Milena Rajić[*], *Dragoljub Živković, Milan Banić, Marko Mančić*

STRESS-STRAIN ANALYSIS OF HOT WATER BOILER TUBE PLATE IN START-UP REGIME

NAPONSKO DEFORMACIONA ANALIZA CEVNIH PLOČA VRELOVODNOG KOTLA U REŽIMU STARTOVANJA

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Adresa autora / Author's address:
University of Niš, Faculty of Mechanical Engineering, Niš, Serbia email: milena.rajic@masfak.ni.ac.rs

Keywords
- hot water boiler
- stress-strain analysis
- numerical analysis
- experimental analysis
- transient operating mode

Abstract

The paper presents stress-strain analysis of hot water fired tube boiler with diversion chamber's screened wall for start-up regime. Previous experiences of hot water boilers indicate failures in operation and the occurrence of breakdown which represent consequence of bringing the plant into the condition characterized by parameters that are higher than allowed. The structure of hot water boilers is exposed not only to high pressures but also to high temperatures that are the reason that thermal stresses are dominant in those boiler elements, especially with thick walls. High thermal stresses occur at the highest temperature gradients and at transient operating modes. Experimental results of measured temperatures of hot water boiler tube plate in the start-up regime are presented, used as boundary conditions for numerical calculation. Stress-strain analysis is performed by using FEM.

Ključne reči
- vrelovodni kotao
- naponsko-deformaciona analiza
- numerička analiza
- eksperimentalna analiza
- prelazni režim rada

Izvod

U radu se analizira naponsko-deformaciono stanje cevne ploče plameno-dimnocevnog kotla sa ekranisanom skretnom komorom za stanje puštanja kotla u rad. Dosadašnja iskustva vrelovodnih kotlova ukazuju na otkaze u radu i pojavu havarijskih stanja, koji su posledica dovođenja postrojenja u stanje koje karakterišu parametri koji su veći od dozvoljenih. Struktura vrelovodnog kotla je izložena ne samo povišenim pritiscima već i visokim temperaturama, zbog čega su dominantna termička naprezanja i to u elementima kotla sa debljim zidovima. Termička naprezanja su najveća pri najvećim gradijentima temperature, koji se javljaju pri prelaznim režimima rada. Prikazani su eksperimentalni rezultati izmerenih vrednosti temperatura cevne ploče vrelovodnog kotla u toku puštanja u rad, koji su korišćeni kao granični uslovi za numerički proračun. Naponsko-deformaciona analiza je urađena primenom MKE.

INTRODUCTION

Hot water boilers represent one of the most commonly used pressure vessels not only in heating but also in industrial plants. Their operating characteristics are defined and regulated by actual standards and norms /1/. Boiler elements are designed and constructed according to the requirements of the standard for pressure vessels /2/ and also subjected to subsequent control. During operations, the boiler elements are subjected to high pressures and temperatures of the working fluid (water or steam). Therefore, thermal stresses in certain parts of the boiler structure have direct impact on the manoeuvring properties of the boiler. The highest thermal stresses occur in non-stationary operating modes or transient modes.

The process of starting up the boiler represents one of the most critical transient modes of the boiler plant, which is presented by Cwynar /3/ and Taler /4/ for steam boilers. Analysis of transient operating modes /4-9/ are done according to the limitations and recommendations defined by the standard /2/, but taking into account the thermal stresses that appear in critical boiler elements. Nevertheless, the structural numerical analysis done by using finite element method (FEM), has shown certain deviations of stress-strain values from the recommended ones defined by /2/, especially in boiler elements with thick walls and with openings /10/ where critical stress occurs. The critical elements of steam boiler and their stress analysis have been specifically analysed in the start-up regime in /10/, where results indicate that stress concentration is present in boiler elements with a sudden change of geometry, such as openings, holes, curves. More analysis, done in /11, 12/, has verified that the stress-strain state of the steam boiler with complex geometry is especially critical in the transient regimes of the start-up or at sudden abrupt stop of the boiler. Transient regimes of hot water boilers are analysed in /13-17/ and more general analysis of thermal stresses under different loading and thermal conditions is presented in /18-28/.

During operation of hot water boilers, certain failures and breakdowns occur. Such failures are usually caused by corrosion process, as well as inadequate handling of the plant, but also by the occurrence of material fatigue of those boiler elements that are exposed to high pressures and temperatures /29/. An overview of emergency conditions and their classification is presented in /19/ in both steam and hot water boilers, where critical elements can be observed that need to be analysed separately.

Transient operation regimes are also non-stationary. In these regimes there is not only the change of load, but also the change of the stress-strain state of the structure. Especially in cases where there is sudden change in loading, the change of operation modes, a start of the boiler or sudden stoppage due to accidents or necessary interventions. In these cases, large temperature gradients occur in boiler elements which cause the appearance of thermal stresses that are dominant and much higher than stresses caused by high pressures of the working fluid. Thermal stresses represent a consequence of the resulting temperature differences in the boiler structure, due to the high temperature gradients of the combustion products during the process of starting-up the boiler and low temperatures of the structure itself. Thermal stresses are especially high in boiler elements with a large wall thickness /5-7/. The thermal stresses of the tube plate of the first reversing chamber are considered to be of great importance, where major failures had been occurring /8-17/, and where the highest temperature differences appear.

This paper presents experimental results of hot water boiler structure temperature change in the regime of start-up and the numerical results of the structural stress-strain state. Thermal stresses in boiler structure are monitored during the start-up process and in critical moments of time.

EXPERIMENTAL PROCEDURE

The experimental procedure is performed to determine the temperatures of tube plates of the first and second reversing chambers, at defined points and at certain boiler loads. The procedure is done during boiler start-up. With a known temperature field of the boiler structure, thermal stress analysis would be more accurate and reliable, compared to the real data.

Temperature probes are used and the measurement procedure required exact locations for their installation. The measurements are planned to be on tube plates on the gas side, where access is enabled, as well as installation of probes. There are 6 measuring points, with 4 on the tube plate of the first reversing chamber, and 2 on the tube plate of the second reversing chamber (Fig. 1). As the flue gas temperature at the nominal operating mode of the boiler is around 1200 °C at the outlet of the fire tube, a mantle probe, 3.5 m long, is adopted. On the same tube plate of the second draft, 2 measuring points are selected at defined locations in the zone of flue gases that leave the third draft and go into the screened reversing chamber from the back, and thus to the chimney. The flue gas temperature in this zone is around 230 °C. There are 2 more measuring points on the tube plate of the second reversing chamber, in the front of the boiler, in the zone of flue gases that leave the second and enter the third draft (gas temperature is around 450 °C in this area) (Fig. 2). The experiment is performed in order to monitor the change in temperature at defined points of the tube plate during the start-up of the boiler, i.e. in the range of 0 to 100 % load change.

The experimentally obtained temperature values are used to set boundary conditions and more precisely to determine the numerical model. In that way, a more accurate temperature field of the structure would be used and the numerical model would approach the exact thermal state of the real boiler structure. Measured temperature values are used for numerical model validation, not only in the nominal operating mode, but also in the transient mode of the start-up. The presented experimental procedure and identification of the temperature field of the hot water boiler structure is of great importance, while there is no available literature data, especially for transient operating regimes.

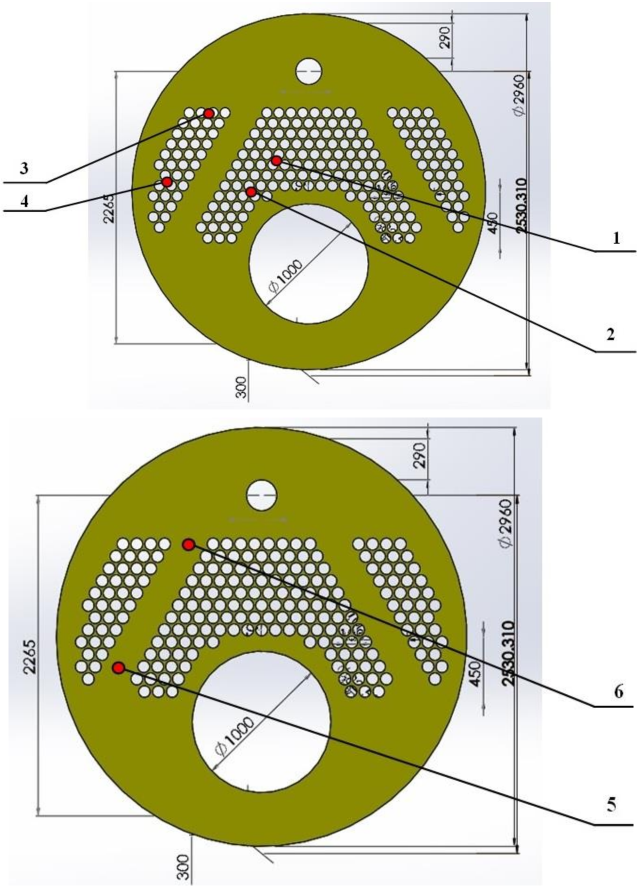

Figure 1. Position of temperature probes.

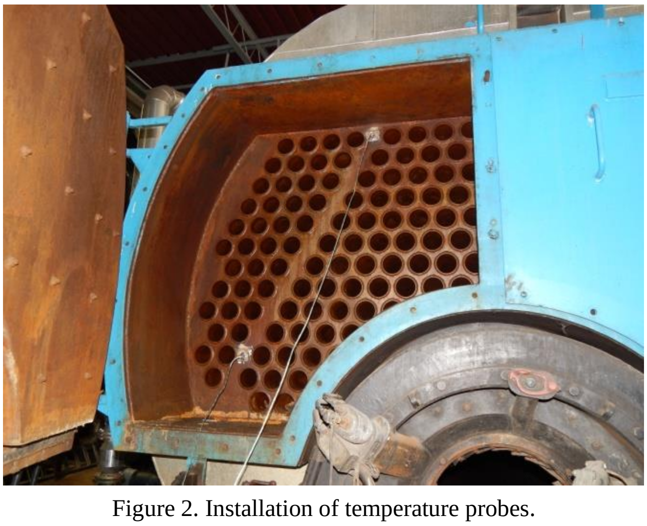
Figure 2. Installation of temperature probes.

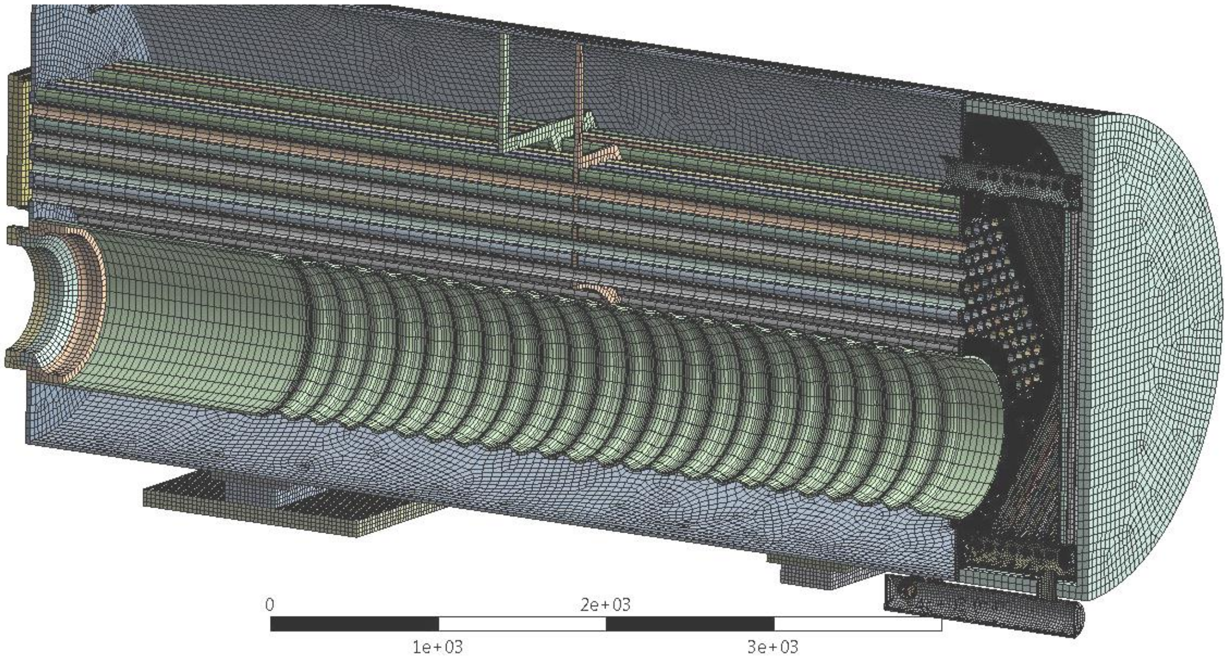

Figure 3. Discretized structure of hot water boiler.

NUMERICAL ANALYSIS

Stress-strain analysis of the hot water boiler structure is performed numerically using FEM in ANSYS® program package, while a CAD model is created using SOLIDWORKS® software according to technical documentation of the boiler manufacturer /14, 30/. The geometric model is transformed into discretized FEM with application of an advanced meshing tool, capable of creating an adaptive discrete model. The discretized model consists of 1 661 038 nodes, forming 310 620 finite elements. The discretized model is presented in Fig. 3. Numerical analysis used materials that correspond to the real state of the boiler structure with characteristics given in /14, 31, 32/.

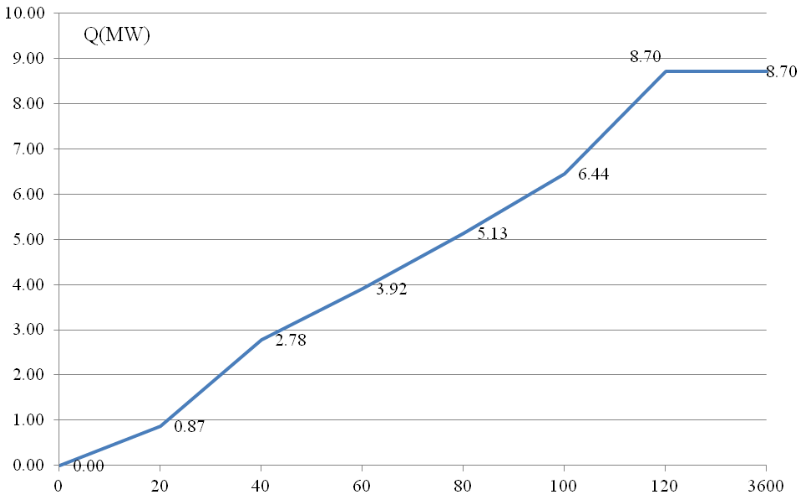

Figure 4. Heat load change of the fire tube Q as a function of time.

The structural load of the boiler is analysed and can be determined as: loads resulting from the weight of boiler elements themselves; loads resulting from thermal expansion at higher temperatures; and boiler operating loads (that change during the observed time period).

The numerical analysis model is analysed in the time domain. The presented model is considered to be of great importance while it is based on the variable operating mode from 0% to 100% of the load in a given time. In the case of the real hot water boiler, based on experimental results, there is a load reduced after 100 s when the boiler starts. In the numerical model, this period of load reducing is not considered. The numerical model is defined so that the load is not reduced as with a real boiler, but that the boiler load increases linearly, as is the case up to 100 s. The aim of this analysis is to see what would happen to the structure if there were no changes in the character of the temperature rise curve of the structure.

The analysis includes the heat load that changes over time. The predicted heat load to which the boiler structure is exposed, which originates from the combustion of fuel in the fire tube is set from 0 to 100 s, based on data obtained experimentally by measurements on a hot water boiler. An increase in boiler load up to 120 s is analysed by extrapolating the curve and then with the case without changing the character of the structural temperature curve (Fig. 4). The change of boiler temperature in the time period is simulated by applying thermal analysis in the transient mode during 3600 s, i.e. one hour from starting up the boiler.

It has been noticed that a relatively short period of time is needed until approximate stationary state is obtained, in which the temperature field of the boiler does not change over time. The results show that after an hour, a steady state is established. The temperature field of the boiler structure, at 100 s after boiler start-up are shown in Fig. 5. The shown numerical results of temperature change in the boiler structure (Fig. 5) are compared to measured values of the real object.

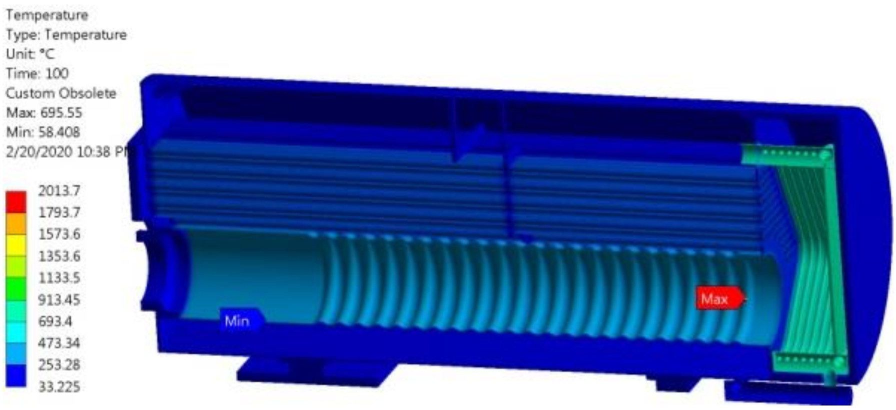

Figure 5. Temperature distribution of boiler elements after 100 s from starting up of the boiler.

RESULTS AND DISCUSSION

Based on experimental results, the overview of temperature changes at 6 selected points depending on the boiler loading is analysed and presented. Figure 6 shows the moment of load drop of the boiler during start-up procedure. Namely, at time $\tau = 100$ s from the start of burner ignition, the load drops from 75 to 58 % and after that, the load continues to grow up to 100 % (blue curve in Fig. 6). A pattern of load reduction is observed, in order to change the temperature growth trend of the structure for safety reasons. During the process of starting up the boiler, the boiler structure is cold, the largest amount of heat is received by the structure at the very beginning, and then it is cooled by fluid, i.e. water in this case. The change in growth trend of the temperature ensures that there are no high temperature gradients in the process of starting up the boiler when the working fluid is relatively cold and/or with a lower temperature than in the operating process.

With measured temperature values received experimentally, the numerical model can be verified. By verifying the temperature field in the tube plates, the resulting temperature field of the structure can be adopted with certainty. The locations of measured points (where temperature probes are located) are identified in the numerical model, in order to compare the values. The comparative results of the temperatures in the tube plate of the first reversing chamber are shown in Table 1.

The presented results indicate a significant match between measured values and values obtained numerically. This is especially evident in the tube plate of the second reversing chamber and in the tube plate of the first reversing chamber, but towards the outer circle (t3 and t4). A relative difference of 26 % refers to measured temperatures of the tube plate of the first reversing chamber, closer to the fire tube (t1 and t2). The measured temperature values, which are higher than those obtained by numerical analysis, can be explained by the high sensitivity of the probes and the positioning of probe tips. Also, in this part, the measurement was difficult due to high flue gas flow rates. This comparative analysis also allows verification of the numerical model. It is very important to emphasize that in the process of starting-up the boiler, the accumulation of thermal energy is done first in the walls of the structure, and only later, when stable operation is achieved, the water is heated. In order to analyse the stress state of the hot water boiler structure in this critical moment, at time 100 s from the boiler start-up, the stress-strain analysis of the structure is presented. As temperature differences between the struc

Table 1. Comparative analysis of measured temperatures and those obtained by numerical analysis.

No.	Position	Large	Small
1	Tube plate 1 – t1	805.5	595.7
2	Tube plate 1 – t2	727	577.9
3	Tube plate 2 – t5	133.6	133.6
4	Tube plate 2 – t6	136.6	133.4
5	Tube plate 1 – t3	83.1	96.1
6	Tube plate 1 – t4	80.7	94.4

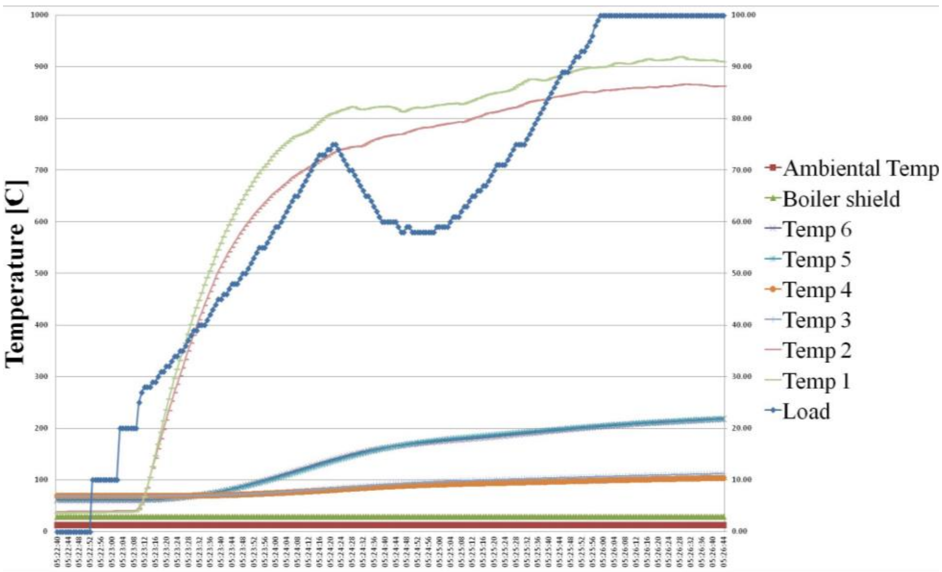

Figure 6. Experimental results of measured temperature vs. boiler load.

ture and heating medium are large at this moment, it is expected that stresses are the highest. Figures 7 and 8 show the stress state and total deformation at specified time, in respect.

As it can be seen from Fig. 9, the maximum stress values are about 410 MPa, while tensile strength of the pipe wall material (P265GH according to DIN EN 10028-2, /14, 31, 32/, is R_m = 410-530 MPa, and yield stress R_p = 255 MPa. At high temperatures of the tube wall, yield stress is even significantly lower. Maximal stress values are exactly on the tube plate, in the zone of the first line flue gas pipes of the second draft (Fig. 7). This also indicates that these are critical values. The stress state in the tube plate is shown in Fig. 9, where these critical stresses can be observed. Under these conditions, the results of direct deformation in the axis normal to the tube plate are given in Fig. 10. The installed control system that reduces heat at τ = 100 s, leads to a reduced stress state from the critical obtained values. Without exposing the boiler structure to elevated stress, the boiler operation is then safe and secure.

One of the most critical transient operating regimes, the start-up of the boiler is analysed as a quasi-stationary state, as Cwynar proposed in /3/. The results of analysis show the appearance of high stress-strain state on the tube plate of the first reflecting chamber, in the zone of the first row of flue pipes of the second draft. This is exactly the location where accidents occur in boilers during this operation.

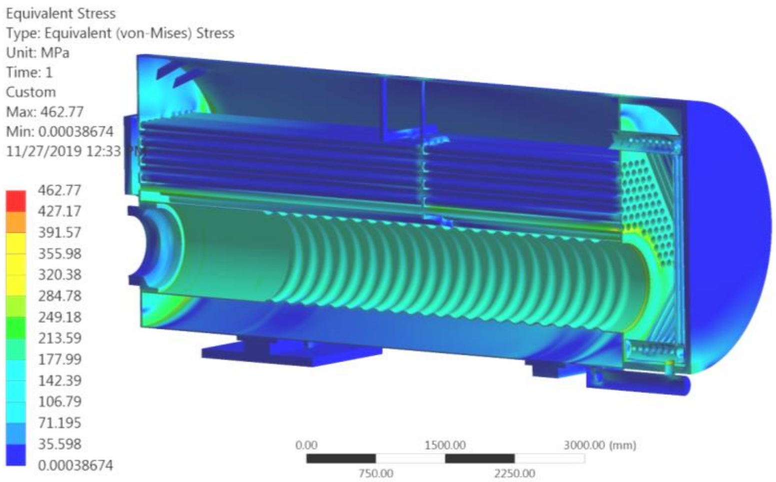

Figure 7. Equivalent stresses of hot water boiler structural elements at 100 s from the moment of starting up the boiler.

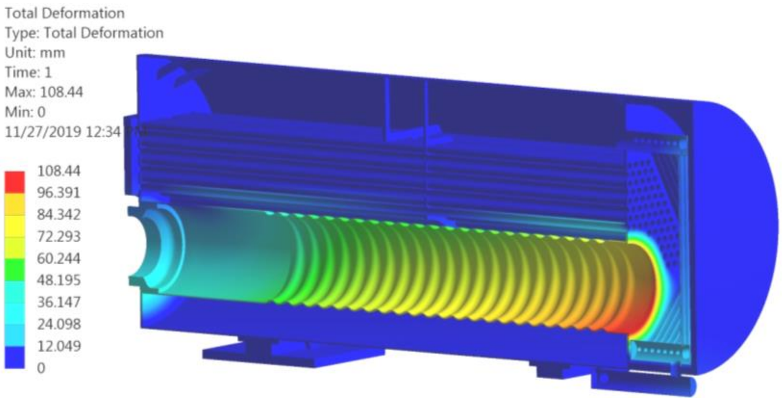

Figure 8. Total deformation of hot water boiler structure at 100 s from the moment of starting up the boiler.

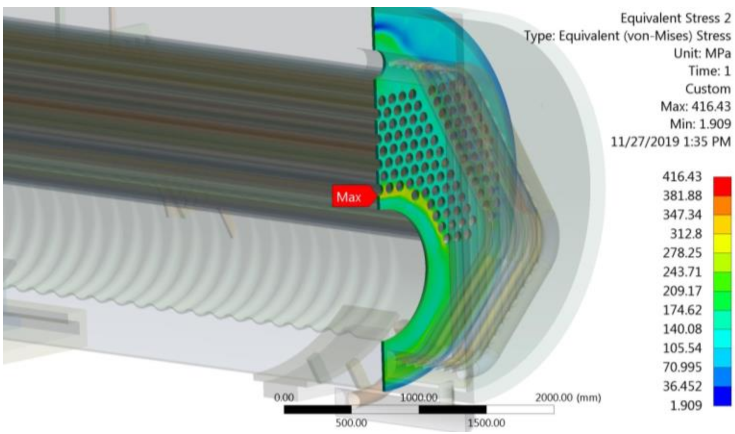

Figure 9. Equivalent stresses of tube plate of the first reversing chamber at 100 s from the moment of starting up the boiler.

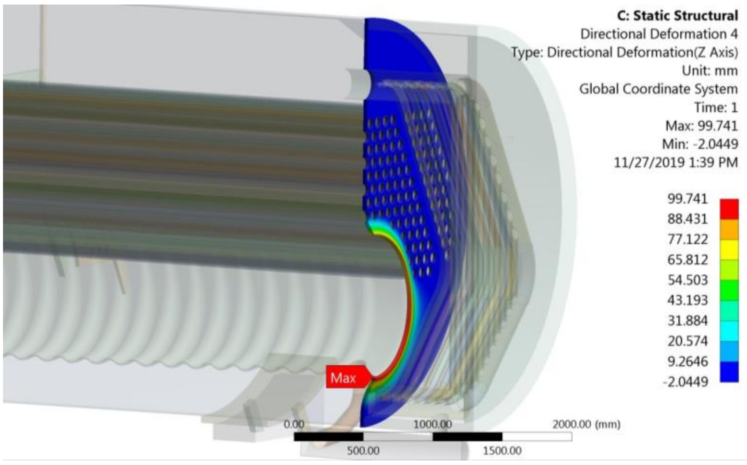

Figure 10. Total deformation (directional Z Axis) of the tube plate of the first reversing chamber at 100 s from the moment of boiler start-up.

CONCLUSION

With numerical analysis results and results obtained experimentally, the numerical model in the time interval up to τ =100 s can be verified. Approximately the same curve characteristic with approximately the same values indicates that a given numerical model can be used with high reliability for transient modes. The numerical analysis is used also to see what would happen when the boiler load would continuously increase and remain in that state for a certain period, and to analyse the temperature distribution in time for such a case. Results show that the temperature of the structure would be up to 370 ℃ on the pipe plate of the second deflection chamber in this analysed case, and the average temperature of the pipe plate of the first deflection chamber would be 613.5 ℃, which exceeds the values of the boiler structure allowed by the given standard, /2/. The justification of reducing the boiler load at τ = 100 s from the moment of starting up the boiler is shown.

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