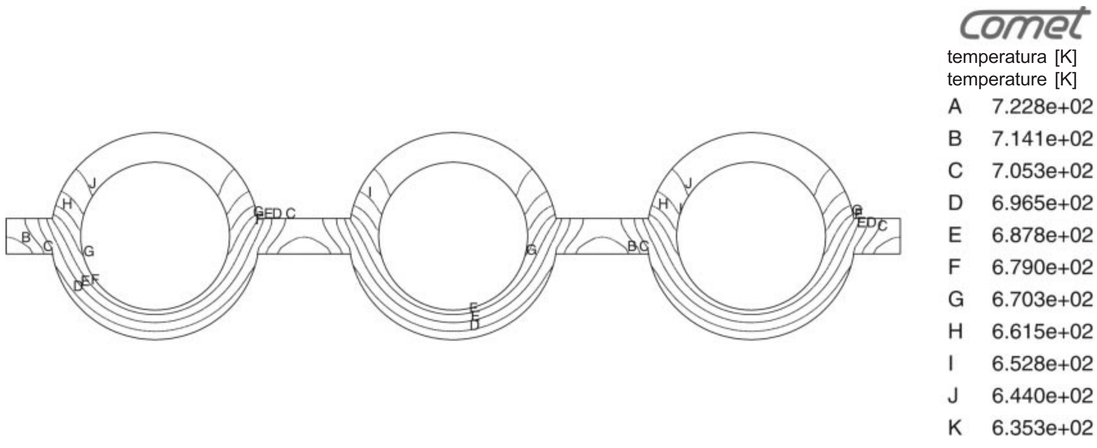
2.3 Results of calculations

It is possible to get a lot of important information from the calculation results. The most interesting results are the temperature within the domain at particular time points, the time period to reach the heat-transfer stationary state, and the time period to reach the stress on the elasticity limit. Thus, for example, Figure 3 shows the temperature fields in the domain at the initial moment, after 6 sec., and after 600 sec.

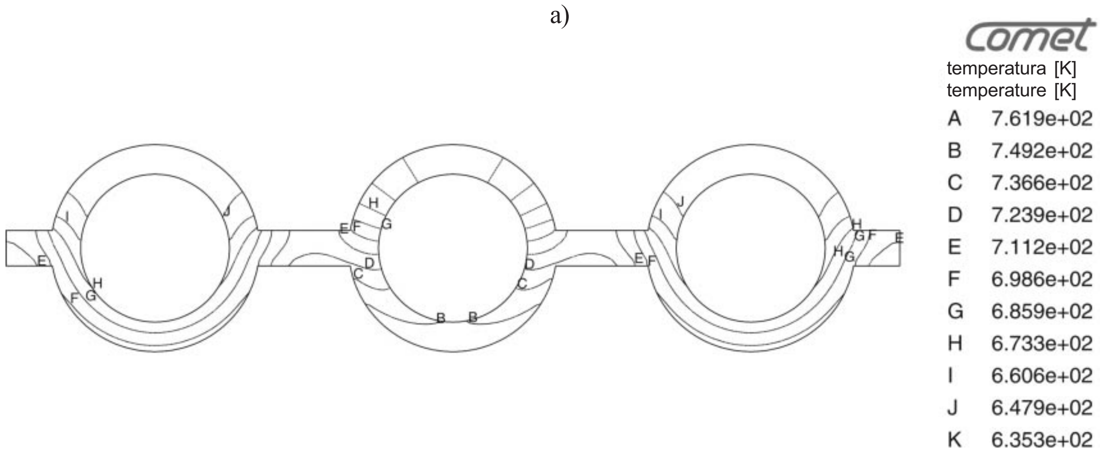
It is obvious (Figure 3) that after 600 sec. the initial boundary condition $q = 0$ kW/m^2 brings the stationary temperature field into a new stationary state. This results in a heat-transfer process carried out by conduction towards neighbouring tubes through connecting membrane plates. The maximum temperature of the tube material after 600 sec. is 1593 K, which is below the melting temperature of iron (1809 K). The velocity needed for local heating of the material can be illustrated by the temperature change over time at the boundary node located on the external diameter of tube No.2 (see Figure 4a). It is clear that the stationary state is almost reached after 600 sec.

On the other hand, the effective stress was calculated on the basis of Mises's hypothesis, using the values of previously calculated main stresses. The change of effective stress over time is shown in Figure 4b. This change also refers to the boundary node located on the external diameter of tube No. 2. The table within the diagram gives the calculated effective stresses in MPa, and shows that the elasticity limit stress is reached after 6 sec.

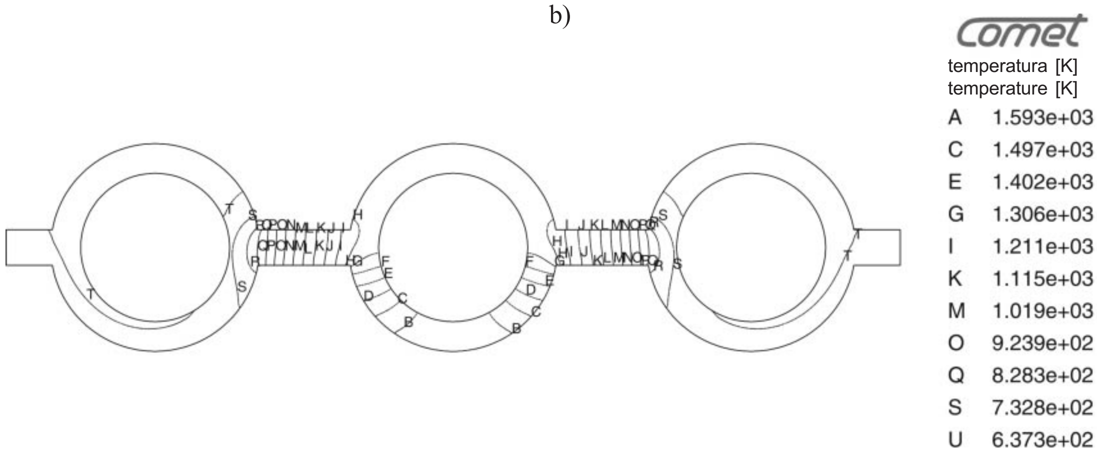
Figure 5 shows the distribution of normal stresses in the tubes (after six seconds), which together with the shear stresses define the stress



a)



b)

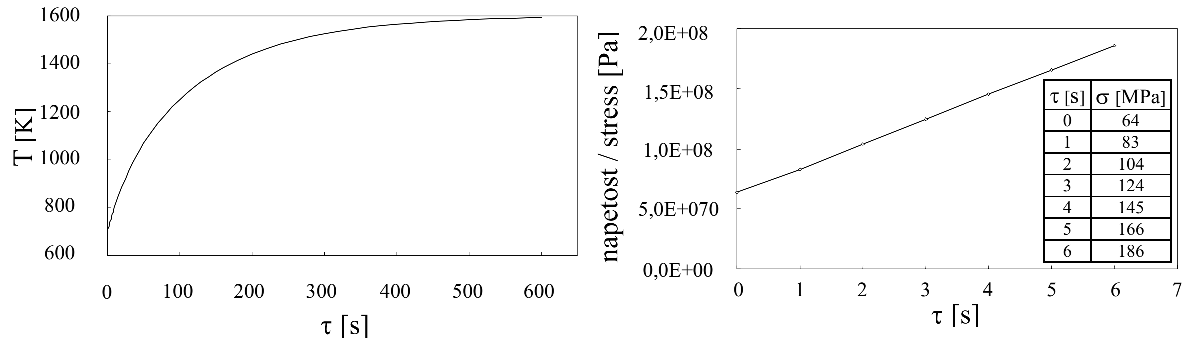


c)

Sl. 3. *Temperaturno polje za: a) τ =0 sekund, b) τ =6 sekund in c) τ =600 sekund*
Fig. 3. *Temperature field for: a) τ =0 sec, b) τ =6 sec and c) τ =600 sec*

Kakor je razvidno, je najvišja vrednost vzdolžnih napetosti (S_{zz}) -197 MPa v robnem vozlišču, postavljenem na zunanjem premeru cevi št. 2. V tem vozlišču ima prav tako najvišjo vrednost dejanska napetost. Normalna napetost (S_{yy}) 113 MPa ima prav tako znatno visoko vrednost vzdolž stene notranje cevi nasproti zvarjene membranske plošče.

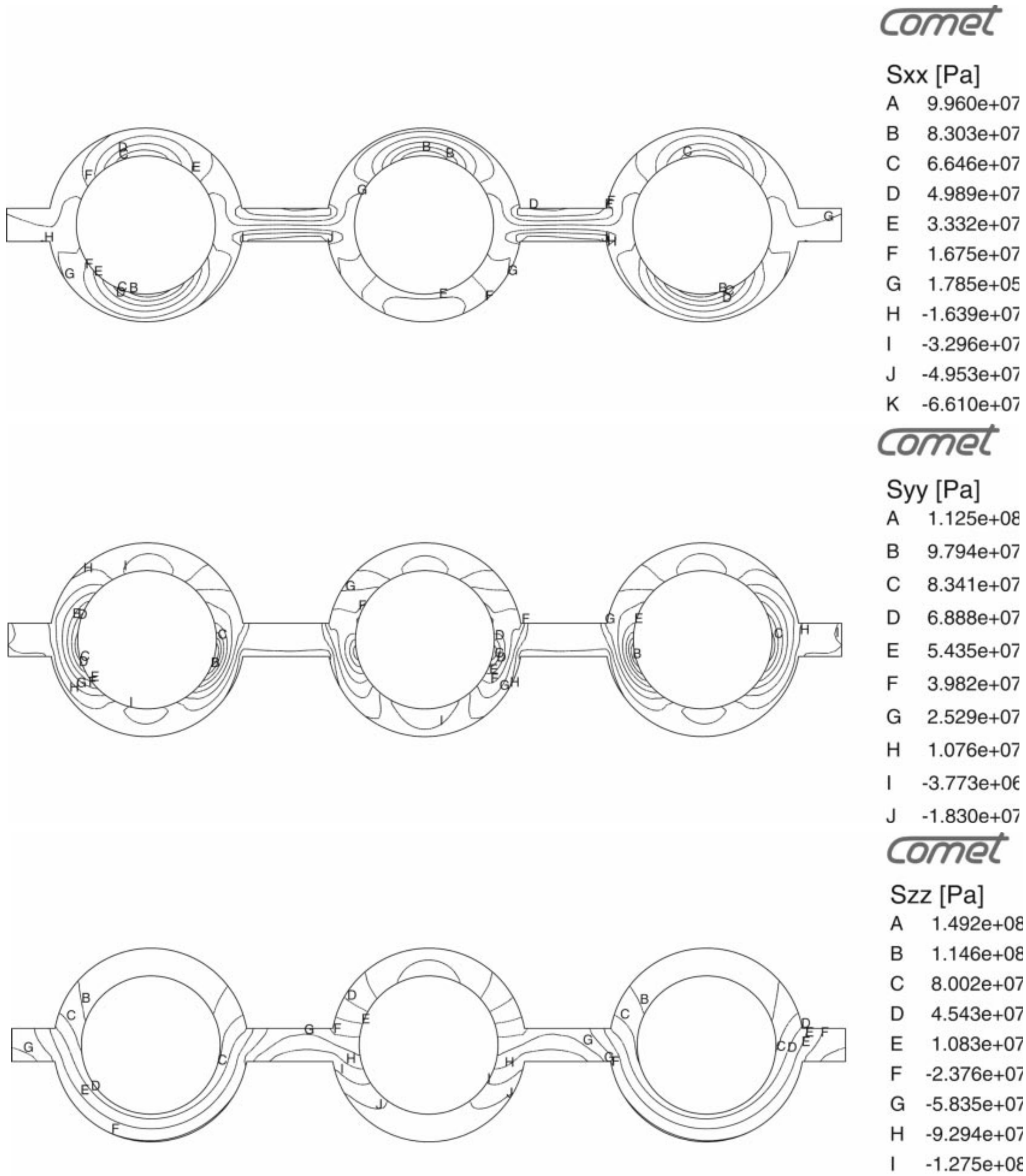
state in the domain. As we can see, the maximum value of the axial stress (S_{zz}) is -197 MPa at the boundary node located on the external diameter of tube No. 2. At this point the effective stress also has its maximum value. The normal stress (S_{yy}) of 113 MPa also assumes a very high value along the internal tube wall, opposite to the welded membrane plate.



a) b)

Sl. 4. *a) – Temperaturna sprememba v vozlišču, ležečem na zunanjem premeru zamašene cevi, b) – vrednost primerjalne napetosti med prvimi 6 sekundami*

Fig. 4. a) - *Temperature change at the boundary node located on the external diameter of the blocked tube, b) - Equivalent stress values within the first 6 sec*



Sl. 5. *Porazdelitev komponent napetosti po 6 sekundah*

Fig. 5. *Distribution of stress components after 6 sec*

3 SKLEP

Numerični izračuni kažejo, da je modeliran pojav zelo hiter. Upoštevajoč, da nimamo možnosti za avtomatično intervencijo, pojava ne moremo pravočasno preprečiti. Pojav ima za posledico razpoko cevi, ustavitev delovanja parnega kotla in zato celotne termoelektrarne.

Numerični izračuni ponujajo številne pomembne parametre, ki določajo dogodek. Ti parametri so: stanje prehodne periode ustaljenega prehoda, najvišja temperatura materiala v razpočeni cevi in čas dosega elastičnih mejnih napetosti. Numerični model je lahko na splošno uporabljen za analize s podobnimi pojavi v proizvodnem postopku.

Med remontom termoelektrarne je pogosta praksa (in prav tako potreba) najetje inštitucij, ki se ukvarjajo s preiskavo materialov. Vsekakor je po zgoraj navedenih dogodkih preiskava vedno obvezna.

Nazadnje je jasno, da informacije o vrednostih in porazdelitvah temperatur in napetosti v materialu omogočajo boljšo diagnostiko posameznega primera. V nasprotju z drugimi metodami zagotavljajo numerični izračuni več informacij ob manjšem trudu ob uporabi sodobnih numeričnih algoritmov in programov, pri čemer ni nujno potrebno uporabiti hitrih računalnikov. Kot primer je izračun v tem delu opravljen z osebnim računalnikom s hitrostjo 233 MHz. V prihodnosti bo razvoj modela najverjetneje usmerjen v numerično modeliranje termoplastičnosti, gibajoče mreže itn.

3 CONCLUSIONS

Numerical calculations show that the modelled process is very fast. Bearing in mind that there is no possibility of automatic intervention, the process cannot be prevented in time. This results in the tube cracking, shutting down of the steam boiler, and, as a result, of the whole of the thermal power plant.

A numerical calculation offers a number of important parameters that determine such an occurrence. These parameters are as follows: the state transition period, the maximum temperature of the material in the broken tube and the time to reach the elasticity limit stress. The numerical model can be widely applied in the analyses of similar occurrences in production processes.

During the periods of thermal power plant overhauls, there is a need to involve institutions dealing with material examination. Indeed, such examinations are obligatory after the above-mentioned occurrences.

Finally, it is clear that information on values and on the distribution of temperatures and stresses in a material enables a better diagnosis of a particular problem. As opposed to other methods, the numerical calculation provides more information for less effort by using modern numerical algorithms and software, but does not necessarily require fast computers. For example, the calculation in this paper was carried out using a PC with a 233-MHz processor. In the future, the development of the model would most probably go in the direction of numerical modelling of themoplasticity, moving grids, etc.

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