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NUMERICAL CALCULATION OF THE WATER-TUBE BOILER USING FINITE ELEMENT OF THE ORTHOTROPIC PLATE

NUMERIČKI PRORAČUN VODENOG CEVNOG KOTLA PRIMENOM KONAČNIH ELEMENATA ORTOTROPNE PLOČE

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- water-tube boiler
- temperature
- membrane wall
- orthotropic plate
- stress field

Ključne reči
- vodocevni kotao
- temperatura
- membranski zid
- ortotropna ploča
- naponsko polje

Abstract

Norms handle the issues concerned with calculation of pressurized boiler components, however not considering the influences of thermal strains. Application of FEM in boiler design is suggested in calculating all components that are not covered by the norm. Detailed numerical calculation of the water-tube boiler type VU60-Minel Kotlogradnja is presented in the paper. Stress and strain fields are obtained based on numerical models for various types of loading. The influences of the over-pressure and thermal loading are discussed. Distribution of membrane and bending stresses for substructures and distribution of deformation energy are involved in the analysis. Membrane walls (tube panels) of the water-tube boilers are exposed to large loads. They are modelled using elements of a thin orthotropic plate. The influence of the buck-stays on the structural behaviour is discussed.

Izvod

Norme uglavnom pokrivaju proračun delova pod pritiskom, ali uglavnom bez uticaja termičkih opterećenja. Primena metode konačnih elemenata predlaže se pri proračunu svih komponenti koje norme ne obuhvataju. U radu je prikazan detaljan numerički proračun vodocevnog kotla tipa VU60 – Minel Kotlogradnja. Na osnovu numeričkih modela određena su polja napona i deformacija za različita opterećenja. Razmatran je uticaj natpritiska i termičkog opterećenja. Primenjeni su i parametri dijagnostike čvrstoće kao što su raspodela membranskih i savojnih napona po podstrukturama i raspodela energije deformacije. Membranski zidovi (cevni paneli) vodocevnih kotlova izloženi su veoma velikim opterećenjima. Modelirani su elementima tanke ortotropne ploče. Razmotren je uticaj pojaseva ukrućenja na ponašanje konstrukcije kotla.

INTRODUCTION

Norms such as EN 12952-3 and EN 12953-3 /1/ give exact rules for calculation of pressurized elements in boiler structures, they define allowed stresses for a given temperature and bring formulas for strength calculation. Norms do not explicitly consider the influence of thermal stresses and local stress-concentration. This problem can be solved with the application of the finite element method-FEM.

Taljat et al. /2/ had done thermomechanic analysis for membrane walls of composite tubes for the black liquor recovery boiler. The problem of contraction of the membrane wall during sedimentation of stainless-steel on damaged panel is considered in /3/. A proposal for partial replacement of boiler wall-tubes is defined in /4/ and a sequence of service recommendations how to prevent the appearance of wall tubing damage was also given. In /5/ it was presented that temperature is the most important factor in failure investigation on deformed horizontal super-heater tube. The influence of welded shanks between super heater-tubes on the high temperature stresses near the welds is considered in /6/. A recent approach in the estimation of boiler integrity using FEM on vertical superheater is presented in /7/. The methodological approach for the state analysis of the boiler pipe system in the case of hot-water boiler VKL50 and methods for testing the parent metal and welded joints are presented in /8/. Distance in thermal dilatations on the coupled components of the steam boiler can lead to large plastic deformation /9/ and to the increase of dynamic strength. Membrane walls can be modelled using finite elements of thin orthotropic plate /10/. This gives a decrease in nodal points and elements of the global model of the boiler structure and a decrease in calculation time /11/.

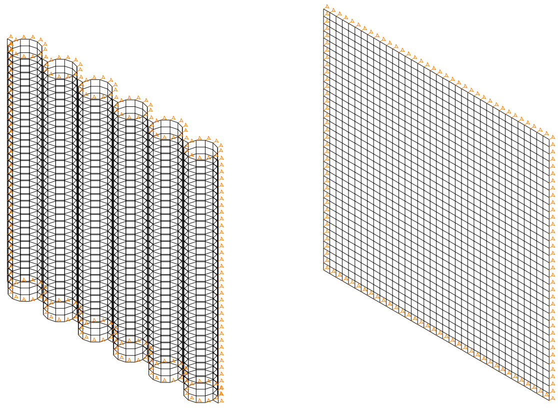
The methodology of condition and behaviour diagnostics for boiler structures which has been necessary to perform in order to make a decision on further operation is presented in /12/. An algorithm is defined that illustrates methods for collecting data needed for diagnostics. During exploitation the boiler state can be evaluated by comparing to the initial stress state. The obtaining of the initial stress state of boiler tubes for structural integrity assessment is shown in /13/.

Water-tube boilers have a large capacity and they are designed for high steam pressures and temperatures. Membrane walls are stiffened with buck-stays placed to prevent large wall deformations. FEM-modelling and analysis are usually applied for individual components, without modelling of a global boiler structure. In the paper, a numerical model of the global structure of the water-tube boiler type VU60 is presented, as well as the results for deformation and stress fields obtained by a numerical procedure.

MODELLING OF THE MEMBRANE WALLS

The membrane wall of the water-tube boiler type VU60 is consisted of tubes diameter 71.6 mm and thickness 4.5 mm with weldments thickness 6 mm. Tube distance is 102 mm. Elastic characteristics of the steel for temperature $T = 321$°C are: modulus of elasticity $E = 18300$ kN/cm^2 and Poisson's ratio $\nu = 0.328$.

In the numerical finite element model of the water-tube boiler, the membrane wall can be modelled using the finite element of the reduced orthotropic plate. For this type of finite element, the reduced elasticity matrix is obtained and involved in the calculation as presented in /10/ and /11/.



a) membrane wall b) plate

Figure 1. Membrane-wall and reduced orthotropic plate.
Slika 1. Membranski zid i redukovana ortotropna ploča

For the presented example of the membrane wall (Fig. 1a), the elasticity matrix for the reduced orthotropic plate thickness of 3 cm (Fig. 1b) has the following form:

– for membrane load

$$\begin{bmatrix} 6832 & 27 & 0 \\ 27 & 82 & 0 \\ 0 & 0 & 6890 \end{bmatrix} \frac{\text{kN}}{\text{cm}^2}, \quad (1)$$

– for bending load

$$\begin{bmatrix} 24406 & 98 & 0 \\ 98 & 367 & 0 \\ 0 & 0 & 6890 \end{bmatrix} \frac{\text{kN}}{\text{cm}^2}. \quad (2)$$

In the same way, for plate thickness of 1 cm, the elasticity matrix for membrane load has the form

$$\begin{bmatrix} 20530 & 82 & 0 \\ 82 & 247 & 0 \\ 0 & 0 & 6890 \end{bmatrix} \frac{\text{kN}}{\text{cm}^2}. \quad (3)$$

For the other type of membrane-wall the whole procedure for obtaining elasticity matrix is performed.

CHARACTERISTICS OF THE WATER-TUBE BOILER

The next calculation is presented for the stress and strain state of the steam water-tube boiler with two drums fabricated by Minel Kotlogradnja Belgrade /14/. The boiler operates in the over-pressure condition.

Maximal permanent steam production is 110 t/h and the short overloading (max. two hours) was 121 t/h. The highest over-pressure in the upper drum was 55 bar. Over pressure in the lower drum was 51 bar and the appropriate water temperature 271°C. On the outlet fitting, steam over-pressure was 44.6 bar and temperature 412°C. Basic dimensions of boiler are: length 9104 mm, width 4896 mm and distance between upper and lower drum 10975 mm. Upper (steam) drum was placed at 13475 mm height and had external radius of ∅1700 mm. The lower (water) one was at 2500 mm with external diameter of ∅1000 mm. The boiler had buck-stays on lateral walls at 5548 mm and at 9148 mm height, as well as flanges on the floor and on the ceiling.

The boiler consisted of following structures: tube system of membrane walls (exposed evaporator), collectors with appropriate tubes, tube colander, tubes between drums (convectional evaporator), upper drum, lower drum, super-heater, economizer, buck-stays, isolation, steel construction with galleries, armature and equipment of the boiler.

Steam super-heater is of bilateral type. Because of the construction it was separated from the boiler and analysed as an individual structure.

MODELS FOR CALCULATION

In the paper the influence of the buck-stays on the strength of the boiler structure is analysed. The load is divided in three parts: pressure load, thermal load and weight of the construction. According to that, five models are formed and discussed:

– Model U1, has no buck-stays; pressure and thermal load,
– Model U2, buck-stays; pressure and thermal load,
– Model U3, buck-stays; pressure and thermal load, weight,
– Model U4, buck-stays; only pressure load,
– Model U5, buck-stays; only thermal load.

The basic geometry of the global model U2 is presented in Fig. 2 using three projections. The whole structure of the boiler is formed using 8385 nodal points, 3747 beam and 5638 plate finite elements.

Substructures of the global model are signed as:
A – upper and lower drum with the supports,
B – membrane walls,
C – sections and flanges of the busk-stays,
D – collectors with supports, tubes,
E – fictive beams.

Substructures A, B and C are formed using plate finite elements, while substructures D and E are formed using beam finite elements.

Membrane walls (substructure B) are important structural parts for strength analysis of water-tube boiler. They can be modelled using finite element of an orthotropic plate which leads to decreasing in node and element numbers of the global boiler model and a reduction in calculation time. For this kind of finite element, a reduced elasticity matrix is obtained.

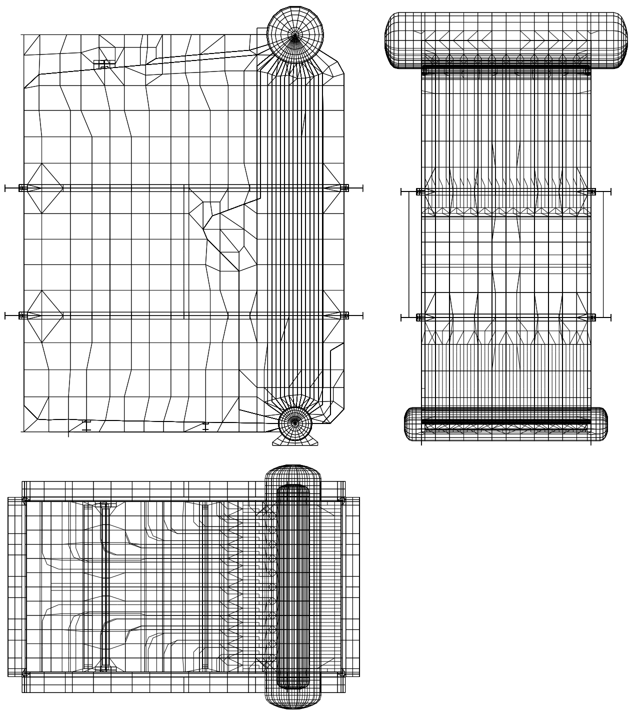


Figure 2. Model for calculation signed as U2.
Slika 2. Model za proračun označen kao U2

Geometry characteristics of beam cross-sections (substructures D and E) are analytically obtained and involved in the finite element calculation.

Loading

The calculation was done for over-pressure of 55 bar in the upper drum and 55.8 bar in the lower one. Over-pressure of 23.4 mbar is adopted in the chamber, while temperatures of the structural parts are adopted according to EN norms and SRPS M.E2.030. So, assumed temperature of the exposed walls is 321°C and 296°C of the convective evaporator. The temperature of the walls under the pressure is adopted as 271°C. The referent temperature is assumed as 20°C.

STRESS AND STRAIN ANALYSIS

Deformations

Numerical calculation is done using the programme package KOMIPS /15, 16/.

The Deformation field for plate elements of Model U1 without busk-stays is presented in Fig. 3. Maximal calculated value is f_{max} = 10.8 cm. This case of construction had great deformations of lateral walls induced by over-pressure.

Appropriate deformation of the Model U2 is shown in Fig. 4. As could be noticed, the maximal calculated value is only 4.9 cm. Buck-stays had dimidiated deformations of the membrane-walls.

Deformations of substructures formed using beam finite elements are presented in Fig. 5. On the model with buck-stays (U2) the dominant influence on the deformation field was the thermal load.

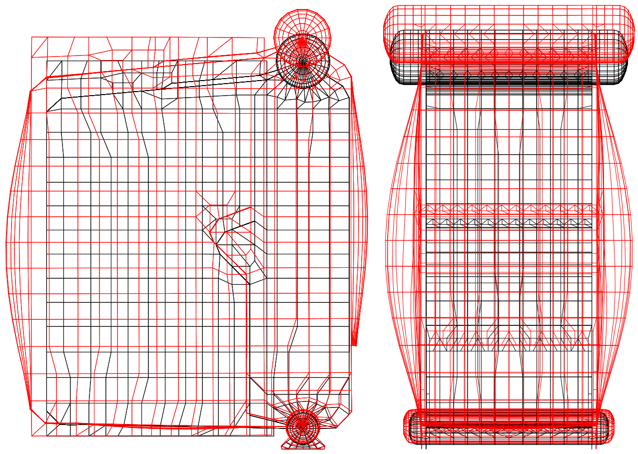


Figure 3. Deformation of the plate elements; Model U1.
Slika 3. Deformacije elemenata ploče; model U1

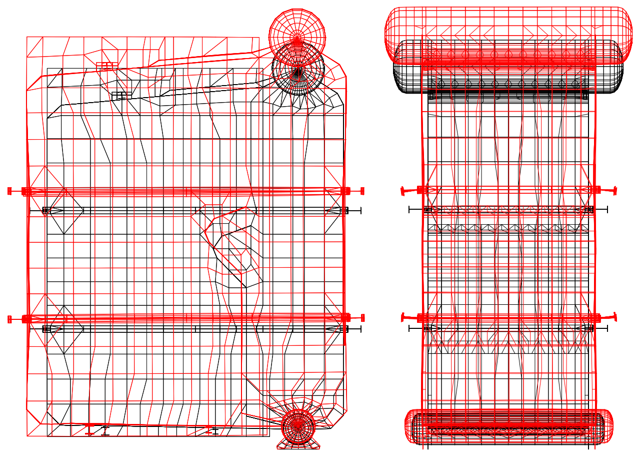


Figure 4. Deformation of the plate elements; Model U2.
Slika 4. Deformacije elemenata ploče; model U2

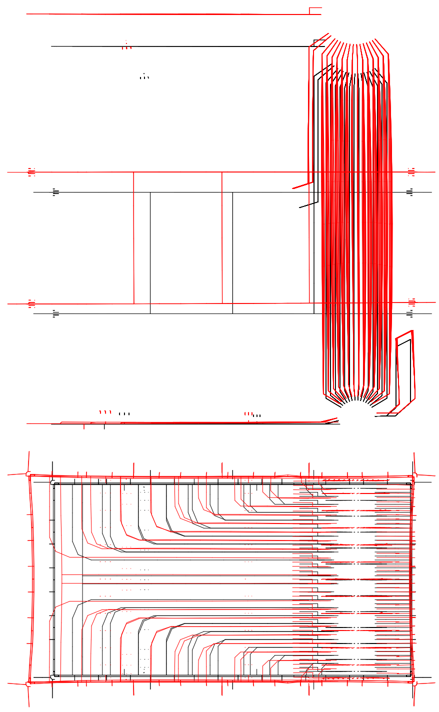


Figure 5. Deformation of beam elements; Model U2.
Slika 5. Deformacije elemenata nosača; model U2

Stress field

The equivalent stress is obtained by using the Huber-Hacky-Misses hypothesis.

The stress field, from 0 to 55.8 kN/cm^2, step 2 kN/cm^2, in the plates of model U1 without buck-stays is presented in Fig. 6. The obtained maximal value due to thermal and pressure load is higher then the tension solidity of the material. So, this type of a structure is unfavourable.

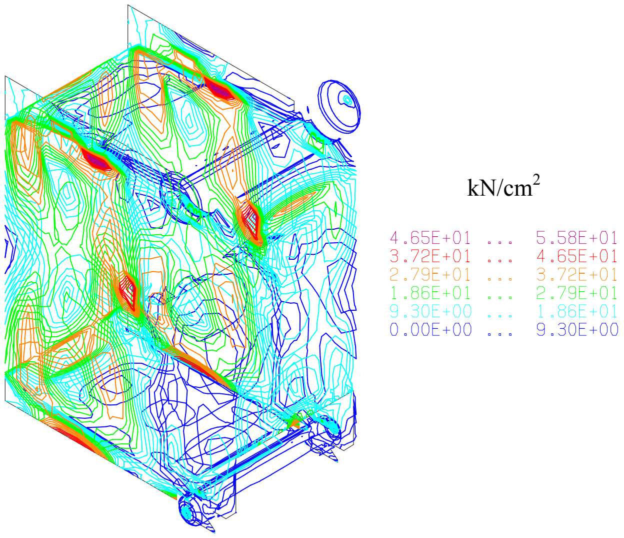


Figure 6. Equivalent stress 0–55.8/2 kN/cm^2 of Model U1.
Slika 6. Ekvivalentni napon 0–55,8/2 kN/cm^2 modela U1

The stress field, from 0 to 19.9 kN/cm^2, step 1 kN/cm^2, in the plates of model U2 with buck-stays is presented in Fig. 7. Maximal stress based on thermal and pressure loading of 19.9 kN/cm^2 is located in horizontal plates of buck-stays, at boiler corners. In lateral walls, stress concentration gave the value of 17 kN/cm^2. In the membrane walls near the boiler corners, the stress was about 16 kN/cm^2.

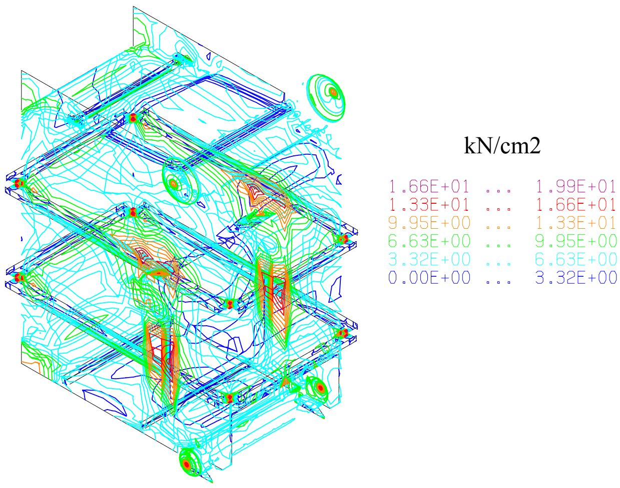


Figure 7. Equivalent stress 0–19.9/1 kN/cm^2 of Model U2.
Slika 7. Ekvivalentni napon 0–19,9/1 kN/cm^2 modela U2

The value of the maximal obtained stress in the beams of Model U2 is 13 kN/cm^2. In the tubes of the lower collector the stress was 5.5 kN/cm^2, while in collectors it was 3.7 kN/cm^2.

The same analysis of Model U3 with added weight of the boiler structure showed that the stress field was similar to the case of the previous Model U2. Maximal stress was 20 kN/cm^2.

DISTRIBUTION OF MEMBRANE AND BENDING STRESS DEFORMATION ENERGY

Distribution of membrane (shear) stress and bending stress /16/ over the beam and plate finite elements of models U1 and U2 is presented in Table 1. As could be noticed, busk-stays gave better behaviour in the boiler structure.

Table 1. Fractions of memb. and bend. stresses in plates and beams.
Tabela 1. Udeli membr. i savojnih napona u pločama i nosačima

Model	Membrane and bending stress (%)			
	Plates		Beams	
	membrane	bending	membrane	bending
U1	32.0	68.0	25.8	74.2
U2	53.1	45.9	60.4	39.6

Detailed distribution over substructures is given in Table 2. Membrane stress is present in plates of the upper (A1) and lower (A2) drum, as well as in their heads and supports (A3). In water-tube panels of membrane walls (B) the bending stress is dominant for Model U1. Model U2 has a better stress distribution. In plates of buck-stays (C) the membrane stress is dominant in case of Model U2. In tubes formed of beam finite elements (D) the stress is in the same relation in both models.

Table 2. Distribution of a deformation energy. Stress distribution over substructures.
Tabela 2. Raspodela deformacione energije. Raspodela napona u podstrukturama.

Substr	Mem. and bend. stress (%)				Deformation energy (%)	
	Model U1		Model U2		Model U1	Model U2
	mem.	bend	mem.	bend		
A1	8.4	0.9	8.9	1.0	28.5	27.7
A2	5.4	1.2	5.8	1.2	8.2	7.7
A3	11.5	8.1	12.2	8.6	4.8	4.6
B	5.0	54.2	7.6	24.1	35.8	35.1
C	-	-	13.2	5.3	-	5.4
D	1.4	3.9	1.4	3.4	22.7	18.7
E	-	-	5.8	1.5	-	0.8
Σ	31.7	68.3	54.9	45.1	100	100
	100		100			

Distribution of deformation energy through sub-structures for both models U1 and U2 is presented in Table 2. The highest value is in the upper drum (A1) and part of the boiler ceiling with walls of chamber (B). The energy distribution is presented in Fig. 8 for plates of Model U2.

STRESS UNDER PRESSURE AND THERMAL LOAD

The equivalent stress field in plates of model U4 (only pressure load) is shown in Fig. 9. The stress concentration is presented in the covers of both drums.

The same analysis is made for Model U5 loaded only by temperature. The obtained results are presented in Fig. 10. As a result of thermal load, a stress concentration in plates of buck-stays placed on boiler corners and in plates of membrane walls appeared.

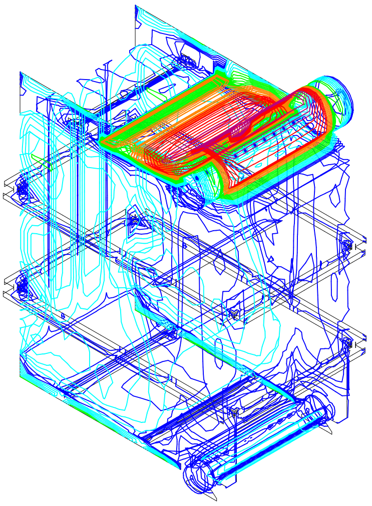


Figure 8. Deformation energy distribution in plates of Model U2.
Slika 8. Raspodela deformacione energije u pločama modela U2

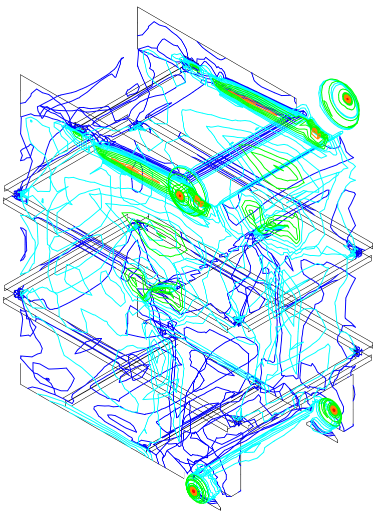


Figure 9. Equivalent stress 0–17.6/1 kN/cm^2 in plates of model U4.
Slika 9. Ekvivalentni napon 0–17,6/1 kN/cm^2 u pločama modela U4

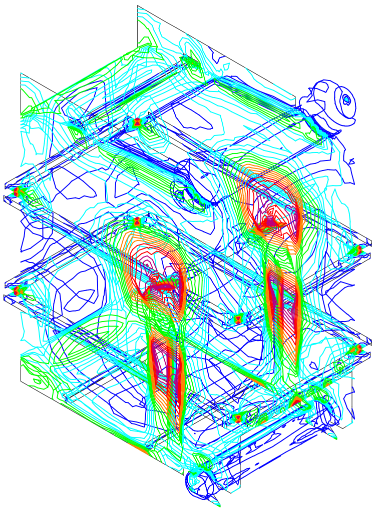


Figure 10. Equivalent stress 0–22.6/1 kN/cm^2 in plates of model U5
Slika 10. Ekvivalentni napon 0–22,6/1 kN/cm^2 u pločama modela U5

CONCLUSION

Obtained results show the great influence of buck-stays on the boiler behaviour. Buck-stays had reduced the deformation and equivalent stress in membrane walls due to over-pressure loading. Distribution of membrane and bending stress is much favourable especially in the lateral sides of the chamber.

Maximal obtained equivalent stress due to the pressure and thermal loading (Model U2) is 19.9 kN/cm^2 and it is located in plates of the buck-stays on boiler corners. The yield stress for the appropriate material P235GH at the estimated temperature is 13 kN/cm^2 (SRPS EN 10028-2). So, plastic deformation could be expected.

In membrane walls of the boiler, the calculated maximal stress is about 17 kN/cm^2. As membrane walls are formed using finite elements of an orthotropic plate, the obtained stress values are average. For the material of the wall-tubes (P235GH) at temperature 321°C, the yield stress is 12.7 kN/cm^2 (SRPS EN 10216-2) and for the material of the flanges (16Mo3) it is 15.2 kN/cm^2. So, small plastic deformation can be expected in some places of membrane walls. The maximal stress in beam elements is about 13 kN/cm^2, close to the value of yield stress in these elements.

The equivalent stress in the lower drum is 17.5 kN/cm^2, less than yield stress 22.7 kN/cm^2 (P355GH) at temperature of 271°C.

The presented analysis showed that the high level of stress in plates on boiler corners is the consequence of the inhibition of thermal dilatations. So, the geometry of buck-stays is unfavourable and needs reconstruction.

ACKNOWLEDGEMENTS

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