INFLUENCE OF FURNACE TUBE SHAPE ON THERMAL STRAIN OF FIRE-TUBE BOILERS

by

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The aim of this paper is to use numerical analysis and fine element method-FEM to investigate the influence of furnace tube shape on the thermal strain of fire-tube boilers. Thermal stresses in corrugated furnace tubes of different shape, i.e. with different corrugation pitch and depth, were analysed first. It was demonstrated that the thermal stresses in corrugated furnace tube are significantly reduced with the increase of corrugation depth. Than deformations and stresses in the structure of a fire-tube boiler were analysed in a real operating condition, for the cases of installed plain furnace tube and corrugated furnace tubes with different shapes. It was concluded that in this fire-tube boiler, which is of larger steam capacity, the corrugated furnace tube must be installed, as well as that the maximal stress in the construction is reduced by the installation of the furnace tube with greater corrugation depth. The analysis of stresses due to pressure and thermal loads pointed out that thermal stresses are not lower-order stresses in comparison to stresses due to pressure loads, so they must be taken into consideration for boiler strength analysis.

Key words: *fire-tube boiler, corrugated furnace tube, thermal load, pressure, finite element analysis, stress, deformation*

Introduction

Norms such as the standard SRPS EN 12953-3 [1] give rules for fire-tube boiler design and calculation of pressure parts. The norms provide material allowable stresses at given temperatures and the formula for pressure part thickness determination, but they do not explicitly consider the effects of thermal loads. Numerical strength analysis of boiler construction by finite element method (FEM) presented in [2] highlighted that the influence of thermal stresses is large and that it must be taken into consideration when the boiler's construction is designed and its working life evaluated.

Thermo mechanical analysis of hot water boiler and recommendation for reconstruction to reduce stresses at the joint of furnace tube and inner reversal chamber were given in [3]. Thermomechanical analysis of the steam boiler of smaller capacity [4] shown that instead of the corrugated furnace tube, the plain furnace tube of the same thickness could be installed in

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it, without reducing its reliability. The influences of boiler endplate thickness and stiffening girder arrangement on the strength of boiler construction were analysed in [5].

The influence of boiler scale on the thermal stresses of hot water boiler structure was investigated in [6]. It was shown that the significant scale deposit can lead to cracks in the welded joints of smoke tubes and tube plate of the first reversal chamber.

The tube plate is one of important components of fire-tube boilers and heat exchangers. The stress state of tube plates of new constructions can be enhanced by numerical analysis [7]. Considering the difficulties in modelling the whole structure, beam and shell elements are recommended for constructions with tubes and tube plates [8]. Simplification of numerical models, the deformation and stress analysis of many boiler constructions were presented in [9]. The reliability of FEM for boiler structure analysis was demonstrated by the examples of the verification of models of the boiler constructions that had failed in operation, as well as by the performed experiments.

The effects of cracks in the cylindrical shells of boilers and storage tanks on natural frequencies of these structures were analysed by FEM in [10]. Fracture mechanics analysis of the furnace tube and cylindrical shell of fire-tube boiler were presented in [11]. In the paper [12] the methodology of condition and behavior diagnostics of boiler constructions was presented, which is necessary to perform in order to make decision on further operation. It was demonstrated how the diagnostics can be significantly improved by the application of FEM.

A characteristic common element of fire-tube boilers is a cylindrical shell with endplates, which contains the working fluid. Fuel combustion is carried out in the furnace tube that is the boiler furnace. Flue gases from the furnace go into the reversal chamber, than into smoke tubes and exit at the stack, or depending on the flue gas pass arrangement turn around again in the second chamber and go into the next smoke tube bundle. The furnace tube could be performed as a flat cylindrical shell, with or without stiffeners, or as a corrugated cylindrical shell.

The furnace tube is the most thermally loaded part of boiler, and as it is located in the water part of boiler and it is also exposed to pressure load. Due to the difference between the wall temperature of furnace tube and the wall temperature of boiler shell, it is occurred the difference between the thermal expansions of furnace tube and boiler shell, i.e. smoke tubes, and the furnace tube performs certain axial thrust to the tube plates that caused additional strain in the tube plates and furnace tube.

The fire-tube boiler constructions of many manufacturers have shown that the furnace tube of smaller capacity boilers is performed as plain, while the furnace tube of larger capacity boilers is performed as corrugated. The aim of this paper is to use numerical analysis and fine element method to investigate the influence of furnace tube shape on the thermal strain of fire-tube boilers. Thermal stresses in corrugated furnace tubes of different shape, i.e. with different corrugation pitch and depth, were analysed first. Than deformations and stresses in the structure of a fire-tube boiler were analysed in a real operating condition, for the cases of installed plain furnace tube and corrugated furnace tubes with different shapes.

The finite element modelling and thermomechanical analysis of the boiler structures were performed by the KOMIPS software [13, 14]. Deformation and stress were obtained by static calculation. Thermal calculation is involved in the KOMIPS in that way that the temperature field of nodal points or finite element is assigned. Thermal load is calculated on the basis of temperature difference between elements and characteristics of the material (coefficient of thermal expansion, modulus of elasticity and Poisson's ratio) and converts into equivalent load acting at the nodal points of model. Equivalent stresses are obtained using the Huber-Hencky-Mises hypothesis.

Thermal stresses in furnace tubes with different corrugation

In order to analyse the influence of furnace tube shape on thermal stresses, the finite element models of furnace tubes with different corrugation were formed, with the same average diameter of 1125 mm, wall thickness of 15 mm and length of 4800 mm. The analysis was performed for the corrugation depths of 50 mm and 75 mm, and pitches of 100 mm, 150 mm, 200 mm and 240 mm. The structures of furnace tubes were discretised by shell finite elements. For all models the corrugation of furnace tube was presented as the line of seven points. The geometry of the finite element model of the furnace tube with the corrugation pitch of 200 mm and depth of 75 mm is shown in fig. 1.

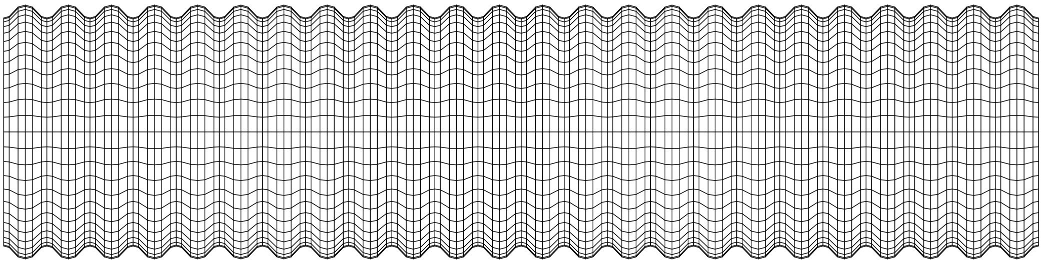

Figure 1. FEM model of the furnace tube with the corrugation pitch of 200 mm and depth of 75 mm

The temperature of nodal points of 270 ºC and the referent temperature of finite elements of 195 ºC were defined. Nodal points at the ends were constrained to move in all three translation direction and the static calculations of all models were performed. The maximal equivalent thermal stresses in furnace tubes with different shapes are presented in fig. 2.

On the basis of performed analysis it could be concluded that with the increase of corrugation depth, for the same corrugation pitch, the maximal thermal stress in furnace tubes is reduced significantly. With the increase of corrugation pitch for the same corrugation depth the maximal thermal stress is increased, but this effect is not so important as the influence of corrugation depth increase.

Finite element model of global boiler structure

The geometry of the base finite element model of the three pass fire-tube boiler of 8000 kg/h steam capacity, with the outer reversal chamber, manufactured by Rudnap Group-Minel Kotlogradnja from Belgrade, is shown in fig. 3 [9]. Due to the symmetry, the model represents only one half of the actual construction. The FEM model geometry of the global boiler structure was obtained by adding the functional substructures modelled by shell and beam finite elements. The substructures modelled by shells elements are the furnace tube and boiler body (the cylindrical shell with flanged ends, gusset stays and boiler supports). The substructures modelled by beam elements are the smoke tubes and tubes of the reversal chamber. The base FEM model has 7325 nodal points, 6412 shell elements and 948 beam elements.

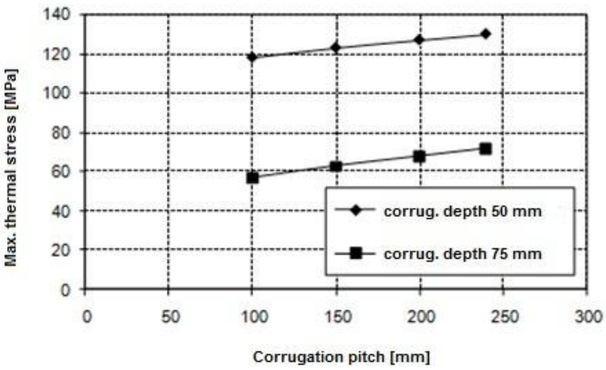

Figure 2. Maximal thermal stress in furnace tubes as a function of corrugation pitch and depth

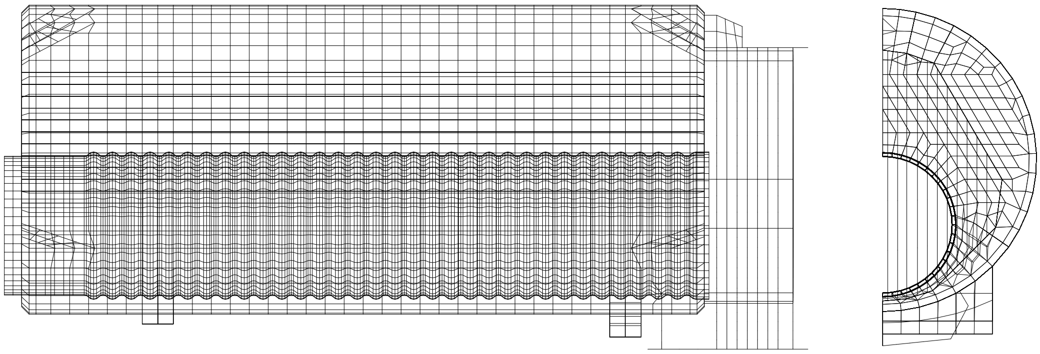

Figure3. Base FEM model of boiler

In order to analyse the furnace shape influence on the boiler construction behavior, the following variations of the FEM model were formed:

- Model V1as the boiler model with plain furnace tube.
- Model V2 as the boiler model with corrugated furnace tube, corrugation pitch of 151 mm and depth of 50 mm. This is the base FEM mode.
- Model V3 as the boiler model with corrugated furnace tube, corrugation pitch of 151 mm and depth of 75 mm.
- Model V4 as the boiler model with corrugated furnace tube, corrugation pitch of 200 mm and depth of 75 mm.

The wall thickness of all furnace tubes is 15 mm. The models V1 and V2 have the same furnace tube average diameter of 1150 mm. The models V2, V3 and V4 have the same furnace tube outer diameter, therefore the furnace tube average diameter of models V3 and V4 is 1125 mm. The overall length of the boiler body is 5500 mm.

Thermo-mechanical analysis of the boiler structure was performed for the combined load due to pressure and thermal loads. The calculation pressure of 1.3 MPa was defined. Temperature field was defined in accordance with the calculation temperature from the SRPS EN 12953-3 [1]. The defined temperature field represents the boiler thermal load.

Deformation and stress analysis of global boiler structure

The deformations (displacements) of shell elements (at the model contour) and beam elements of models V1 and V2 are illustrated in figs. 4 and 5. It is obvious from these figures that the deformations of boiler ends, i.e. tube plates, in the axial direction of furnace tube are larger for the model with the plain furnace tube. It is concluded that the corrugations of furnace tubes perform the compensation of these deformations by itself deformations.

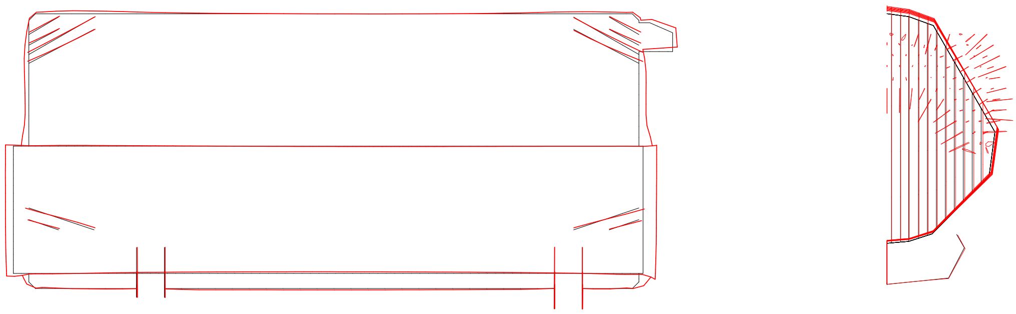

Figure 4. Deformations of the shell and beam elements of model V1

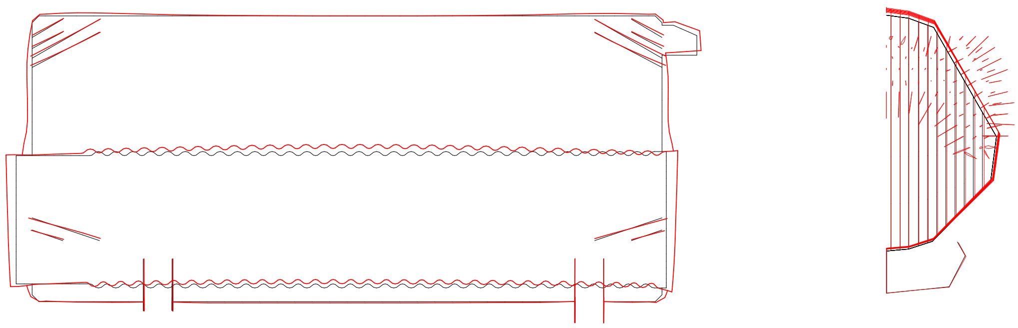

Figure 5. Deformations of the shell and beam elements of model V2

The maximal deformations and stresses in the substructures of the boiler constructions with plane and corrugated furnace tube are given in tab.1, for the combined load due to pressure and thermal loads. The results of stress analysis in the shell elements of model V1 and V4 are illustrated by equivalent stresses lines in fig. 6-9.The stress concentration locations could be seen in these figures.

In the shell elements of model V1 the maximal stresses of 281 MPa are occurred at the joints of the furnace tube and the boiler ends. The maximal stress value is higher than the yield strength of the material of these components at their calculation temperature, which is 211 MPa for the furnace tube of material P295GH and 187 MPa for the boiler ends of material P265GH [15]. The maximal stresses in the shell elements of the models with corrugated furnace tube are occurred in the front boiler end, and for model V2 their value of 186 MPa is almost as the yield strength of the ends material. Model V4 has the smallest value of 155 MPa for the maximal stress in the shell elements. The maximal stresses in the beam elements of all models are lower than the yield strength of the material of the tubes [16] at their calculation temperature.

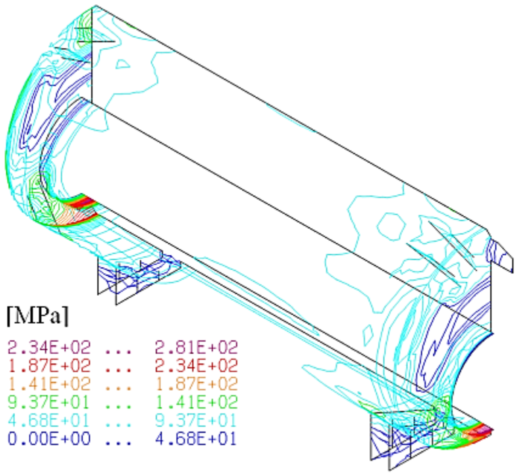

Figure 6. Stress field in the shell elements of model V1

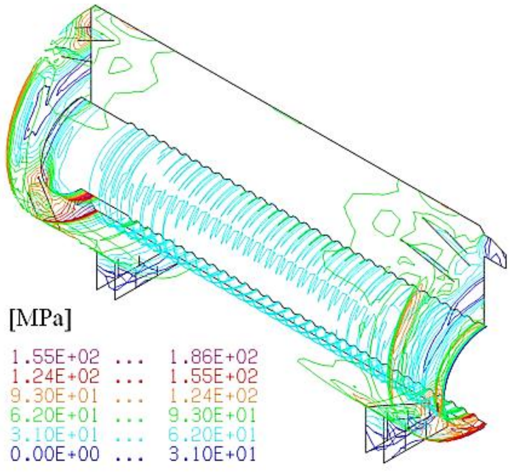

Figure 7. Stress field in the shell elements of model V2

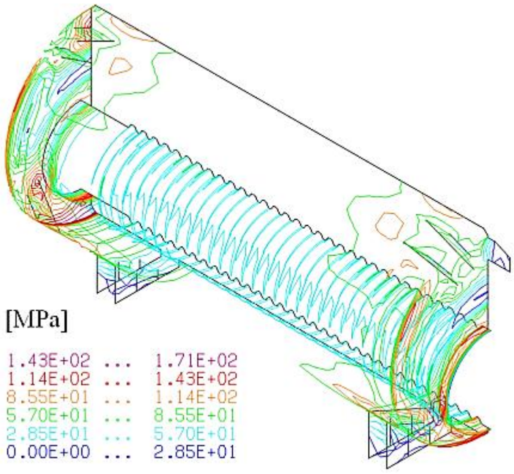

Figure 8. Stress field in the shell elements of model V3

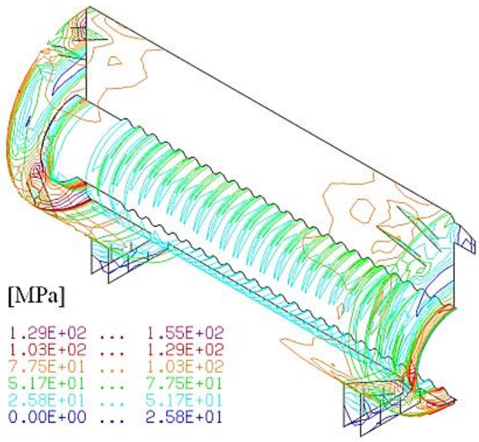

Figure 9. Stress field in the shell elements of model V4

Table 1: Maximal deformations and stresses in the boiler substructures

Boiler model	Furnace tube corrugation		Combined pressure and thermal loads				
			Maximal deformation [mm]	Maximal stress [MPa]			
	Pitch [mm]	Depth [mm]		Furnace tube	Boiler body	Smoke tubes	Reversal chamber
V1	-	-	10.84	281	281	80	128
V2	151	50	11.24	180	186	70	87
V3	151	75	12.69	148	171	79	66
V4	200	75	13.47	130	155	94	81

Analysis of stresses due to pressure and thermal loads

The maximal deformations and stresses in the shell elements due to the load only of pressure inside the boiler are given for all models in tab. 2. The results of deformation and stress calculation for the case that the boiler constructions are exposed only to thermal loads for the shell elements are also given in tab. 2. The stress fields in the shell elements of models V1 and V2 for the cases of acting only pressure loads or only thermal loads are presented in figs. 10-13.

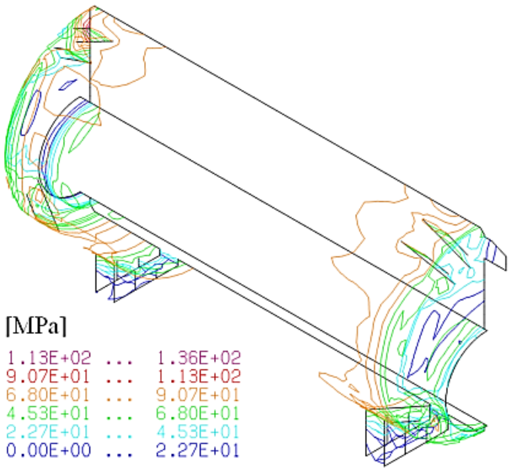

Figure 10. Stress field in the shell elements of model V1 for pressure loads

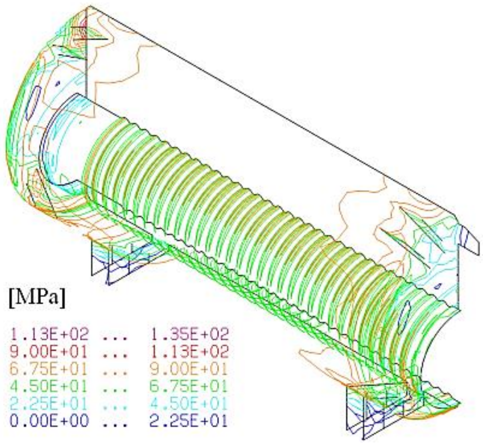

Figure 11. Stress field in the shell elements of model V2 for pressure loads

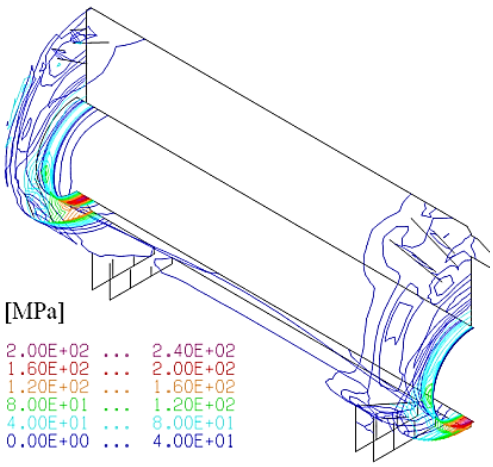

Figure 12. Stress field in the shell elements of model V1 for thermal loads

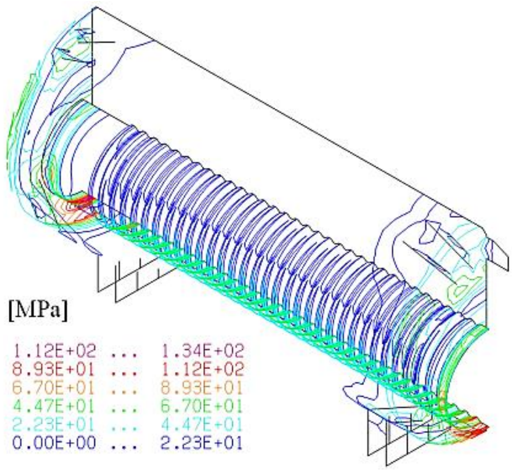

Figure 13. Stress field in the shell elements of model V2 for thermal loads

The maximal equivalent stresses due to pressure loads in the shell elements are occurred for all models in the front end of the boiler body, between two gusset stays located above the smoke tubes. In this case it has almost the same value for the model with plain furnace tube and the models with corrugated furnace tube. The maximal stress in the shell elements of plain furnace tube is lower that the maximal stress in the corrugated furnace tubes. It could be concluded that the stiffness of plain furnace tube against pressure loads is greater compared to the stiffness of corrugated furnace tube of the same wall thickness.

Table 2. Maximal deformations and stresses in the boiler substructures

Boiler model	Pressure loads			Thermal loads		
	Maximal deformation [mm]	Maximal stress [MPa]		Maximal deformation [mm]	Maximal stress [MPa]	
		Furnace tube	Boiler body		Furnace tube	Boiler body
V1	4.19	70	136	7.91	240	240
V2	5.66	85	135	7.37	134	134
V3	9.77	105	135	7.30	80	80
V4	10.50	111	135	7.50	84	84

The maximal equivalent stresses due to thermal loads in the shell elements of all models are occurred at the joints of furnace tube and boiler ends. The thermal stresses in the shell elements of the model with plain furnace tube are very high, while those in the shell elements of the models with corrugated furnace tube are significantly lower. The thermal stresses are lower in the furnace tubes with greater corrugation depth. It is come to conclusion that the corrugated furnace tube has greater flexibility under thermal loads than the plain furnace tube of the same wall thickness.

Conclusions

The analysis of thermal stresses in furnace tubes of different shapes, i.e. with different corrugation pitch and depth, carried out in this paper indicated that the thermal stresses in corrugated furnace tubes are significantly reduced with the increase of corrugation depth.

Therefore the deformations and stresses were analysed in the steam boiler constructions of 8000 kg/h capacity, with different shape of furnace tube, in the real operating condition. It was shown that the deformations of the tube plates in the axial direction of the furnace tube are the greatest for the model with the plain furnace tube. It is obvious that the corrugations of corrugated furnace tubes perform the compensation of these deformations by itself deformations.

Thermomechanical analysis of the boiler construction with corrugated furnace tube installed, that has the corrugation pitch of 151 mm and depth of 50 mm, shown that the high value of the maximal stresses of 186 MPa was occurred in the shell elements of the front boiler end. Yield strength of the material of this component has almost the same value. It was concluded that the maximal stress in the boiler construction of this type could be reduced to 155 MPa by the installation of the furnace tube with the corrugation pitch of 200 mm and depth of75 mm.

The stress analysis of the global boiler model for the cases of acting only pressure loads or only thermal loads pointed out that thermal stresses are not lower-order stresses in comparison to stresses due to pressure loads, so they must be taken into consideration for boiler strength analysis. Thermal stresses could even have greater value than stresses due to pressure in the boiler.

The obtained results confirm the knowledge based on the experience that the corrugated furnace tube must be installed in larger steam capacity boilers. The installation of plain furnace tube in such boilers would cause large plastic deformations of the furnace tube and boiler ends.

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