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OCENA PODOBNOSTI ZA UPOTREBU ZAGREJAČA NAPOJNE VODE POSLE POPRAVKE

FITNESS-FOR-PURPOSE ASSESSMENT OF REPAIRED FEEDWATER HEATER

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Ključne reči
- zagrejač vode
- podobnost za upotrebu
- popravka zavarivanjem
- modelovanje
- analiza napona

Izvod

Pricurivanje na spoju cevi i cevne ploče na ulazu u zagrejač vode je zahtevalo rekonstrukciju i popravku dodatnim zavarivanjem cevi. Prvobitnim projektom je u obzir uzeto samo zaptivanje i posle nekog vremena u radu je došlo do curenja zbog pomeranja cevi u cevnoj ploči, izazvanog termičkim i mehaničkim preopterećenjem. Postupak popravke je predvideo isecanje glave zagrejača po zavarenom spoju, pripremu i zavarivanje cevi za cevnu ploču, i ponovno zavarivanje glave. Glava i cevna ploča su izrađeni od ugljeničnog čelika. Postupak zavarivanja je predvideo austenitni meki sloj i lokalnu termičku obradu za otpuštanje zaostalih napona pre završnog spajanja. Ocena podobnosti za upotrebu je zahtevana i razvijeni su modeli prema projektnom rešenju i stanju posle popravke analizom konačnim elementima. Rezultati mehaničkog i termičkog odgovora modela su potvrdili da je popravljeni zagrejač napojne vode podoban za upotrebu.

Keywords
- water heater
- fitness-for-purpose
- repair by welding
- modelling
- stress analysis

Abstract

The leakage of tube-tubesheet joint of feedwater heater on the inlet required redesign and repair by additional tube welding. The original design took into account only the sealing, and subsequently after some period leakage occurred due to tube displacement in tubesheet, caused by thermal and mechanical overload. Repair procedure included cutting out the heater header along the welded joint, preparing and welding the tubes to the tubesheet, and repeated welding of the header. The header and tubesheet are made of carbon steel. Welding procedure anticipated an austenitic soft interlayer and local heat treatment for residual stress relaxation before final joining. Fitness-for-purpose assessment has been issued and models were developed by finite element analysis according to the design solution and condition after repair. The results of mechanical and thermal responses of model confirmed that repaired feedwater heater is fit for purpose.

UVOD

Problem procurivanja i otkaza komponenata zagrejača napojne vode u konvertoru amonijaka je dobro poznat. Jedan od čestih problema, koji zahteva posebnu pažnju, je procurivanje na spoju cevi i cevne ploče, /1/. Takav problem se pojavio u proizvodnji amonijaka u Hemijskoj industriji (HIP), Pančevo. Inspekcija je u toku rada uočila curenje na više prodora cevi u cevnu ploču zagrejača napojne vode, što je zahtevalo popravku. Prvobitno rešenje glave zagrejača i zavarenog spoja sa cevnom pločom prikazano je na sl. 1, zajedno sa cevnom pločom i cevima. Raspored cevi u cevnoj ploči je dat na sl. 2. U prvobitnom rešenju spoja, koje se sastojalo od uvaljivanja cevi u cevnu ploču i njihovog mehaničkog širenja (sl. 3), uzeto je u obzir samo zaptivanje, ali ne i termičko i mehaničko opterećenje spoja. Posle kratkog vremena rada zagrejača vode pojavilo se procurivanje zbog pomeranja cevi u cevnoj ploči, uzrokovano termičkim i mehaničkim preopterećenjem. Da bi se sprečilo dalje cure

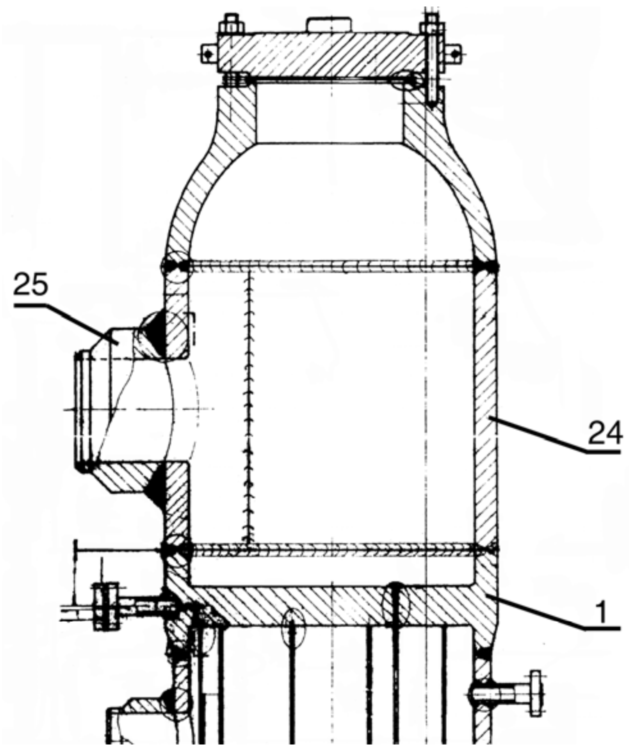
INTRODUCTION

The leakage problem and failure of feedwater heater components in ammonia converter is well known. One of the frequent problem requiring special attention is the leakage on the tube-to-tubesheet connection, /1/. Such a problem had occurred in the production of ammonia in the Chemical Industrial Plant (HIP) at Pančevo. In-service inspection revealed leakage in several tube-to-tubesheet joints of the feedwater heater, that required repair. The original water heater header design and tube-to-tubesheet welded joint is presented in Fig. 1, along with tubesheet and tubes. The disposition of tubes in tubesheet is given in Fig. 2. The original joint design consisted of rolling tubes into tubesheet and their mechanical expansion (Fig. 3) and had only taken into account the sealing, neglecting thermal and mechanical loads of the joint. After a short service time of the water heater, leakage occurred due to tube displacements in the tubesheet, caused by thermal and mechanical nje bilo je potrebno rekonstruisati spoj cevi i cevne ploče i popraviti zagrejač.

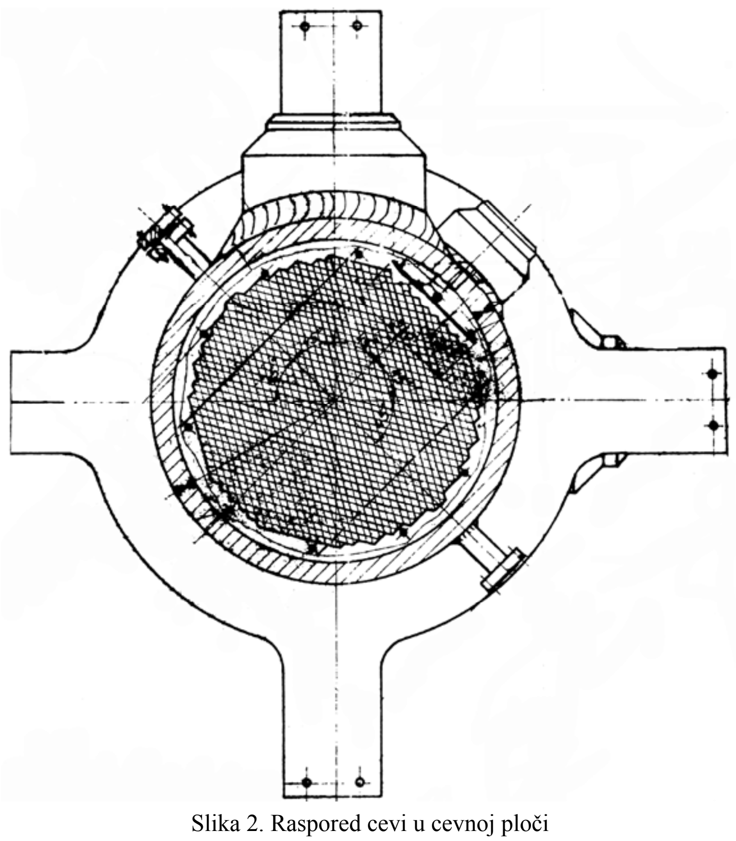
Prikazani su novo rešenje spoja cevi i cevne ploče, postupak popravke i analiza podobnosti za upotrebu.

overload. In order to prevent further leakage, the tube-to-tubesheet joint had to be redesigned and the heater repaired.

Design solutions for tube-tubesheet joints, the repair procedure, and fitness-for-service analysis are presented.



Slika 1. Konstrukcija zavarenog spoja podsklopa glave zagrejača vode (poz. 24) i napojne cevi (poz. 25) sa cevnom pločom (1)
Figure 1. Welded joint design of the water heater header (pos. 24) and the feed pipe (pos. 25) substructure to the tubesheet (pos. 1).



Slika 2. Raspored cevi u cevnoj ploči
Figure 2. Distribution of tubes in the tubesheet.

KONSTRUKCIJA GLAVE ZAGREJAČA I SPOJA CEVI SA CEVNOM PLOČOM

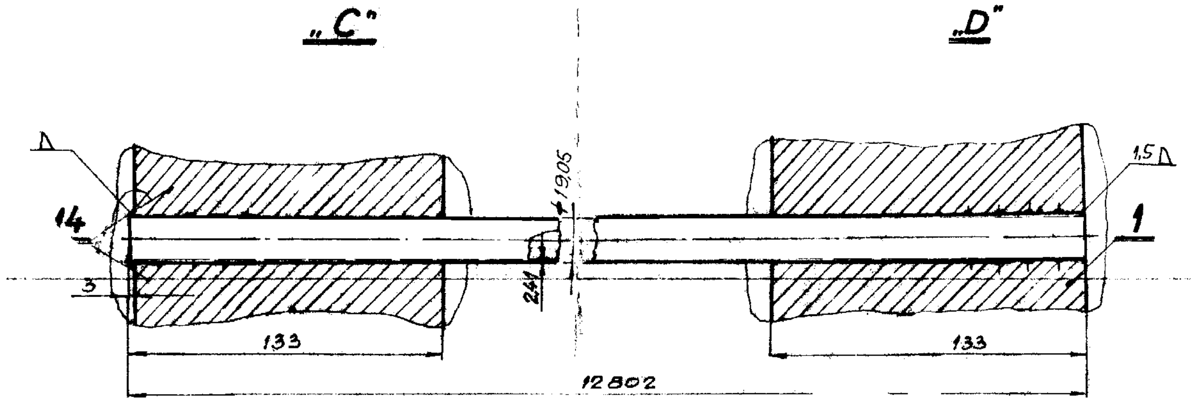
Glava i cevna ploča su izrađene od ugljeničnog čelika, a cevi su izrađene od čelika Cr1/2Mo, /2/. Prvobitno rešenje spoja cevi i cevne ploče, dato na sl. 3, zahtevalo je presovani spoj duž 90% debljine ploče (133 mm) i obezbeđivalo je zaptivanje u početnoj fazi rada. Spojevi su izvedeni uvaljivanjem cevi u cevnu ploču (sl. 1, poz. 1), a zatim mehaničkim proširivanjem.

Novim rešenjem je dodatno izvedeno zavarivanje spoja krajeva svih cevi za cevnu ploču, posle zahtevanog uvaljivanja i širenja u ranijem rešenju. Usvojeno novo rešenje spoja cevi i cevne ploče sa dodatnim zavarivanjem je prikazano na sl. 4. Ono je izvedeno uz nanošenje mekog sloja Inkonela. Prema preporuci Hemijske kompanije Sumitomo to može doprineti smanjenju curenja na spoju cevi i cevne ploče i omogućiti lakše reparaturno zavarivanje na licu mesta, /3/.

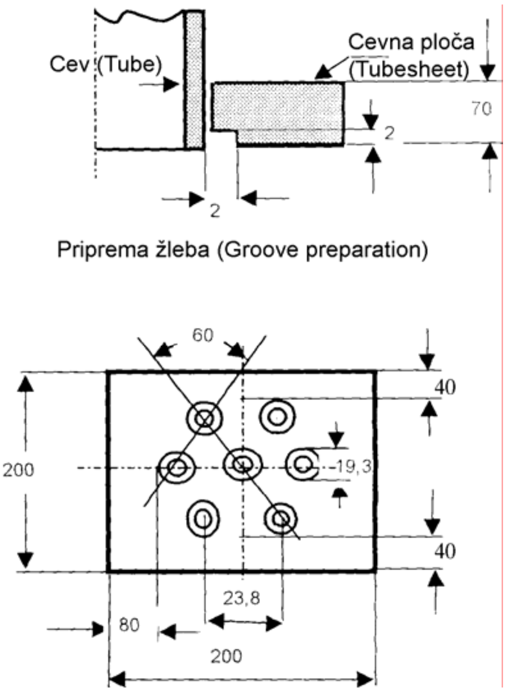
DESIGN OF WATER HEATER HEADER AND TUBE-TO-TUBESHEET CONNECTION

The header and tubesheet are both made of carbon steel, and the tubes of Cr1/2Mo steel, /2/. Original design of tube-to-tubesheet connections, shown in Fig. 3, had required a pressed joint along 90% of sheet thickness (133 mm) and provided sealing in the initial operating stage. Joints were performed by rolling tubes into the tubesheet (Fig. 1, pos. 1), followed by mechanised expanding.

New design introduced welding the tube-to-tubesheet connection at all tube ends in addition to the former design that required only rolling and mechanical expansion. The accepted new tube-to-tubesheet joint design with additional welding is presented in Fig. 4. It is performed by applying additional surfacing with an Inconel soft layer. According to the recommendation of Sumitomo Chemical Company this can help to reduce leakage on tube-to-tubesheet joints and make in-situ weld repairing easier to achieve, /3/.



Slika 3. Prvobitno rešenje veze cevi i cevne ploče
Figure 3. Original design of tube-to-tubesheet connection.



Slika 4. Konstrukcija pripreme ploče i dimenzije uzorka za kvalifikaciju postupka zavarivanja sa rasporedom cevi
Figure 4. Design of plate preparation and dimensions of sample for welding procedure qualification with tube distribution.

POSTUPAK POPRAVKE

Svrha zahtevane popravke je da se spreči dalje curenje na spoju cevi i cevne ploče. Rekonstrukcija i postupak popravke zagrejača napojne vode moraju biti odobreni u proceduri uobičajenoj za osiguranje kvaliteta zavarivanja.

Prvobitnim rešenjem zagrejača vode nije predviđena zamena ili popravka cevi, pa je na kraju izrade glava zavarena za omotač zagrejača. Da bi se omogućilo naknadno zavarivanje cevi sa cevnom pločom (sl. 4) trebalo je rezanjem odvojiti priključeni cevovod, kao i podsklop glave (sl. 1, poz. 24) i napojne cevi (poz. 25) od cevne ploče (poz. 1). Prema standardima postupak zavarivanja mora biti kvalifikovan radi osiguranja kvaliteta posle popravke. Zbog toga su sprovedene kvalifikacije tehnologije zavarivanja cevi za cevnu ploču (sl. 4) i završnog zavarivanja cevne ploče i omotača (sl. 5).

Sem toga, zahtevana je i ocena podobnosti za upotrebu popravljenog zagrejača.

Postupak popravke je predvideo sledeće operacije:

- Analizu oštećenja.
- Rekonstrukciju spoja cevi i cevne ploče.
- Modeliranje i numeričku analizu čvrstoće za ocenu podobnosti za upotrebu.
- Specifikaciju i kvalifikaciju postupka zavarivanja.
- Popravku u radionici.

Postupak je uključio primenu standardnih zahteva za kvalitet zavarenih spojeva, JUS ISO 3834, /4/, i kvalifikaciju postupka zavarivanja, JUS EN 288, /5/.

Popravljena oprema mora da bude ispitana probnim pritiskom propisanog nivoa za osiguranje kvaliteta i ocenu podobnosti za upotrebu. Preporuka proizvođača zagrejača je da se probno ispitivanje izvede u radnim uslovima, kako je prihvaćeno za novu opremu ove vrste.

Redosled operacija u postupku popravke je bio:

- Odvajanje priključnog cevovoda i podsklopa glave i napojne cevi od cevne ploče, postupkom koji je definisan u reparaturnoj tehnologiji zavarivanja.
- Priprema cevi i cevne ploče, sl. 4.
- Predgrevanje cevne ploče prema elementima dobijenim detaljnom analizom numeričkim modelom.
- Zavarivanje cevi za cevnu ploču.
- Brušenje ivica glave i cevne ploče, sl. 5.
- Oslojavanje glave i omotača austenitnom elektrodom.
- Termička obrada posle zavarivanja glave i omotača radi otpuštanja napona, sl. 6.
- Oslojavanje (puterovanje) austenitnom elektrodom glave i cevne ploče pre završnog zavarivanja.
- Završno zavarivanje spoja glave i omotača (cevne ploče).
- Zavarivanje cevovoda.

Specijalni uređaj je korišćen za pripremu cevne ploče za zavarivanje cevi. Sem stroge kontrole pri izvođenju pažnja je posvećena predgrevanju kao operaciji važnoj za uspeh reparaturnog zavarivanja. Posle predgrevanja je izvedeno TIG zavarivanje žicom INCO 82. Kako je korak cevi mali, u stvari je gornja površina cevne ploče oslojena pri zavarivanju, kako je i preporučeno, /3/. Time je izbegnuta prekomerna krutost spoja i omogućeno pomeranje cevi u cevnoj ploči u radu, čime je sprečeno curenje u daljem radu.

REPAIR PROCEDURE

The aim of required repair is to prevent further leakage in tube-to-tubesheet joints. Redesign and repair procedures of feedwater heater must be approved in the usual procedure for welding quality assurance.

The original water heater design does not foresee replacement or repair of tubes, and so manufacturing was finalized by welding the header to the heater shell. In order to allow additional welding of tubes to tubesheet (Fig. 4), the attached pipeline had to be separated by cutting, as well as the header (Fig. 1, pos. 24) and feed pipe (pos. 25) substructure of the tubesheet (pos. 1). According to standards, welding procedure has to be qualified for quality assurance after repairing. Thus, procedures for qualification of technologies for tubes to tubesheet welding and final welding of tubesheet to mantle (Fig. 5) were performed.

In addition, the fitness-for-purpose assessment of the repaired heater is requested.

The repair procedure included following operations:

- Analysis of damage.
- Redesign of tube-to-tubesheet connection.
- Modelling and numerical strength analysis for fitness-for-service assessment.
- Welding procedure specification and qualification.
- Repair in the workshop.

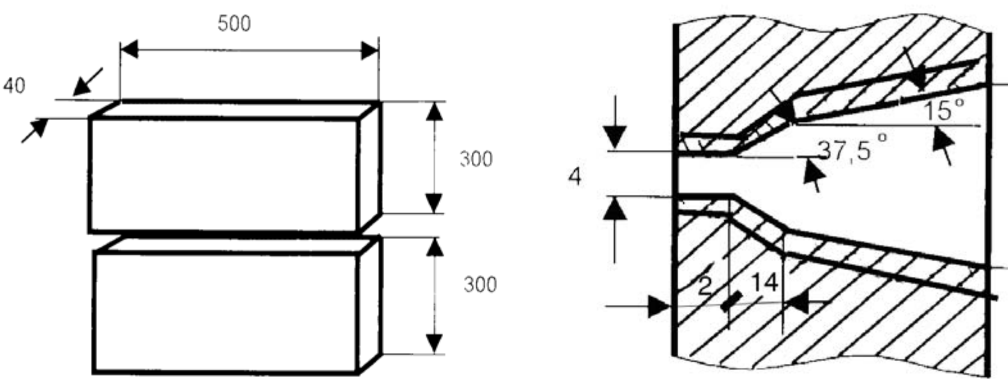
The procedure included application of standard requirements for welded joints quality, JUS ISO 3834, /4/, and welding procedure qualification, JUS EN 288, /5/.

Repaired equipment had to be pressure proof tested at the level prescribed for quality assurance and fitness-for-service assessment. According to recommendation of the heater manufacturer a proof test is performed under working conditions, as accepted for new equipment of this type.

The sequence of repair procedure operations was:

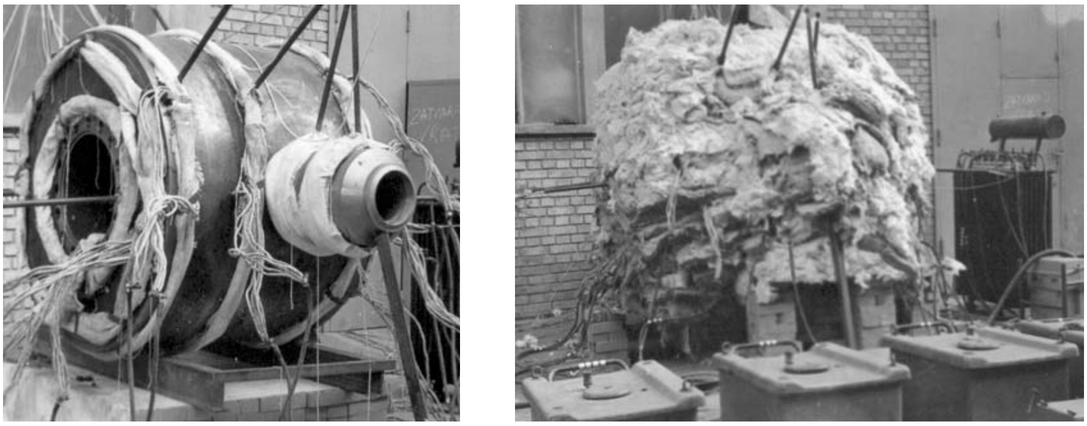
- Separation of attached pipeline and substructure of header and inlet pipe from the tubesheet, by procedure defined in repair welding technology.
- Preparation of tubes and tubesheet, Fig. 4.
- Tubesheet preheating according to elements obtained by detailed analysis by numerical model.
- Welding of tubes to tubesheet.
- Grinding the edges of header and tubesheet, Fig. 5.
- Header and mantle surfacing with austenitic electrode.
- Post weld heat treatment of header and mantle for stress relaxation, Fig. 6.
- Surfacing (buttering) with austenitic electrode of the header and the tubesheet before final welding.
- Final welding of header to mantle (tubesheet) joint.
- Welding of pipeline.

A special device is used for preparing the tubesheet for welding tubes. Additionally to strict manufacturing control, attention is paid to preheating as an important operation for successful repair welding. After preheating, TIG welding is performed with INCO 82 wire. Since the tube pitch is small, the tubesheet upper surface is in fact cladded during welding, as recommended, /3/. Excessive stiffness of the joint is avoided, allowing displacement of tubes in tubesheet in service, thus preventing leakage in future service.



Priprema uzorka (Sample preparation) Priprema spoja (Joint preparation)

Slika 5. Dimenzije uzorka za kvalifikaciju postupka zavarivanja i priprema oslojavanjem za zavarivanje glave i cevne ploče
Figure 5. Dimensions of sample for welding procedure qualification and preparation by surfacing for header to tubesheet welding.



(a) (b)

Slika 6. Priprema glave za termičku obradu posle zavarivanja (a) i izgled tokom termičke obrade (b)
Figure 6. Preparation of header for post-weld heat treatment (a) and the view during heat treatment (b).

Ponovno zavarivanje glave i cilindričnog omotača je zahtevalo posebnu pažnju da bi se izbegli veliki zaostali naponi. Posle brušenja ivica glave i omotača propisano je oslojavanje TIG žicom INCO 82 (sl. 5). Probno zavarivanje uzorka izvedeno je prema operacijama kvalifikovane tehnologije. Termička obrada posle zavarivanja na 600°C sa minimalnim držanjem tokom 1 časa za svakih 25 mm debljine glave i omotača da bi se otpustili naponi uneti oslojavanjem je propisana na osnovu iskustva, /6/, i izvedena lokalnim zagrevanjem i prikladnom izolacijom uz strogu kontrolu procesa (sl. 6). Isti postupak je primenjen i za termičku obradu posle zavarivanja glave i cevne ploče. Sledeća operacija je bila oslojavanje elektrodom Inconel 180 pre završnog zavarivanja elektrodom koja odgovara primenjenom ugljeničnom čeliku.

NUMERIČKI MODELI I REZULTATI ANALIZE

Tri različita modela su razvijena za numeričku analizu primenom KOMIPS programa (Kompjutersko modeliranje i proračun struktura – *Computer Aided Modelling and Calculation of Structures*), /7/.

Zagrejač vode je prvo modeliran da bi se dobila slika o stanju pre popravke.

Izvedeni model polovine dužine zagrejača koji odgovara realnom ponašanju u radu je dat na sl. 7. Glavne komponente zagrejača (cilindrični omotač, cevna ploča i ojačanja)

Repeated welding of the header and cylindrical mantle required special precaution in order to avoid excessive residual stresses. After grinding the edges of header and mantle, the surfacing by TIG using INCO 82 wire was prescribed (Fig. 5). Trial welding of samples had been performed following operations of qualified technologies. Post-weld heat treatment at 600°C with minimum 1 hour holding time for each 25 mm thickness of header and mantle for relaxing residual stresses induced by surfacing is required based on experience, /6/, and performed by heating locally with proper insulation and strict process control (Fig. 6). The same procedure was applied for post-weld heat treatment of header and tubesheet. Next operation was buttering with Inconel 180 electrode before final welding by electrodes, corresponding to the carbon steel used.

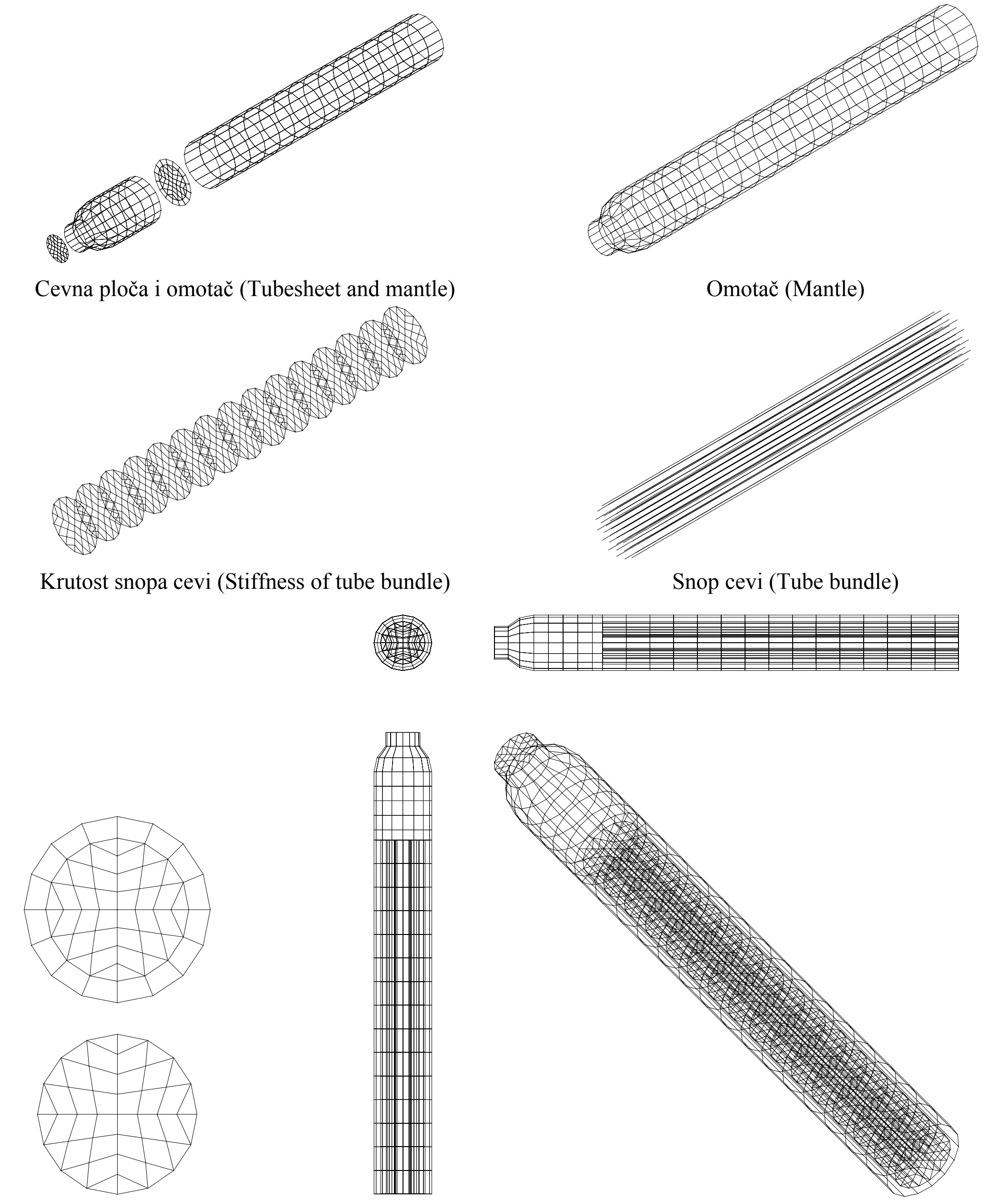
NUMERICAL MODELS AND RESULTS OF ANALYSIS

Three different models have been developed for numerical analysis by applying KOMIPS software (*Kompjutersko modeliranje i proračun struktura* – Computer Aided Modelling and Calculation of Structures), /7/.

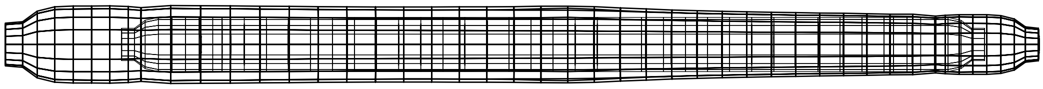
The water heater is modelled first in order to get a picture about the situation before repair.

A generic half length model of the heater corresponding to real service behaviour is presented in Fig. 7. Main components of the heater (cylindrical mantle, tubesheets and su modelirani konačnim elementima kao ploča, a cevi su modelirane kao greda, i predstavljaju grubi model. U grubi model je uneto samo nekoliko cevi, koje opisuju ponašanje svih cevi. Raspodela pomeranja zbog unutrašnjeg pritiska i termičkog opterećenja zagrejača je modelirana na sl. 8. Maksimalno pomeranje zagrejača je bilo 1,13 cm, što je omogućilo da se zaključi da deformacija cevne ploče dopušta popravku zagrejača.

reinforcements) are modelled by finite elements as plates, and tubes are modelled as beams, representing a coarse model. In the coarse model only several tubes are involved, but they describe behaviour of all tubes. Distribution of displacements due to inner pressure and thermal loading of the entire heater is modelled in Fig. 8. The maximal displacement of the heater was 1.13 cm, enabling to conclude that tubesheet deformation allows for the heater repair.



Slika 7. Izvedeni numerički model konačnih elemenata polovine dužine zagrejača
Figure 7. Generic numerical finite element model of water heater half length.



f_{max} = 1.13 cm

Slika 8. Raspodela pomeranja na modelu zagrejača
Figure 8. Distribution of displacements on the heater model.

Mehanička i termička pomeranja su uzeta odvojeno da bi se razmotrio njihov pojedinačni uticaj na veličinu i stanje napona, jer nije bilo moguće njihovo razdvajanje u shemi ukupnog pomeranja.

Interesantno je područje gornje glave (sl. 1, pos. 24) i cevne ploče (pos. 1) sa cevima. Izmerene vrednosti pritiska i temperature u realnim uslovima eksploatacije su unete u model. Unutrašnji pritisak je 15,1 bar, a temperatura omotača je 266°C. Temperatura cevne ploče je sa gornje strane 286°C, a sa donje strane je 262°C. Temperatura spoja omotača i cevne ploče je 254°C. Izolovano područje omotača zagrejača (između gornje i donje cevne ploče) je izloženo pritisku 12,3 bar i temperaturnom gradijentu od 262°C u gornjem do 126°C u donjem delu. Cevi su izložene istom gradijentu temperature. Veličina napona u gornjoj cevnoj ploči i u njenoj okolini, koja odgovara uslovima eksploatacije, je data u tab. 1. Analiza raspodele napona je otkrila da se maksimalni napon dobro slaže sa obimnim naponom ($\sigma = pR/t$; p–pritisak, R–unutrašnji poluprečnik, t–debljina zida). Gornja strana cevne ploče (u području zavarivanja cevi) je izložena zatezanju, što može biti nepovoljno za zaptivanje između cevi i cevne ploče, i verovatno je najvažniji uzrok curenja.

Gornji znak u „±“ i „∓“ odgovara vrsti napona („+“ za zatezanje, „–“ za pritisak) na strani cevne ploče izloženoj većem naponu i višoj temperaturi, a donji znak označava stranu manjeg napona i niže temperature. Prvi broj u veličini napona predstavlja komponentu membranskog napona (napon ploče u njenoj ravni), drugi predstavlja savojnu komponentu (napon upravan na ravan ploče).

Oba maksimalna napona, u omotaču (121,5 MPa) i u cevnoj ploči (90,7 MPa) su znatno ispod napona tečenja čelika. Međutim, zatezni napon u cevnoj ploči je nepovoljan za zaptivanje cevi, jer doprinosi curenju.

The mechanical and thermal displacements were taken separately in order to consider their individual effects on stress magnitude and state, since it was not possible to separate them in total displacements scheme.

The region of interest is the upper header (Fig. 1, pos. 24) and tubesheet (pos. 1) with tubes. Measured values of pressure and temperature in real service conditions are involved in the model. Inner pressure is 15.1 bar and the mantle temperature is 266°C. The tubesheet temperature is 286°C on upper side and 262°C on bottom side. The temperature of the joint between mantle and tubesheet is 254°C. Insulated region of heater mantle (between upper and lower tubesheets) is exposed to pressure of 12.3 bar and temperature gradient from 262°C in the upper to 126°C in bottom part. Tubes are exposed to the same temperature gradient. Stress magnitude in upper tubesheet and close to it, corresponding to operating conditions, is given in Table 1. The analysis of stress distribution revealed that maximum stress corresponds well to the hoop stress ($\sigma = pR/t$; p–pressure, R–inner radius, t–wall thickness). The upper side of tubesheet (in position of tube welding) is exposed to tension, that could be inconvenient for sealing between tube and tubesheet, and is probably the most important cause of leakage.

Upper sign in "±" and "∓" corresponds to stress type ("+" for tension, "–" for compression) on tubesheet side exposed to higher stress and temperature, and lower sign indicates the side of lower stress and temperature. First number in stress magnitude represents membrane stress component (sheet stress in its plane), the second represents bending component (stress normal to sheet plane).

Both maximum stresses, in mantle (121.5 MPa) and in tubesheet (90.7 MPa) were well bellow yield strength of the steel. Anyhow, tensile stress in tubesheet is inconvenient for sealing of the tubes, contributing to the leakage.

Tabela 1. Raspodela napona u radijalnom i obimskom pravcu u području gornje cevne ploče

Komponenta napona	Udeo u radijalnom naponu (MPa) od			Udeo u obimskom naponu (MPa) od		
Položaj	pritiska	temperature	ukupno	pritiska	temperature	ukupno
omotač, udaljeno od cevne ploče, gore	52±2	≈0	52±2	109±0	≈0	109±0
omotač, blizu cevne ploče, gore	52∓44	0±32	52∓12	52∓13	17±10	69∓3
cevna ploča - sredina	23∓30	–10±56	13±26	23∓30	–10±56	13±26
cevna ploča – blizu omotača	23∓2	3±57	26±55	23±19	–8,3±57	14,7±76
omotač, blizu cevne ploče, dole	78∓1	8∓2	86∓3	54∓3.5	0∓6	54∓9.5
omotač, udaljeno od cevne ploče, dole	54,3±8,4	≈0	54,3±8,4	119±2,5	≈0	119±2,5

Table 1. Stress distribution in radial and hoop directions in the region of upper tubesheet.

Stress components	Contribution to radial stress (MPa) from			Contribution to hoop stress (MPa) from		
Position	pressure	temperature	total	pressure	temperature	total
mantle, remote of tubesheet, up	52±2	≈0	52±2	109±0	≈0	109±0
mantle, close to tubesheet, up	52∓44	0±32	52∓12	52∓13	17±10	69∓3
tubesheet – centre	23∓30	–10±56	13±26	23∓30	–10±56	13±26
tubesheet – close to mantle	23∓2	3±57	26±55	23±19	–8.3±57	14.7±76
mantle, close to tubesheet, down	78∓1	8∓2	86∓3	54∓3.5	0∓6	54∓9.5
mantle, remote of tubesheet, down	54.3±8.4	≈0	54.3±8.4	119±2.5	≈0	119±2.5

Da bi se ocenio uticaj različitih vrsta elektroda na zaptivanje zavarenog spoja, izveden je drugi model za odgovarajuće čelike i debljine. Razmatrana su dva slučaja: isti koeficijent termičkog širenja za osnovni metal i metal šava (α_1 =

In order to evaluate the effect of different electrode types on welded joint sealing, a second model is generated for the corresponding steels and thicknesses. Two cases were considered: the same thermal expansion coefficient for both

α_2), i austenitni metal šava, sa 50% većim koeficijentom termičkog širenja u odnosu na osnovni metal ($\alpha_2 = 1,5\alpha_1$). Dobijene vrednosti za maksimalni napon u zavarenom spoju cevne ploče prikazani su u tab. 2. Detalji razvijenog modela mogu se naći u ref. /7/. Najvažniji zaključak iz ove analize je da je maksimalni napon od 90 MPa u cevnoj ploči pritisni, što je povoljno za zaptivanje cevi u eksploataciji.

weld and parent metals ($\alpha_1 = \alpha_2$), and austenitic weld metal with 50% higher thermal expansion coefficient compared to parent metal ($\alpha_1 = 1.5\alpha_2$). The obtained values for maximal stresses in tubesheet welded joint are presented in Table 2. The details of developed model can be found in Ref. /7/. The most important conclusion from this analysis is that maximal stress of 90 MPa in tubesheet is compressive and is beneficial for tube sealing in service.

Tabela 2. Maksimalni lokalni napon u spoju cevi i cevne ploče za dva tipa elektrode

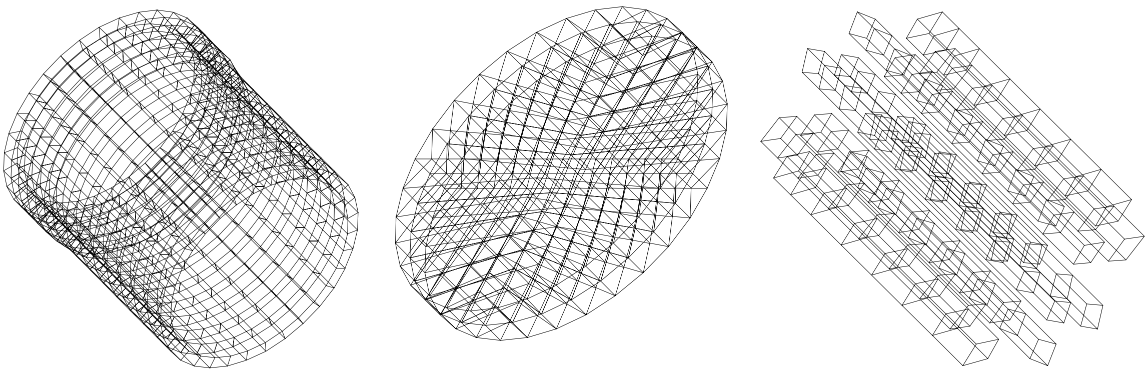
Napon (MPa)	Koeficijent termičkog širenja osnovnog metala α_1 i metala šava α_2	
	$\alpha_2 = \alpha_1$	$\alpha_2 = 1,5\alpha_1$
Gornja strana zavarenog spoja	9 (zatezanje)	–90 (pritisak)
Donja strna zavarenog spoja–zona uticaja toplote	9,4 (zatezanje)	8,4 (zatezanje)

Table 2. Maximum local stress in tube-to-tubesheet joint for two electrode types.

Stress (MPa)	Thermal expansion coefficient of parent metal α_1 and weld metal α_2	
	$\alpha_2 = \alpha_1$	$\alpha_2 = 1.5\alpha_1$
Upper side of welded joint	9 (tension)	–90 (compression)
Lower side of welded joint–heat-affected-zone	9.4 (tension)	8.4 (tension)

Treći model predstavlja gornji deo zagrejača, koji približno odgovara sl. 1. On je izveden za analizu lokalnog zagrevanja u zavarenom području pri termičkoj obradi posle zavarivanja. Model od 1299 čvorova, koji definiše 736 prostorna konačna elementa, je dat na sl. 9. Prostorni model izabranog segmenta zagrejača i njegove projekcije su prikazani na sl. 10.

The third model represents upper heater part, approximately corresponding to Fig. 1. It is generated for the analysis of local heating in welded region at post-weld heat treatment. Model of 1299 nodes, defining 736 solid finite elements for substructures of mantle, tubesheet and tubes is presented in Fig. 9. The volumetric model of selected heater segment and its projections are presented in Fig. 10.



Omotač (Mantle) Cevna ploča (Tubesheet) Snop cevi (Tube bundle)

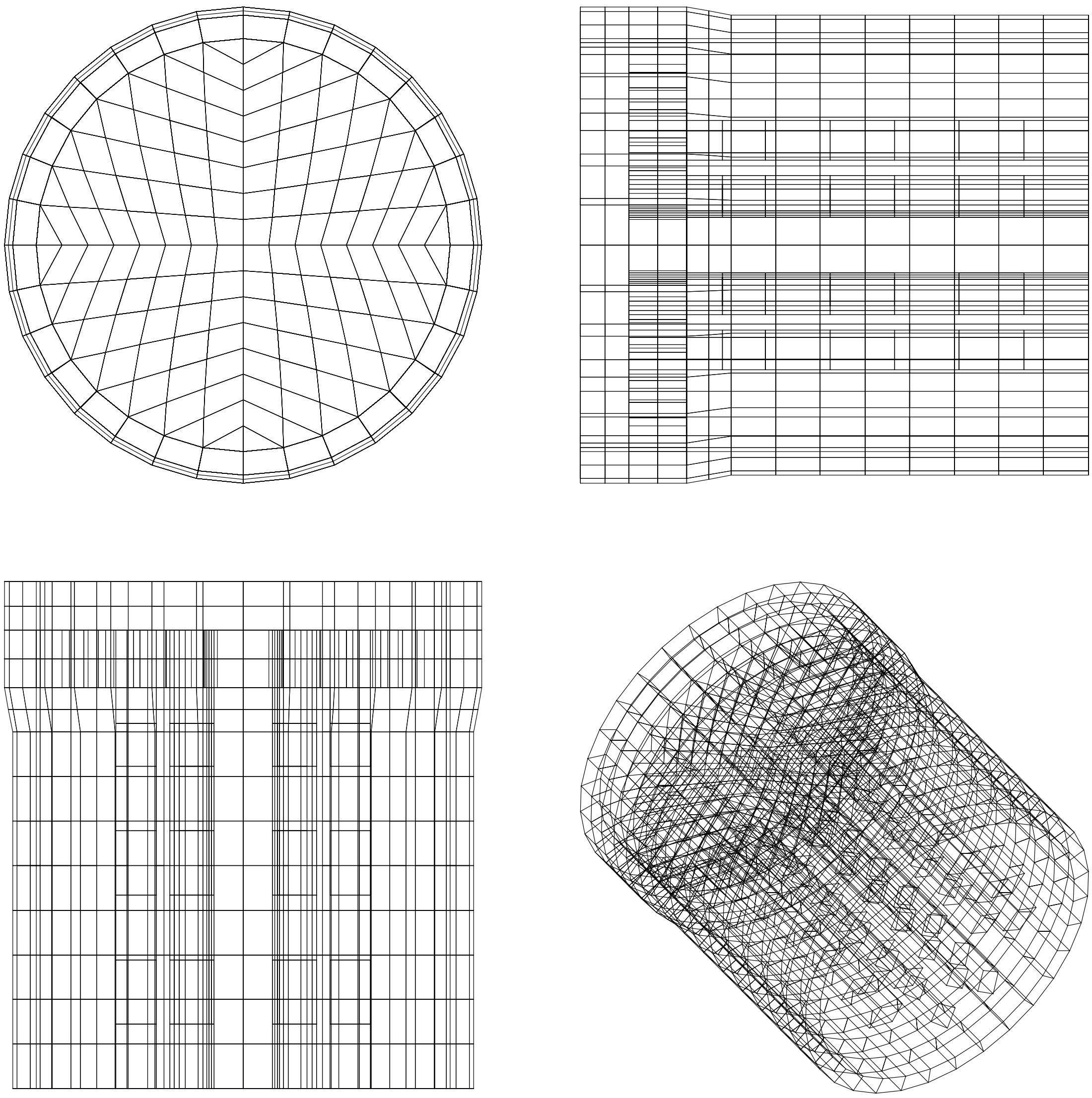
Slika 9. Modeli podsklopova glavnih komponenata zagrejača za simulaciju termičke obrade posle zavarivanja
Figure 9. Substructure models of heater main components for post-weld heat treatment simulation.

Program za nestacionarno nelinearno provođenje toplote je korišćen da se odredi temperaturno polje tokom termičke obrade. Izvor toplote od 4 kW po metru obima je simuliran na gornjem delu omotača na osnovu iskustva. Uzeta su fizička svojstva čelika koja odgovaraju očekivanoj temperaturi zagrevanja. Temperaturno polje je računato svakih 30 minuta sve do 15 sati, kada je dostignuta temperatura 680°C, kako je zahtevano (sl. 11). Raspodela temperature u zidu je bila parabolična.

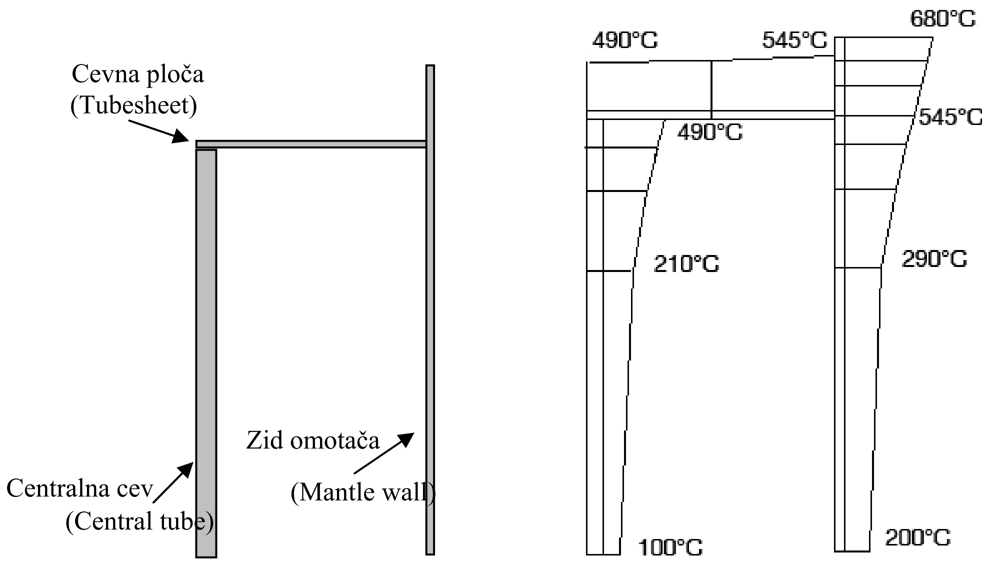
Proračun je izveden korišćenjem drugog modela, ali za drugačije toplotno polje. Pomeranja i naponi su sračunati za dato temperaturno polje i njihova raspodela je data na sl. 12. Rezultati su ukazali na nizak nivo napona, pa je zaključeno da je zagrejač podoban za upotrebu.

A programme for nonstationary nonlinear heat conduction was used to obtain temperature fields during heat treatment. Heat source of 4 kW per metre of perimeter is simulated on the upper mantle part, based on experience. Physical properties of steel are used, corresponding to expected heating temperature. Temperature field is calculated every 30 minutes up to 15 hours, when 680°C is achieved, as required (Fig. 11). Temperature distribution in the wall was parabolic.

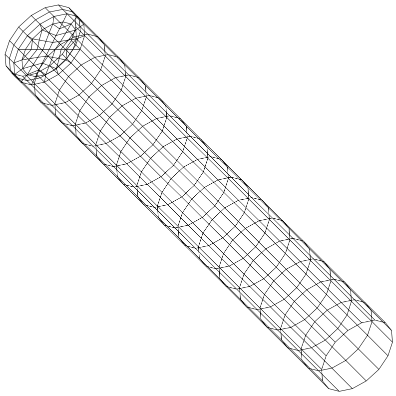
The calculation was performed using the second model, but for a different thermal field. Displacements and stresses were calculated for given temperature field and their distribution is given in Fig. 12. Results indicate low stress level, enabling to conclude that the heater is fit for service.



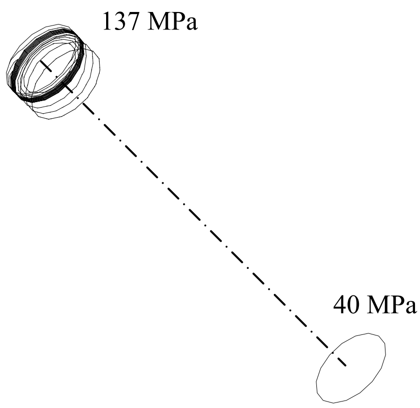
Slika 10. Tri projekcije i prostorni model (desno dole) za simulaciju termičke obrade omotača
Figure 10. Three projections and the volumetric model (lower right) for heat treatment simulation of the mantle.



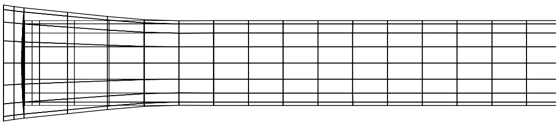
Slika 11. Temperaturno polje koje simulira termičku obradu posle zavarivanja (temperatura 680°C je dostignuta posle 15 sati)
Figure 11. Temperature field simulating post-weld heat treatment (tmeperature 680°C was reached after 15 hours).



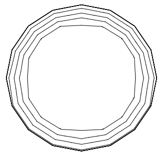
Prostorni model ljuske sa snopom cevi
(Volumetric shell model of mantle with tube bundle)



Naponi u području 40 do 137 MPa
(Stresses range between 40 and 137 MPa)



Deformisano stanje, f_{max} = 0,75 cm
(Deformed state, f_{max} = 0.75 cm)



Izonaponske linije na obimu cevne ploče
(Iso-stress lines at tubesheet periphery)

Slika 12. Model, pomeranja i polje napona u zagrejaču napojne vode posle 15 sati termičke obrade za otpuštanje napona
Figure 12. Model, displacement and stress fields in feedwater heater after 15 hour heating for stress relaxation.

ZAKLJUČAK

Za rešavanje problema curenja na spoju cevi i cevne ploče je bilo potrebno naći uzrok curenja. Analiza prvobitnog projektnog stanja numeričkim modelom je pokazala da se u toj konstrukciji curenje može očekivati.

Problem je rešen dodatnim zavarivanjem krajeva cevi i cevne ploče austenitnom elektrodom, što je uslovilo odsecanje glave zagrejača i njeno ponovno zavarivanje posle popravke spoja cevi i cevne ploče zavarivanjem. Pokazano je da je oslojavanje cevne ploče austenitnom elektrodom povoljno za naponsko stanje u njoj, jer se uvode naponi pritiska, a smanjuju (ili otklanjaju) naponi zatezanja. To je ocenjeno kao povoljno u pogledu zaptivanja.

Stanje napona tokom termičke obrade posle zavarivanja (cevna ploča i omotač) je ocenjeno kao prihvatljivo. Maksimalni napon u rekonstruisanom grejaču je znatno manji od napona tečenja materijala. Time je pokazano da je sigurnost zagrejača u eksploataciji osigurana predloženom tehnologijom popravke i da je zagrejač podoban za upotrebu.

CONCLUSION

In order to solve the leakage problem in the tube-to-tubesheet joint it was necessary to discover the leakage cause. Analysis of the original design solution by numerical modelling revealed that leakage can be expected in this structure.

The problem is solved applying additional welding with austenitic electrode at tube ends and tubesheet, that required cutting the heater header and its repeated welding after repair welding of the tube ends and the tubesheet. It is proved that surfacing the tubesheet with austenitic electrodes is beneficial for its stress state, introducing compressive stress and reducing (or eliminating) tensile stress. This is evaluated as convenient regarding the sealing.

Stress state during post-weld heat treatment (tubesheet and mantle) is evaluated as acceptable. Maximal stress in the re-designed heater are well bellow material yield strength. In this way it is demonstrated that heater service safety is assured by proposed repair technology and that the heater is fit for service.

LITERATURA – REFERENCES

1. R.J. Sherwood, N.M. Patel (Air Products and Chemicals, Inc., Allentown, PA), K.J. Kittelstad (Air Products and Chemicals, Inc., New Orleans, LA), *Modifications Made to 123-C BFW Exchanger with Problems*, pp. 180-189, 1991.
2. American Petrol Institute (A.P.I.), Publication 941, *Steels for Hydrogen Service at Elevated temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*.
3. Sumitomo Chemical Company, *Hydrogen Attack on the Heat Exchanger Installed at the Outlet of Ammonia Converter*, 1990.
4. JUS ISO 3834, *Quality requirements for welding – fusion welding of metallic materials*, 1995.
5. JUS EN 288, *Approval of welding procedures for metallic materials*, 1995.
6. T.L. Huurdeman, H.C. Schrijen (DSM Fertilizers, Gelen, The Netherlands), *Post-Weld Heat Treatment of a Repaired Synloop Waste Heat Boiler*, pp. 195-206, 1991.
7. T. Maneski: KOMIPS Software (*Kompjutersko modeliranje i proračun struktura–Computer Aided Modelling and Calculation of Structures*), Faculty of Mechanical Engineering, University of Belgrade, 1998.