CONSTRUCTION OPTIMIZATION OF HOT WATER FIRE-TUBE BOILER USING THERMOMECHANICAL FINITE ELEMENT ANALYSIS

by

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Exploitation experience of hot water boiler plants indicates relatively frequent and permanent breakdowns resulting from the accident state of various elements of the boiler. In addition to the damages caused by the corrosion processes and inadequate management of the plant, the phenomena of fatigue of boiler elements exposed to high pressures and temperatures can occur. Due to high pressure and temperature certain boiler elements are exposed to, high strain and stress of these elements can eventually lead to breakdowns. In this paper, a hot water fire tube boiler, produced by "Minel-Kotlogradnja" Belgrade, type TE110V, installed within the plant "Technical Faculties" at Faculty of Mechanical Engineering in Nis, Serbia, is analyzed. Thermomechanical stress-strain analysis is performed with loads typically occurring during operation. Finite element analysis is performed using ANSYS Workbench 17 Software package, while the CAD model is formed using SOLID WORKS 2015. The results were used to investigate and to give recommendations for the thickness of tube plate of the first reversing chamber based on determined functional dependence of equivalent stress in the tube plate from the thickness of the plate. The noted functional dependence was determined by Kriging response surface based on results of virtual numerical experiment with different thicknesses of the tube plate.

Key words: *hot water boiler, finite element analysis, thermomechanical analysis, Kriging response surface optimization*

Introduction

Boilers represent devices where thermal energy is produced as a consequence of combustion of fossil fuels, where heat is transferred through the heating surfaces to the working fluid. Water, which evaporates in the steam boiler, is most commonly used as a working fluid (heat receiver), when the final product is superheated steam. The final product can also be hot water, when such boilers are called hot water boilers [1]. Fire tube hot water boilers are commonly used in thermal and industrial plants. The combustion process takes place in the fire tube and flue gasses pass to the first reflecting chamber into the flue gas pipes II pass. Then they are changing their direction and flow into the second reflecting chamber on the front of the boiler. Then the gasses flow into the flue gas pipes III pass, coming back into the first reflecting chamber, but flows on the back of water-screened wall of the chamber and then

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flow through pipes into the smokestack out into the atmosphere. Software packages with appropriate finite element method (FEM) implementation may be used to determine the stress-strain structure state in the elements of hot water boiler with certainty. In this way, critical zones of the boiler can be located and critical elements where the potential accidental states can occur during boiler operation.

Boilers are generally quite different from each other, not only by their construction, but also by their purpose, size, parameters, fuel type and numerous features, according to which they can be classified in several ways. The classification into two boiler types with respect to relative flow of combustion products (flue gases and hot water) can be found in [1, 2]. The first group represents the fire tube boilers, where the hot combustion gas flows through pipes surrounding the hot water in a cylindrical casing sheath closed at the ends with flat plates. The second group represents the water tube boilers, where water flows through the pipes of the pipe system, while the hot combustion gas flows around these pipes, thus heating the water. In this paper the fire tube boilers will be analyzed.

The boiler elements are exposed to high pressure and high temperatures which cause strain and stress that may lead to breakdowns and serious damages. In this paper the fire tube hot water boiler produced by *Minel kotlogradnja*, Belgrade, type TE110V, installed within the heating plant *Technical faculties* in Faculty of Mechanical Engineering in Nis, Serbia, is analyzed.

In order to avoid the boiler's accidents, that can cause property damage, even human casualties, strength calculation of the most critical and responsible elements of the boiler are standardized and are subjected to supervision by competent inspections. In boiler design and sizing of its parts, designers apply a *design by norm* method, where explicit rules for the calculation of each of the boiler elements are provided, such as wall thickness of individual elements, reinforcements around the holes, elements under pressure, *etc*. However, this design method has many disadvantages, since the details which could be used by the designer are not included. For example, the allowed stress values provided within the standard are based on simplified membrane stress caused by the loads originating from pressure of working fluid only. Other load, such as the thermal load, causes different type of stress which is not included in safety norms and standards [2-8]. It is also important to note, that the calculations provided in the existing norms and standards impose a certain allowed safety factor for the stress calculations and for calculating the wall thickness while adopting at the same time the first major value for standard thickness. A large value of the safety factor can lead to an over-dimensioned element thickness, which, in addition to the increased costs, may have an unfavorable impact to the strength of the structure. The paradox of this phenomenon is the fact that with the wider wall the stress caused by the pressure is lower, and with the wall wider the thermal stress is higher under the same conditions. The designer should therefore choose a wall thickness such that the total cumulative load, *i. e*. pressure load and thermal load, is minimized. Also, it is possible to get suitable values for element thickness by using the norms and standards which meet the criteria in terms of strength, but still come to permanent deformation, causing accidents and breakdowns on boiler structure during operation.

Exact application of elasticity method is not possible due to the complex structure of the boiler, so it is not always possible to obtain an analytical problem solution. For the boiler structure calculation, FEM has been used more frequently recently. The FEM represents a numerical method that enables modelling and calculation of complex constructions and problems by dividing the structure into numerous finite elements with correct geometric form, whose behavior is possible to describe [9-12].

Numerous articles have been published so far, using this method to perform modelling and calculation of the overall structures subjected to thermoplastic load and hot water boilers. The thermoplastic analysis for the metal honeycomb structure is analyzed by Zhanling *et al.* in [13]. The analysis of the fire tube geometry and its influence on thermal loads in boiler construction is given in articles [14-17]. The influence of the scale deposits contaminated on heat exchange surfaces on thermal stress formation in hot water boiler structure was analyzed by authors in [18-20].

This paper presents a thermomechanical analysis of hot water fire-tube boiler in order to investigate the state of strain and stress of hot water boiler elements. The analysis is done on a hot water boiler, with the heating capacity of 8.7 MW. Stress and strain analysis based on FEM was conducted using ANSYS WORKBENCH 17 software. The main contribution in this paper is the numerical experiment, which was done to determine the recommended thickness of the tube plate of the reversing chamber, as the most critical element in this type of hot water boiler construction. The analysis was performed with bilinear isotropic hardening model in order to capture hardening of the structure elements as well as their plastic deformations.

Stress-strain analysis of the hot water boiler

The stress-strain analysis of the construction during exploitation requires a detailed analysis of its exploitation conditions, loads and behavior. The main objective of the analysis is to present the real state of the structure and its behavior during exploitation. This is achieved by applying appropriate methods of numerical and experimental investigations. The aim is also to discover the causes of problems arising during exploitation, as well as to solve problems that should ensure reliable and safe operations of equipment over a longer period of time while reducing maintenance costs.

Boiler breakdowns and destruction of their elements are caused by extreme values of contaminated stresses in the structure itself [18-24]. Other values are also important, because breakdowns in the structure do not always occur on locations where maximum stresses are located. To determine the extreme stress value, it is necessary to determine the stress distribution in the analyzed structure. This can be determined in numerous ways, but in this paper FEM will be used for determining the stress-strain state of the hot water boiler structure.

Thermoelastic equations

The generalized thermoelastic governing equations, in vector form, representing a coupled transient problem of thermoelasticity, is presented in [25, 26]:

$$\mu\nabla^2\vec{\mathrm{u}} + (\lambda+\mu)\mathrm{grad}\,\mathrm{div}\vec{\mathrm{u}} - (3\lambda+2\mu)\alpha_t\mathrm{grad}\,\theta + \vec{\mathrm{F}} - \rho\ddot{\vec{\mathrm{u}}} = 0 \tag{1}$$

$$\nabla^2\theta - \frac{1}{a}\dot{\theta} + \frac{W}{\lambda_0} - \frac{(3\lambda+2\mu)\alpha_t T_0}{\lambda_0}\mathrm{div}\dot{\vec{\mathrm{u}}} = 0 \tag{2}$$

where $\vec{\mathrm{u}}$ is the displacement vector and $\vec{\mathrm{F}}$ – the load vector.

Equation coupling is done by the fourth member of the eq. (2).

Decoupled quasi-static problem of thermoelasticity defined by eqs. (3) and (4) is formed by neglecting coupling and displacement acceleration:

$$\mu\nabla^2\vec{\mathrm{u}} + (\lambda+\mu)\mathrm{grad}\,\mathrm{div}\vec{\mathrm{u}} - (3\lambda+2\mu)\alpha_t\mathrm{grad}\,\theta = 0 \tag{3}$$

$$\nabla^2\theta - \frac{1}{a}\theta + \frac{W}{\lambda_0} = 0 \tag{4}$$

Steady-state problem of thermoelasticity defined by eqs. (5) and (6) is formed when there is no change of values with respect to time. Generalized equations are additionally simplified and take the following form:

$$\mu\nabla^2\vec{\mathrm{u}} + (\lambda + \mu)\mathrm{garddiv}\vec{\mathrm{u}} - (3\lambda + 2\mu)\alpha_t \mathrm{grad}\theta = 0 \tag{5}$$

$$\nabla^2\theta + \frac{W}{\lambda_0} = 0 \tag{6}$$

It should be noted that the temperature fields and the displacement fields are by nature decupled for a steady-state problem.

Obtained system of differential equations of thermoelasticity, including initial and boundary conditions, generally represent a difficult mathematical task which should be solved in a closed form. One of the numerical methods which is successfully used for solving previously described problems is certainly FEM.

Numerical model with calculation of strain and deformation with FEM

Stress-strain analysis of the boiler structure produced by *Minel kotlogradnja* type TE110V was performed using FEM in ANSYS 17 program package, while a CAD model was created using SOLIDWORKS 2015 software package according to technical documentation of the boiler manufacturer [27]. The analyzed boiler is oil or gas fired high pressure hot water fire-tube boiler for flow temperatures up to 170 °C and permitted operating pressures of 6.0 to 12.0 bar.

Since the geometric model is symmetrical in relation to the plane that passes through its longitudinal axis and is normal to the plane of the substrate, considering the assumed heat load symmetry, half of the geometric model is neglected – the right side of the symmetry plane. The influence of the neglected part of the model is defined by the limitation of the number of degrees of movement freedom of nodes in the symmetry plane applied by a software package symmetry relation. The geometric model analysis results have determined that some elements of the model have a function of connecting the hot water boiler to the water supply network. These elements are also excluded from the analysis since they have no significant effect on the stress-strain state of the model. In addition to these elements, the boiler connection elements that have safety features are also neglected.

The geometric model was transformed into the discretized FEM with the application of advanced meshing tool capable of creating adaptive discrete model. The discretized model consisted of 1661038 nodes, forming 310620 finite elements. The discretized model of the analyzed boiler is presented in fig. 1.

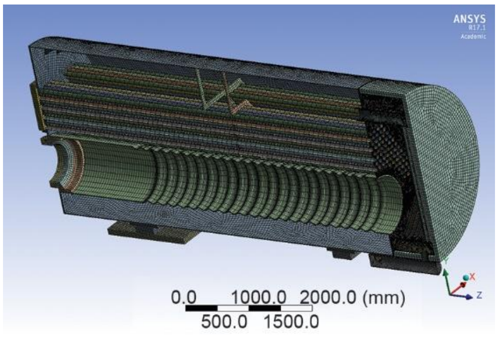

Figure 1. Discretized structure of hot water boiler (*for color image see journal web site*)

In the analysis, the materials that are used (which correspond to the real state of boiler construction) have the following characteristics [28, 29] as given in figs. 2-5.

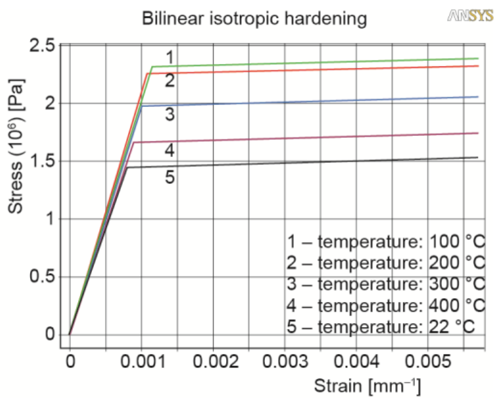

Figure 2. Bilinear isotropic hardening model of steel P265GH

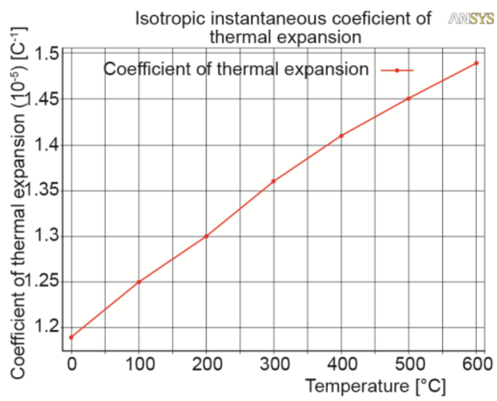

Figure 3. Coefficient of thermal expansion of steel P265GH

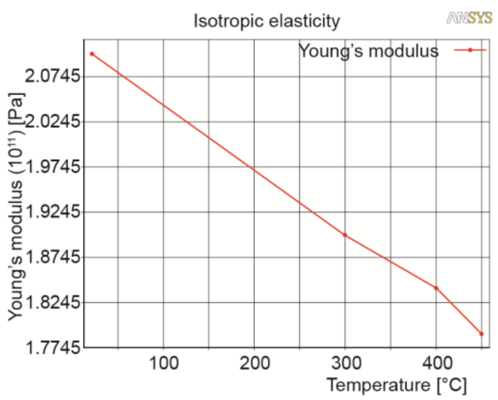

Figure 4. Isotropic elasticity Young's modulus of steel P265GH

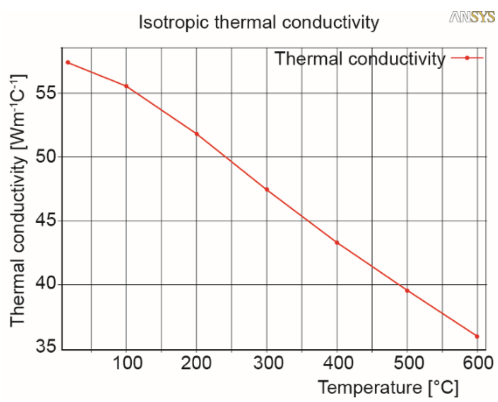

Figure 5. Thermal conductivity coefficient of steel P235GH

By analyzing the structural load of the boiler, it can be determined that boiler loads are:
– loads resulting from the weight of the boiler elements themselves,
– loads resulting from the thermal expansion on higher temperatures, and
– boiler operating loads.

In the stress-strain analysis of hot water boiler *Minel kotlogradnja*, the method of sequential load transfer was used, by pairing static thermal and static structural analysis. First, the steady-state thermal analysis was performed which provided the temperature field of the hot water boiler elements based on the specified thermal loads, and then the transfer of resulting temperature field into the static structural analysis was performed. The static thermal analysis was performed by defining a temperature load of the key boiler elements based on data from boiler manufacturer and calculated according to current standards [27]. Boiler operation loads for static structural simulation were taken from manufacturers boiler technical documentation. Figure 6 shows the loads and boundary conditions used in static thermal analysis, while fig. 7 shows the loads and boundary conditions used in static structural analysis. Connections between the boiler elements were defined as bonded as the all the elements were joined by welding procedure. The connection between the boiler foundation, which was added to the finite element model, and the boiler foot closer to the burner was defined as frictionless to account realistic boiler support.

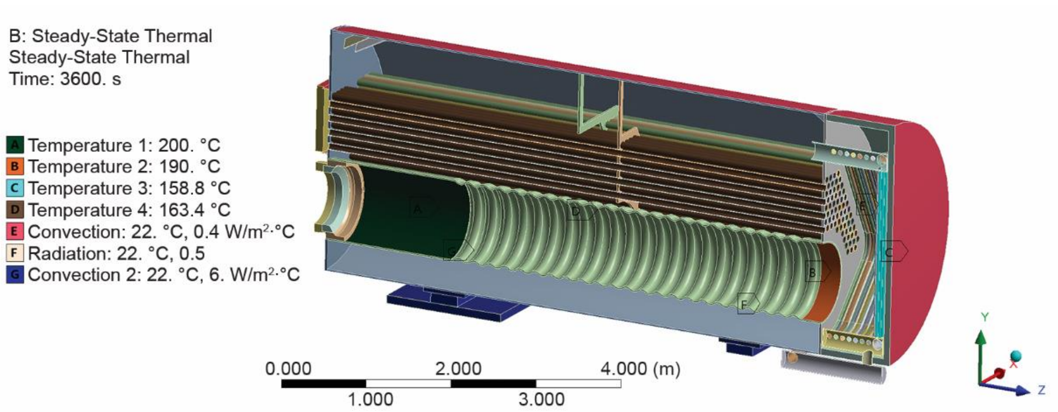

Figure 6. Loads and boundary conditions for a steady-state thermal analysis
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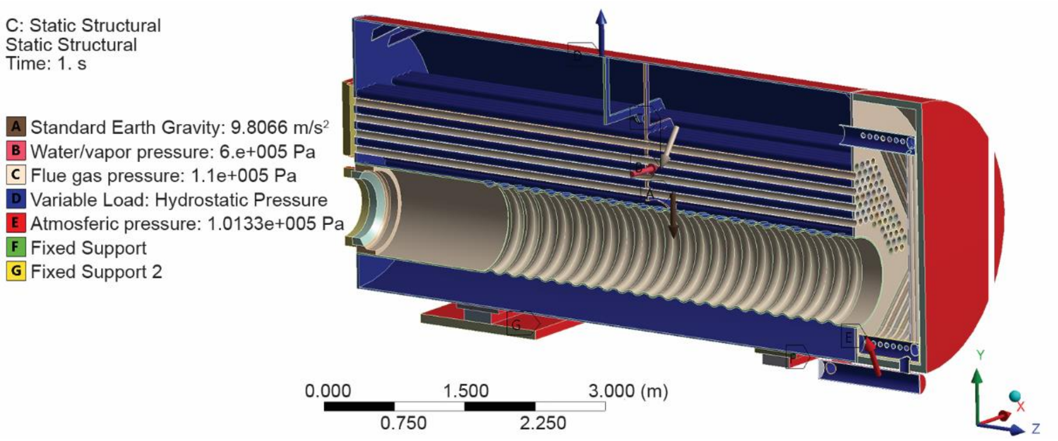

Figure 7. Loads and boundary conditions for a static structural analysis
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Imported thermal load into the static structural analysis as a temperature distribution field is given in fig. 8.

Beside the thermal and hydraulic pressure loads, other mechanical loads were also accounted during the static structural analysis: the gravity force, the load due to the pressure of flue gas (1 bar), and the hydrostatic water pressure. Figure 9 shows the total deformation, while fig. 10 shows the equivalent (Von Misses) stresses of the boiler structural elements during the operating regime with the nominal load.

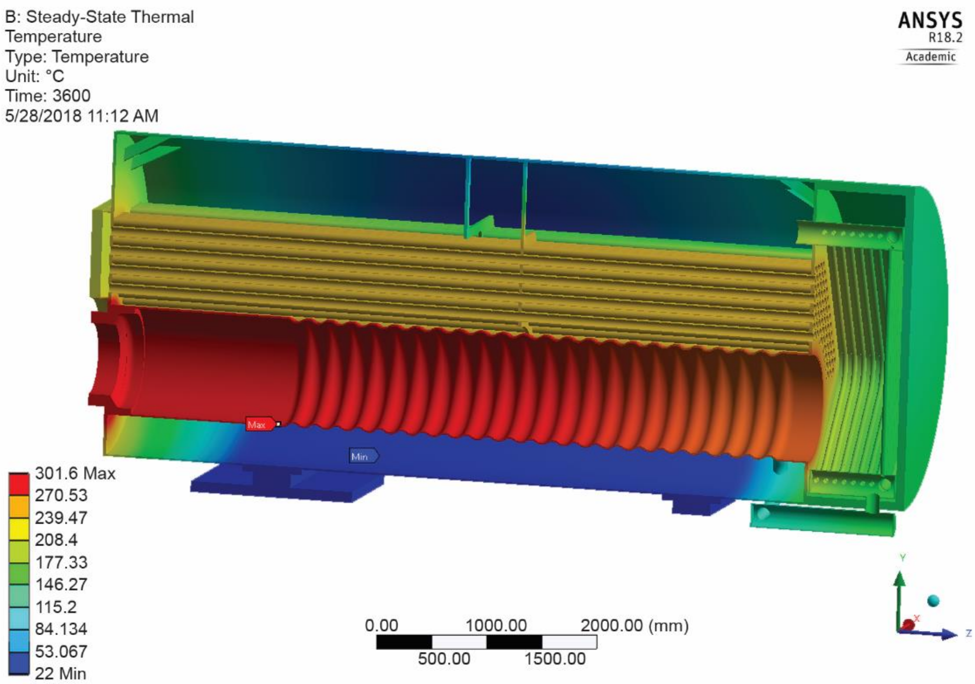

Figure 8. Temperature distribution of boiler elements
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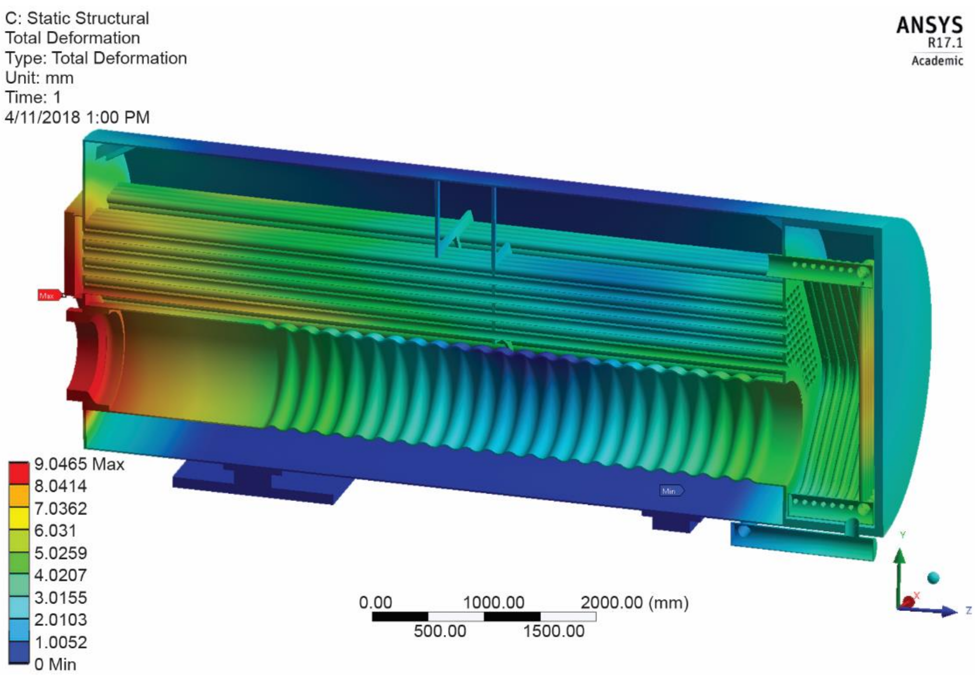

Figure 9. Total deformation of hot water boiler structure during the operating regime with the nominal load (*for color image see journal web site*)

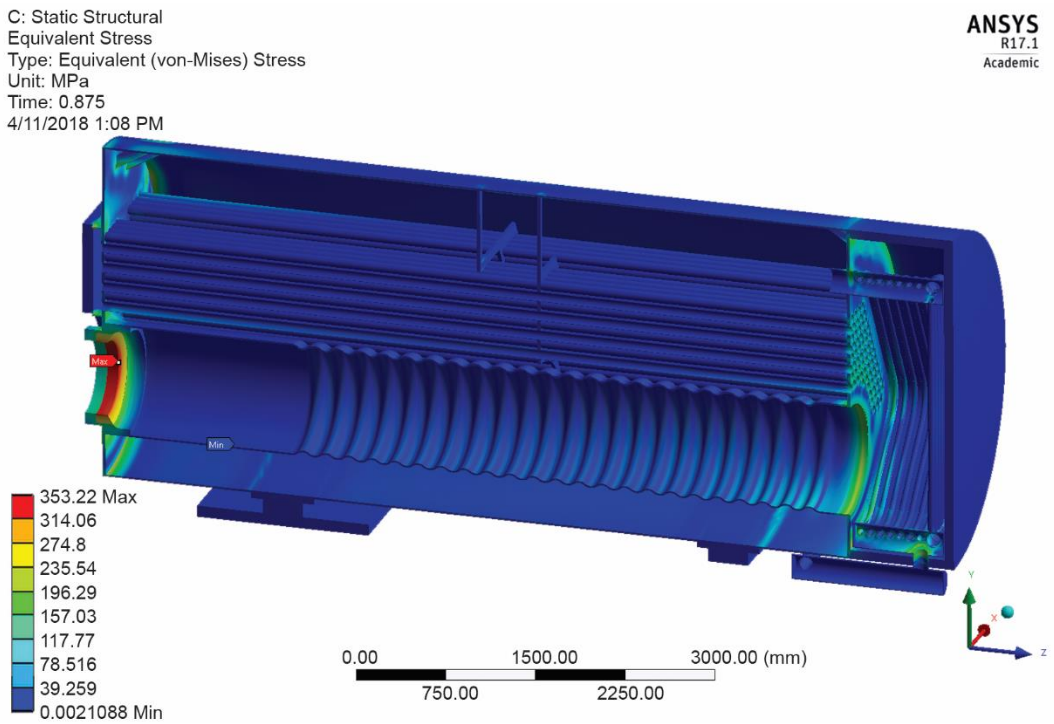

Figure 10. Equivalent stresses of hot water boiler structural elements during the operating regime with the nominal load (*for color image see journal web site*)

The results of analysis show that maximal stresses and deformations occur at the furnace tube inlet, where combustion takes place and where the maximum temperatures are determinate. It is very important to consider the entire element of the reversing chamber, the tube plate and the screened walls of the reversing chamber, where accidents commonly occur. The major breakdowns of the hot water fire-tube boilers are caused by the damage and failure of the welding joints on these elements [24]. As observed, the results of this analysis show that the maximal deformation on the screened wall of the reversing chamber is 6.984 mm, located at the welding joint on the screened wall, and the maximal deformation on the tube plate is 4.921 mm, located at the welding joint of the fire tube (Fox corrugated pipe) and the tube plate. It should be emphasized that the presented numerical experiment takes into account the *empty* boiler, without any deposits, dirt contamination or boiler sludge, fig. 11. If the actual real-life conditions would be considered, the situation would most certainly be more critical, with higher deformations. The maximal equivalent stress is 254.25 MPa, located on the outer border of the tube plate, which is welded with the outer cylindrical boiler shield, fig. 12.

As yield strength of used boiler material is approximately 220 MPa at the temperature of the noted component, in operation with the nominal load there will be no plastic deformations when the present situation is analyzed without any scale deposits and with clean heating surfaces. But in the real operating regime plastic deformations in this zone of the tube plate may occur. This indicates that the critical element should be further analyzed and monitored. It should be emphasized again, that in this paper an absolutely clean boiler was analyzed, with clean boiler surfaces at nominal operation mode. The situation is certainly more

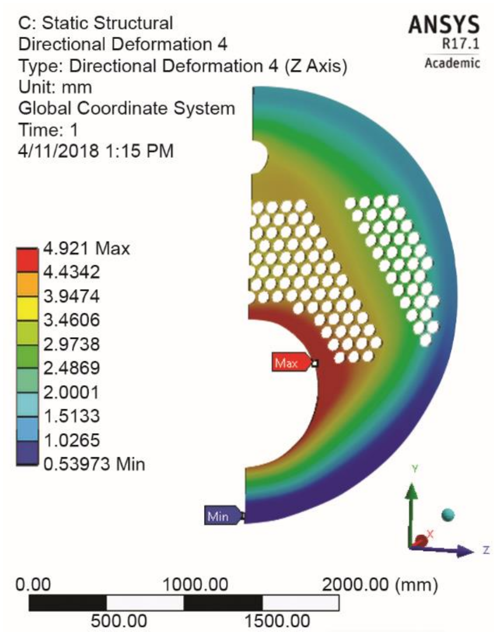

Figure 11. Total deformation (directional Z Axis) of the tube plate
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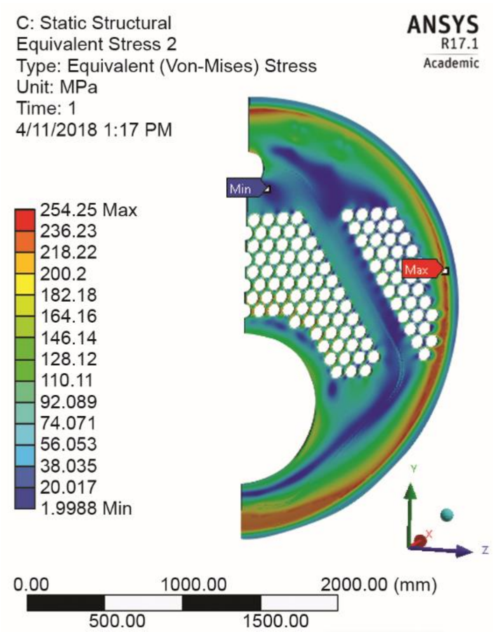

Figure 12. Equivalent stresses of tube plate of the first reversing chamber
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critical with real operation conditions [18, 24]. Accidents and failures that have so far occurred in hot water boilers with similar design mentioned in [18], occur in welded joints of pipe carrying wall and screened wall of the reversing chamber. The presented results can confirm that the most vulnerable zone of the boiler is most certainly the reversing chamber, especially the zone of the first two pipe rows located closer to the welded joint with the fox corrugated pipe. Figure 13 presents the deformation of the screened wall, where the maximum value is 6.8668 mm. The numerical experiment undeniably shows that the most critical zones are locations where should be paid most attention.

The numerical experiment

Based on the previously described finite element model, a virtual experiment was defined by application of ANSYS design of experiments module as a central composite design. In total, five virtual experiments were defined with different values of DSL *i. e.* the thickness of the tube plate of the reversing chamber. The different common values of the wall thickness were monitored. By solving the noted virtual experiments, a set of numerical results of equivalent stress and directional deformation for given thickness of the tube plate were obtained as shown in tab. 1.

The response surface, which is defined as a function of equivalent stress in the tube plate from the thickness of the plate, was determined by Kriging or Wiener-Kolmogorov prediction method, which gave an optimal interpolation based on regression against observed z values of surrounding data points weighted according to spatial covariance values [30, 31]. The coefficient of the determination value was $R^2 = 1$ and the root mean square error was below 10^{-11}. Presented predicted values of equivalent stress in the tube plate with an appropriate plate thickness obtained by the applied virtual experiment are shown in fig. 14.

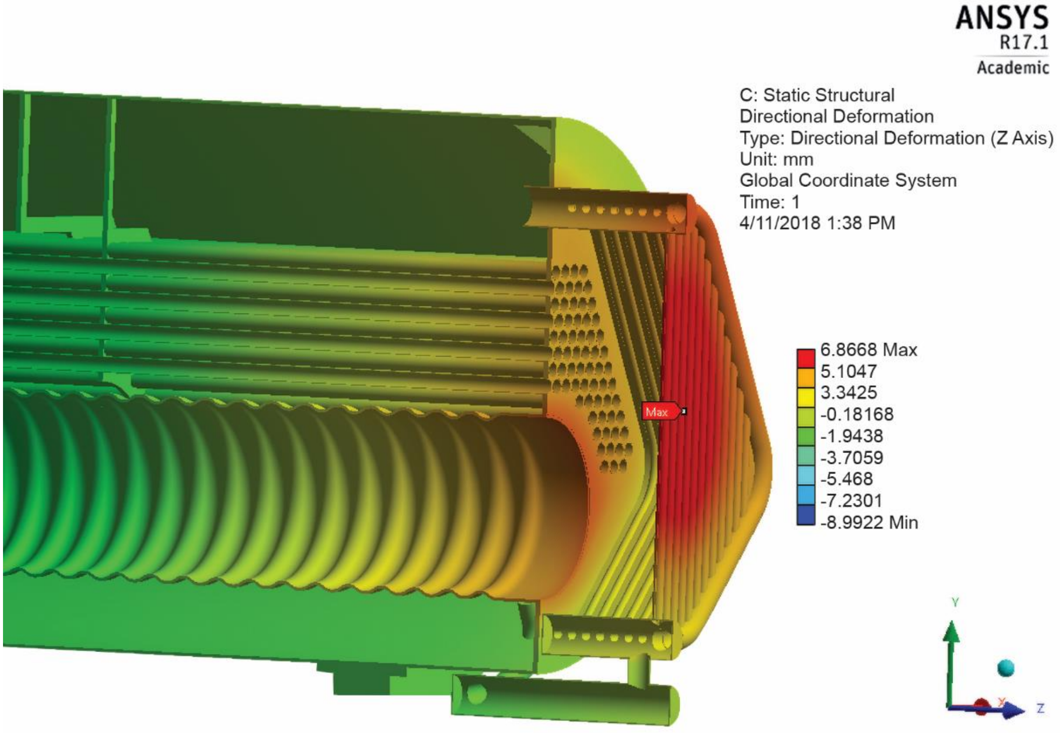

Figure 13. Total deformation of screened wall of the reversing chamber
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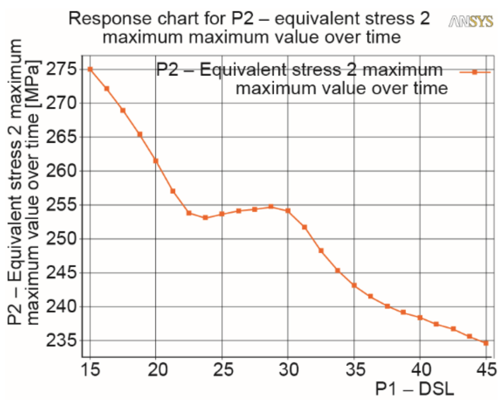

Figure 14. Predicted values of equivalent stress for the analyzed tube plate thickness from the numerical experiment

Table 1. Virtual experiment set-up and results

DSL value – thickness of plate [mm]	Equivalent stress [MPa]	Directional deformation [mm]
45	234.61	2.2053
37.5	240.11	2.154
30	254.25	2.0787
22.5	253.82	1.9764
15	274.94	1.878

Based on the results of the numerical experiment, it is obvious that the equivalent stress decreases with the increase of the tube plate thickness. But there is a situation with the plate thickness of 22.5 mm where equivalent stress is 253.82 MPa, and the plate thickness of 30.0 mm where the equivalent stress value is 254.25 MPa. Hence, in the range of plate thicknesses from 22.5 mm and 30 mm, the equivalent stress stays approximately the same, even with the slight increase of thickness. It can be observed that there is almost no difference between using a tube plate 30 mm and the tube plate 22.5 mm thick, which the constructors should take into account. The stress is even more convenient and appropriate (the value is lower than the one for the thicker plate). The construction of the tube plates of hot water boilers with similar designs has a thickness between 20 and 30 mm. According to conducted numerical experiment it is recommended to use the tube plate with thickness of 20-26 mm. The lowest equivalent stress would be obvious with 45 mm tube plate. Therefore, it is unavoidable to conduct a techno-economic analysis, but the costs are definitely higher for a two times thicker plate, while only 10% lower stress that is expected to obtain with maximal thickness. The obtained results should give the exact value of plate thickness that should be used and implemented into the design. Accidents and breakdowns which have happened so far on this kind of boiler design refer to the tube plate as the most vulnerable part of the boiler, especially the zone of the first two pipe rows located closer to the corrugated flue fox. Figure 15 shows failures and plastic deformation on the tube plate of the first reversing chamber of analyzed boiler *Minel kotlogradnja* type TE110V with the capacity of 8,7 MW.

Figure 15. Cracks on the tube plate of the first reversing chamber

Conclusion

The aim of this paper is to analyze and investigate the possibility of existing design modification. The recommendation to optimize thickness the most critical element of this type of boiler was performed by application of a numerical experiment. The analysis of thermal stress and strain was performed by using operational data and with the exact CAD model. Simulation results indicate that the tube plate and the screened wall of the reversing chamber are under the greatest load (more precisely the first row of the welding joints of smoke tubes and tube plate). The functional dependence between the stresses of tube plate and the tube plate thickness was determined by Kriging response surface based on results of virtual numerical experiment with different thicknesses of the tube plate. Further analysis should include investigation of the behavior of welding joints in this critical part by using the sub-modelling procedure. The sub-modelling procedure is a modelling approach that allows solving a small part of a bigger model, with more refined meshes and results.

The obtained results take into account the *clean* boiler, with the *clean* heating surfaces *i. e*. without any scale deposit layers or dirt on the boiler water side surfaces. The presented methodology for thermomechanical analysis of hot water boilers structure should be a starting point for manufacturers and constructors of the hot water boilers, to improve future designs and ensure stability and safety of operating regimes of the analyzed type of boilers, without any failures or breakdowns common in long term exploitation.

Nomenclature

a – coefficient of heat conductivity, (= λ_0/c_ε) [m^2s^{-1}]
c_ε – specific heat reduced to a unit of volume, [$JM^{-3}K^{-1}$]
DSL – thickness of plate, [mm]
T – absolute temperature, [K]
T_0 – absolute temperature of natural (referent) state, [K]
W – specific intensity of the heat source (sink), [Wm^{-3}]

Greek symbols

α – coefficient of linear thermal expansion, [K^{-1}]
λ_0 – coefficient of heat conduction, [$Wm^{-1}K^{-1}$]
λ, μ – Lame's constant, [Nm^{-2}]
θ – relative temperature, (= $T - T_0$) [K], [°C]

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