NUMERICAL AND EXPERIMENTAL STRENGTH ANALYSIS OF FIRE-TUBE BOILER CONSTRUCTION

Branka Gaćeša, Vesna Milošević-Mitić, Taško Maneski, Dražan Kozak, Josip Sertić

Preliminary notes

Norms, such as EN 12952-3 and EN 12953-3 handle the issues concerned with calculation of the pressurized boiler components, not however considering the influences of thermal strains that are often of vital importance for the integrity of boiler's construction. Application of FEM in boiler design in EN is suggested in calculating all components that are not covered by the norm. In this way, the calculation of thermal stress is left to the free will of designer and technical inspectorate which supervises and approves placement of a boiler into operation. This paper demonstrates that the influence of thermal stresses is great and that it must be taken into consideration when the boiler's construction is designed and its working life evaluated. It is shown that for every construction a numerical-experimental behaviour diagnostics should be conducted prior to putting it into operation. First, a numerical model must be experimentally verified and then it can be used in considering different parameters of strength diagnostics, such as distribution of membrane and bending stresses for substructures, and distribution of deformation energy. They indicate, in an optimal way, root causes of insufficiently good behaviour of the construction. Also, a dynamical calculation of natural oscillations should always be suggested.

Keywords: deformation energy, experiment, finite element analysis, steam-boiler, stress, temperature

1 Introduction

Pressures and increased temperatures to which boiler components are exposed initiate deformations and stresses that can lead to a construction break down. So, strength calculations for most reliable boiler elements are standardized and subject to supervising inspection control. Norms such as EN 12952-3 and EN 12953-3 [1] state the allowed stresses for a given temperature and bring explicit formulas for strength calculation through determining wall thickness for pressurized elements, but do not explicitly consider the influence of thermal stresses, local concentrations of stresses and load changes.

Numerical analysis is increasingly applied in diagnosing boiler construction strength. The finite element model of the overall shell and tube waste heat recovery boiler is presented in paper [2]. The simplification of models, stress calculation of smoke tubes for boilers in elastic-plastic analysis by FEM and reforming suggestion are provided in [3]. The cause and prevention of boiler tube plate cracks are presented in [4] and [5]. Fracture mechanics study of the fire tube and the outer shell of a boiler can be obtained from a special fracture mechanics finite element program as presented in [6]. In the design of boiler components, the influence of the temperature loading does not have appropriate consideration. Temperature dilatations of some components of a steam boiler can lead to great plastic deformations [7] and to increasing of dynamic strength. Influence of fire tube geometry on behaviour of steam boiler of lower capacity [8] was examined by Gaćeša B. In [9] a diagnostic procedure for behaviour of hot water generator is demonstrated due to previous construction compliance during the course of cold testing procedure. It was shown that calculation based on norms is not sufficiently reliable. Improvement of steam boiler plant efficiency based on results of on-line performance monitoring is provided in [10] and the application of a fuzzy logic in boiler control in [11]. Numerical analysis of strength uses FEM, analysis of calculation results and determination of the behaviour parameters. Experimental analysis encompasses the measurement of input quantities for numerical calculation and evaluation of calculation results[12].

In this paper a complete numerical-experimental strength analysis of fire-tube boiler is shown. Numerical analysis for pressure and temperature load is conducted using software package KOMIPS [13]. In the paper it is shown that the influence of thermal boiler loads is great and that it must be taken into consideration in designing and estimating operation life of boiler construction. It is shown that the best procedure for each construction is to perform numerical-experimental behaviour diagnostics. First, a numerical model must be experimentally verified after which it can be used in considering different parameters of strength diagnostics such as distribution of membrane and bending stresses and distribution of deformation energy. They indicate in a best way root causes of insufficient behaviour of construction. Also, a dynamical calculation of eigen oscillations is suggested.

A hot water flame-tube boiler (constructed strictly in accordance with norms) has been experimentally examined in boiler factory KIRKA-Suri by being fired with thatch up
Numerical and experimental strength analysis of fire-tube boiler construction

B. Gaćela, V. Milošević-Mitić, T. Maneski, D. Kozak, J. Sertić

... to a pressure of 3 bar. A calculation model is created to simulate the behaviour of the boiler in testing conditions. Statics calculation is performed for pressure and thermal load. Model verification results have shown that the developed calculation approach that is based on FEM is capable of predicting the behaviour of boiler construction in realistic load conditions. Parameters for strength diagnostics have pointed out the causes of inadequate construction behaviour. Dynamical calculation of boiler natural oscillations has confirmed the identified static behaviour.

2 Experiment description

A boiler that was thermally uninsulated was filled with water and fired up with bundles of thatch. Around 10 min after the start of the experiment the boiler pressure reached 2.3 bar after which measurement of physical quantities was initiated. Measurements of boiler water pressure, outlet and inlet water temperature, temperatures of metal on selected points of boiler construction as well as deformations and stresses in one point of rear head have been conducted. After 25 min from the beginning of the experiment, another group of measurements was taken with boiler pressure being at 2.5 bar. Third group of measurements was taken after 40 min with the boiler pressure being 2.8 bar, while the fourth group of measurements was taken after 55 min when the pressure reached 3 bar.

Measurement of boiler pressure was performed with burden tube manometer, while the measurements of inlet and outlet water temperature were taken with boiler thermometers that were already installed within the boiler’s fine pipe fitting. Measurements of construction temperatures were taken by a non-contact laser device.

Temperature of the metal was measured in multiple points of construction that were accessible to placement of measurements, especially in the rear head (Fig. 1) and in boiler shell in which the temperature measurements were taken aside shell length and height. Deformations were measured between the bottom most edge anchor and the one above it.

Tab. 1 lists the measured values of boiler pressure \( p \), inlet water temperature \( \vartheta_i \) and outlet water temperature \( \vartheta_o \) as a function of time.

Stress measurements were performed using strain-gage method. On 50 mm below the lowest edge anchor of rear head, an active strain-gage was applied in vertical direction along with foil to the cleaned metal surface. Since active and passive gages were subjected to the same load conditions, thermal strains were compensated for, so that the deformations measured were due to pressure alone. Measurement equipment has analog-digital (AD) converter and a USB communication signals to a computer.

3 Numerical analysis by finite element method

Fig. 3 shows two projections of boiler model together with measurement points of temperatures T1-T12. Flue gas recirculation from fire tube to smoke tubes in the second pass is performed in the back chamber which is placed within boiler. Recirculation of flue gases into the tubes of third pass is performed in the front chamber. The geometry of the entire boiler supporting structure is obtained by means of addition of three substructures: A – fire tube (A1) with back recirculation chamber (A2) and inspection orifice (A3); B – boiler shell, composed of housing (B1), back (B2) and front (B3) head with front recirculation chamber (B4) and lugs (B5); C – smoke tubes (C1) and anchors (C2) with fictional beams. Substructures A and B represent the supporting elements of the construction which are loaded thermally and by surface pressure, so they are discretized using the shell elements. Substructure C presents support elements shaped as tubes and bars and is discretized with the beam finite elements. This greatly reduced the number of model elements and points thereby reducing total calculation time.

Several different meshes are analyzed and typical mesh with its substructures is shown in Fig. 4. Due to the symmetry, the model represents only one half of the actual construction. It is composed of 2873 nodes that describe 2677 plates and 507 beam elements.

In order to compare the stress and strain calculation results obtained by FEM with the measured values obtained experimentally, four options of computational model have been created (M1 to M4) for four different boiler pressures and water temperatures on inlet and outlet fittings in...
Calculation was performed for two load cases: compounded pressure and temperature load, and separated pressure load for purposes of model validation. Surface pressure load was defined for all models according to measured values. Characteristic temperatures that were measured on rear head and boiler shell are schematically shown in Fig. 5a. Temperature T1 was measured between upper anchors of the rear head, temperature T2 was measured in the point of deformation measurement, while temperature T3 was measured in the point of stress measurement. Temperatures T4, T5 and T6 were measured on various heights in the middle of boiler shell length.

According to EN computational temperature is equal to the working fluid temperature increased by a temperature addition which is created for pressurized components subjected to fire or flue gases.

Measurements of flame tube and chambers were unfeasible, as well as temperature of rear head at the boiler flue gas outlet fitting. These temperatures were, therefore, adopted on the basis of boiler water temperature values and on adopted temperature additions. Temperature load was calculated on the basis of temperature difference between elements and characteristics of the material. Adopted temperatures are shown on the diagram in Fig. 5b. On the basis of measured and assumed temperatures a temperature field for boiler construction was defined.

### 3.3 Results of FEM calculation

Global image of model M4 for compounded pressure and temperature load is shown in Fig. 6. Maximum total displacement (deformation) is 2.17 mm.
Stress field of plate elements for the contours of the entire model M4 and especially for its rear head, in the range of 0-20.9 kN/cm², is shown in Fig. 8. Equivalent stresses are calculated by the Huber-von Mises hypothesis.

Maximal stresses in the construction are located in the drum housing near the location of junction with the rear head and amount to 20.9 kN/cm². Yield stress for the calculation temperature of this element and for material P265GH (EN 10028-2:2009) is 21.5 kN/cm². In the rear head somewhat lower stresses appear in the place of junction with drum housing. Calculation rendered that in some anchors high stresses are also produced.

Diagram in Fig. 10 shows that FEM calculation rendered somewhat higher strains than those obtained by the experiment, but also these differences are small. The most important conclusion is that FEM renders a more reliable representation of stresses and strains in realistic working conditions of boiler.

The basis for defining choice parameters (a new
construction) and behaviour parameters (reconstruction or repairment of an existing construction) is standard calculation (static, thermal, dynamic) of a boiler using FEM. System KOMIPS possesses specific calculations for a closer definition of choice parameters by determining load distribution, membrane and bending stresses, deformation energy and kinetic and potential energy. This enables a very efficient state analysis and diagnosis of construction behaviour. These parameters of behaviour diagnostics – the elements for optimization suggest that changes in the construction need to be done in order to obtain better construction exploitation behaviour [12].

Efforts towards creating good exploitation behaviour of a construction include: evenly distributed stresses, strains and energy, lowered presence of stress concentration, higher resilience to crack initiation and growth, dynamical responses that are distanced from their excitations, higher first harmonic and greater distance between harmonics, lower factor of dynamical gain.

Stress analysis in model plates has shown that its highest values and concentrations are located in the boiler shell near the welded joint that connects it to rear head. Maximum equivalent stress value is as high as 20.9 kN/cm² and close to yield stress for the calculation temperature. For plates of model M4 the ratio of membrane and bending stresses was 68.5/31.5 while in the beams this ratio was 41.5/59. That means that the beams are dominated by bending stresses. Detailed display of membrane and bending stresses distribution, as well as energies of deformation for substructures of model M4 is given in Tab. 2. This distribution gives us the initial element for the optimization. Membrane stresses prevail significantly in the boiler shell (B1), as well as in the fire tube (A1), which is good in the sense of construction carrying capacity. Bending stresses prevail in plates of back chamber (A2) and the rear head (B2), as well as in the smoke tubes (C1) and anchors (C2). Total deformation energy distribution for substructures points to the conclusion that fire tube and smoke tubes are being mostly deformed.

### Table 2

**Stresses and deformation energy distribution over the boiler substructures**

<table>
<thead>
<tr>
<th>Substructures</th>
<th>Stress distribution / %</th>
<th>Deformation energy / %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>membrane</td>
<td>bending</td>
</tr>
<tr>
<td>A1</td>
<td>5.7</td>
<td>3.1</td>
</tr>
<tr>
<td>A2, A3</td>
<td>3.6</td>
<td>6.9</td>
</tr>
<tr>
<td>B1</td>
<td>30.3</td>
<td>7.0</td>
</tr>
<tr>
<td>B2</td>
<td>3.2</td>
<td>6.9</td>
</tr>
<tr>
<td>B3, B4</td>
<td>4.2</td>
<td>3.8</td>
</tr>
<tr>
<td>B5</td>
<td>18.4</td>
<td>2.1</td>
</tr>
<tr>
<td>C1</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>C2</td>
<td>0.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>Σ=67.1</td>
<td>Σ=32.9</td>
</tr>
</tbody>
</table>

One of the important behaviour parameters is the distribution of the difference between kinetic and potential energy for the first oscillation mode [14]. In designing certain parts of boiler that are pressurized appropriate norms are used. Strength calculation using the formulas given in norms is based on the experience of the constructor with previous similar constructions. Application of norms, as well as experimentation, cannot determine the location and quantity of maximal stress due to testing or working pressure and temperature. It is not a rare case that within a relatively short period of time of operation a hazard occurs for a boiler that has been previously tested by water pressurization defined by norms. The advantages of numerical method over norms and experimentation are expressed through possibilities of determining a nearly realistic image of stresses and strains, confirming the solution choice, determining the root cause of poor behaviour (or compliance), decision making abilities regarding reconstruction or working regime changes.

In this paper a complete numerical-experimental procedure for diagnostics is shown for the construction of a fire-tube boiler fired by thatch. A FEM model is formed and static and dynamic calculation performed. Experimental measurements have verified the numerical model. On the basis of conducted static analysis it can be clearly seen that the first critical location of the boiler construction is the boiler shell in the vicinity of junction with the rear head. Boiler shell is the element that has the highest concentrations of stresses and strains, as well as great

### Table 3

**Distribution of potential and kinetic energy E₀, Eₖ, %**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>E₀</th>
<th>Eₖ</th>
<th>E₀</th>
<th>Eₖ</th>
<th>E₀</th>
<th>Eₖ</th>
</tr>
</thead>
<tbody>
<tr>
<td>f₀₁ = 21 Hz</td>
<td>0.8</td>
<td>19.2</td>
<td>38.6</td>
<td>9.0</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>f₀₂ = 33.3 Hz</td>
<td>0.6</td>
<td>34.4</td>
<td>73.4</td>
<td>1.0</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>f₀₃ = 45.6 Hz</td>
<td>46.8</td>
<td>25.6</td>
<td>9.1</td>
<td>0.6</td>
<td>95.0</td>
<td>95.6</td>
</tr>
</tbody>
</table>

**Figure 11** First main mode of oscillation f₀₁ = 21 Hz

**Slika 11.** Prvi glavni oblik oscilacija f₀₁ = 21 Hz

Raspodjela razlike između potencijalne i kinetičke energije

### Conclusion

Zaključak

In designing certain parts of boiler that are pressurized appropriate norms are used. Strength calculation using the formulas given in norms is based on the experience of the constructor with previous similar constructions. Application of norms, as well as experimentation, cannot determine the location and quantity of maximal stress due to testing or working pressure and temperature. It is not a rare case that within a relatively short period of time of operation a hazard occurs for a boiler that has been previously tested by water pressurization defined by norms. The advantages of numerical method over norms and experimentation are expressed through possibilities of determining a nearly realistic image of stresses and strains, confirming the solution choice, determining the root cause of poor behaviour (or compliance), decision making abilities regarding reconstruction or working regime changes.

In this paper a complete numerical-experimental procedure for diagnostics is shown for the construction of a fire-tube boiler fired by thatch. A FEM model is formed and static and dynamic calculation performed. Experimental measurements have verified the numerical model. On the basis of conducted static analysis it can be clearly seen that the first critical location of the boiler construction is the boiler shell in the vicinity of junction with the rear head. Boiler shell is the element that has the highest concentrations of stresses and strains, as well as great
deformation energy. The rear head is shaped as a flat plate, so transition was performed without the curvature radius, which is a feature that might be altered in new boiler constructions. The plates of back chamber and rear head are dominantly loaded with bending, while for some anchors, stabilizing these elements, high stresses are present.

Therefore, the application of numerical methods (FEM, FDM, etc.) in designing boilers in EN is suggested in calculating all components not covered by norms and not analytically calculated using the theory of elasticity.

The paper shows that the influence of thermal strains is significant and that it must be taken into consideration in designing and evaluating the working time of boiler constructions. It has been shown that it is best to perform numerical and experimental diagnostics of behavior for each construction prior to putting it into operation. First, a numerical model must be experimentally verified and then used in considering various parameters for strength diagnostics, such as distribution of membrane and bending stresses for substructures as well as distribution of deformation energy. They are the best indicators of inadequate construction behavior. Also, a dynamical calculation of eigen-oscillations should always be suggested.

Acknowledgements

Zahvale

We would like to thank the boiler factory KIRKA-Suri for allowing us to perform our experiment during the course of boiler testing procedure.

7 References

Literatura


Authors’ addresses

Adrese autora

Branka Gaćeša  Taško Maneski
Vesna Milošević-Mitić
Mašinski fakultet Univerziteta u Beogradu
Faculty of Mechanical Engineering University of Belgrade
Kraljice Marie 16
11120 Belgrade, Republic of Serbia
branka@vektor.net
tmaneski@mas.bg.ac.rs
vmilosevic@mas.bg.ac.rs

Dražan Kozak
Josip Sertić

Strojarski fakultet u Slavonskom Brodu
Mašinski fakultet Univerziteta u Osijeku
Mechanical Engineering Faculty in Slavonski Brod
J. J. Strossmayer University of Osijek
Trg Ivane Brlić-Mažuranić 2
HR-35000 Slavonski Brod, Republic of Croatia
dkozak@sfsb.hr
jsertic@sfsb.hr