Condition and Behavior Diagnostics of Boiler Constructions

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In the paper the methodology of condition and behavior diagnostics of boiler constructions is presented, which is necessary to perform in order to make decision on further operation. An algorithm is defined that illustrates the methods for collecting data needed for the diagnostics: analysis of construction, visual inspection, non-destructive and destructive examinations, engineering analysis, experimental measurements and expert condition assessment-diagnostics of behavior. The diagnostics can be significantly improved by the application of finite element method-FEM. The main advantages of this numerical method over the calculation by design norms are expressed through possibilities of determining a nearly realistic image of deformation and stress, and reliable assessment and prediction of boiler construction behavior under service condition. The application of FEM is illustrated by the examples of designing a new fire-tube boiler and behavior diagnostics of water-tube boiler in service.

Keywords: boiler, condition assessment, behavior diagnostics, design norms, finite element method.

1. INTRODUCTION

The aim of performing the condition and behavior diagnostics of boiler construction is to evaluate the operational reliability in the further defined period and to determine actions as needed for its life extension.

Condition assessment and remaining life evaluation are required, under normal operation condition, after the period of service approaching the designed life. Condition assessment should occur sooner in the following cases: operation above nominal capacity; excessive cycling and/or variation of load; history of stops and starts faster than those anticipated by the design; known evidence of accumulated damages; and history of accumulated damages on similar units [1].

The scope of boiler condition survey is dictated by the scope of data needed for the evaluation of its future service. The first level of survey depends on visual inspection and minimal if any non-destructive examination-NDE. The second level in addition to visual inspection includes non-destructive testing, possibly with a little material sampling (tube samples). The third level incorporates removal of material for extensive laboratory analysis, engineering studies, such as stress analysis by finite element method and boiler performance analysis, and site experimental testing, such as stress measurement by strain gauges, etc [2].

Through the benefits of performed solution analysis, current condition assessment has acquired important information considering the improvement in design methods of boiler components, development of new technical solutions and testing techniques, for improving maintenance procedures, as well as for development and choice of materials with improved characteristics and processing technology [3].

Design of boiler components depends much on the experience of designers. Departure from conventional design, although in compliance to the boiler norms for pressure part design and calculation, can result in premature failure. A stress analysis by numerical finite element method-FEM applied has highlighted the need for considering effects of thermal loads due to the constraint of thermal expansion in designs that otherwise meet the basic boiler norms [4].

2. METHODOLOGY OF CONDITION AND BEHAVIOR DIAGNOSTICS OF BOILER CONSTRUCTIONS

Methodology of condition and behavior diagnostics of boiler constructions is presented by an algorithm in Figure 1 [5]. The algorithm illustrates methods for collecting data needed for condition assessment and behavior diagnostics, and it is mainly related to boiler constructions in service, but also is applicable for new ones.

2.1 Analysis of construction

Analysis of construction is the first step in structural diagnostics. It includes forming the database of boiler construction and auxiliaries and defining critical components. The database is formed on the basis of: literature; available documentation (attest and technical documentation, catalogues, operation instructions); reports on performed inspections; reports on past damages, tasting, repairs and replacements; and data about technical achievements in similar constructions.

Critical components are those substructures of boiler that are directly related to the reliability, safety and performance of the boiler. Critical components that are the focus of non-destructive and destructive examinations are boiler pressure parts since their damage or failure directly affects the reliability of boiler.

. Literature
. Technical documentation
. Operation and maintenance history
. Technical achievement
. Critical components

. Solution expertise
. Possibility of improvement

. Visual examination of accessible areas
  of boiler and/or auxiliaries
. Identification of the root cause of damage

. Inspection report with recommendations

. Inspection program and testing plan
. Non-destructive testing, possibly with
  tube samples
. Destructive testing as necessary, removal
  of materials for laboratory analysis
. May include audits of controls and safety
  system and boiler performance testing

. Analysis of examination results
. Diagnostics parameters
. Requirements for additional examination
. Requirements for engineering analysis

. Design by norms
. Design by analysis, using FEM
. Fatigue and creep analysis
. Fracture mechanics analysis
. Boiler performance analysis

. Analysis of calculation results
. Diagnostics parameters
. Requirements for experimental
  measurements

. Pressure   . Metal temperature
. Stress   . Deformation (strain)
. Vibration

. Analysis of measurement results
. Diagnostics parameters

. Boiler operational reliability evaluation
. Recommendations of actions as needed for
  boiler life extension
. Overhaul   . Upgrade
. Reconstruction   . Operating regime change
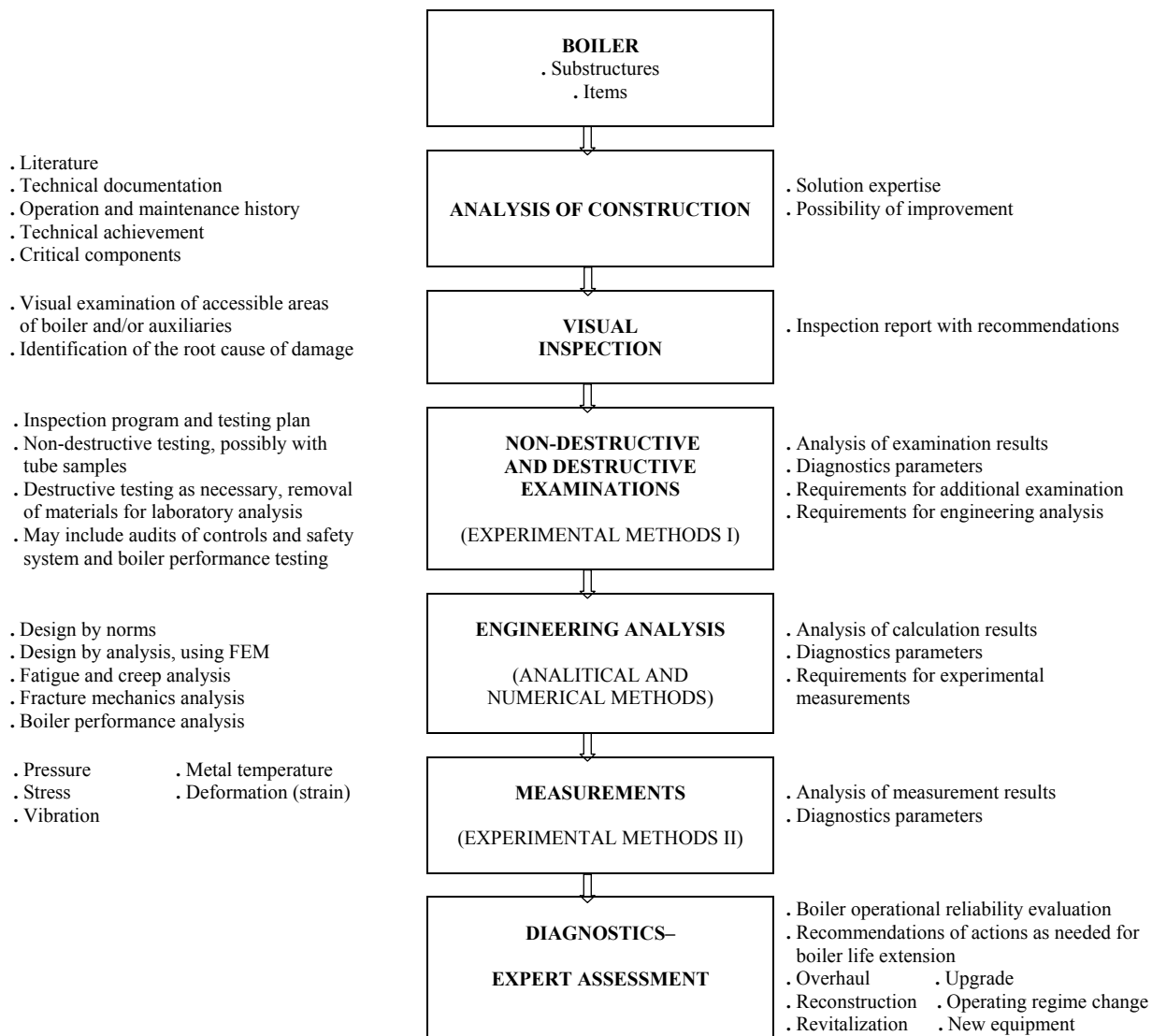. Revitalization   . New equipment

Figure 1. Algorithm of condition and behaviour diagnostics of boiler construction

Components such as safety valves, burners, flame safety system and combustion controls, directly affect the safe operation of the boiler and therefore their function must be maintained and tested properly. Components whose deterioration with age has adverse effects on boiler performance are: air-heaters, fans, fuel preparation equipment, boiler casing, refractory and insulation and structural supports.

2.2 Visual inspection

On the basis of available boiler database, experience with similar units and future plans for the boiler, critical boiler components are identified. A visual inspection implies visual examination of accessible areas of boiler and/or auxiliaries. External boiler inspection is done to evaluate boiler general condition. Damages or suspicion of damages are identified by internal boiler inspection, when non-destructive and destructive examinations are needed to be performed. An inspection report with recommendations is developed (for damage overhaul in a case the root cause of damage found is identified or for performing examinations and/or engineering analysis).

2.3 Non-destructive and destructive examinations

Non-destructive and destructive examinations fall into experimental methods I. They are followed up by the inspection program and testing plan established on the basis of performed visual inspection. Audits of controls and safety system and boiler performance testing may be included that can be of particular value in making decision of possible unit upgrade. Examination is based mainly on NDE methods, possibly with tube samples, and in special cases also with the removal of the materials for extensive laboratory analysis.

The choice of NDE method depends upon location and type of potential damage, as well as the limitations caused by the geometry of component to be tested. NDE methods that are typically used for boilers are:
- visual examination
- magnetic particle testing
- penentrant testing
- ultrasonic testing
- metallographic replication
- hardness reading
- radiography

Visual examination is the most basic method of NDE and is performed for all components for identification of visible damages. Endoscope inspection is used for internal visual examination of tubes. Magnetic particle and penentrant testing are used to examine the presence of surface damages (of crack type) and testing of welds. Ultrasonic testing may be used for examination of welds and material homogeneity, and is also used for thickness testing, to assess thinning due to metal loss. Metallographic replication implies, from previously polished surface, lifting an image of the metal surface, and afterwards examination of the metal grain structure under a microscope. Hardness reading is complementary examination of material micro structural degradation. Radiography is primarily used to test welds at field following boiler erection or repair and is not normally used for boiler condition assessment.

Destructive examination implies removal of material samples and examination of removed samples that might be mechanical, metallographic and examination of chemical composition. Sampling or removal of material sample is done on the basis of visual inspection of characteristic deviations, as well as at the locations of the highest thermal loads.

Through examination results analysis, the parameters of metal condition diagnostics of boiler critical components are obtained. Condition assessment is performed on the basis of boiler service data and comparison of examination results to criteria acceptability. From condition assessment, recommendations for actions as needed for boiler life extension are provided.

To evaluate condition more precisely, additional examinations may be required that should be performed immediately or in the near future. A need for extensive engineering analysis, by analytical or numerical methods, can also arise from examination results analysis.

2.4 Engineering analysis

There are two approaches for new boiler constructions design that can be used by designers: 1) design by rules, or design by norms and 2) design by analysis. Unless otherwise specified, design by norms (for strength calculation) is typically used by the boiler manufacturers.

Norms such as Serbian standards of group SRPS M.E2 [6] and European norms EN 12952-3 and EN 12953-3 [7] dictate rules for boiler design. Norms provide material allowable stress at a given temperature and explicit formula for a boiler pressure part wall thickness determination under static load.

European norms for design and calculation of boiler pressure parts allow design by analysis using finite element method. Besides being used for boiler design, which should meet the applicable norms, FEM can also help in fitness-for-service assessment of the boiler construction. It is also used for failure investigation by simulating the conditions present at the time of the incident, as well as for simulation of failure mechanism such as fatigue and brittle fracture.

In the standard SRPS M.E2.031 [6] for the design of cylindrical shell under internal pressure it is also given the calculation for the case of load variation due to the variation of internal pressure or the combined changes of internal pressure and temperature. When additional requirements should be fulfilled, the rules from standard SRPS M.E2.041 [6] are applied. Standard SRPS M.E2.213 [6] describes additional testing of the components, calculated with time-dependent strength characteristics and calculation method of total operation time and fatigue for installed boiler components.

European norm EN 12952-3, Section 13, incorporates a fatigue assessment and calculation method for water-tube boiler pressure parts subjected to significant fluctuating loading. The examples are as follows: application of fluctuations in pressure (including testing, temperature transients, restrictions of expansion or contraction during normal temperature variations, forced vibrations and variations in external loads. Finite element analysis may be applied to obtain more exact life predictions. Norm EN 12952-4 [7] describes procedures for calculating the creep and/or the fatigue damage of boiler components during operation. The highest loaded components shall be chosen for monitoring purposes.

The design norms are applied to the initial design of boiler pressure parts. Degradation and damages occur during service, so it is necessary to carry out boiler integrity assessment and remaining life evaluation. There are two main approaches for structural integrity evaluation, the first one based on the application of the design norms, and the second approach is fitness-for-service assessment [1].

The "Design norms" approach for the remaining life evaluation is a traditional approach that uses the same design criterions for evaluating the condition and damages of boiler resulting from service. Through testing, repairs and replacements, this approach aims to restore the boiler condition and reliability. The control strength calculation of boiler pressure parts is performed, which is based on comparison of the minimal measured wall thickness to the necessary wall thickness calculated according to the formula from the applicable norm.

The "Fitness-for-service" approach is the newer approach that evaluates the fitness-for-service of equipment, in spite of accumulated damages and degradation. Analytical methods to determine the possibility to continue operating with existing defects are applied. The assessment may include stress analysis using FEM, calculations through fracture mechanics, and use of standards such as API 579. This approach aims to minimize repairs and replacement, without comprising reliability.

Analysis of the main boiler performances is necessary when the change of boiler operating regime or significant reconstruction is considered, and implies additional calculations, such as control thermal calculation, hydraulic calculation, etc.

2.5 Experimental measurements

Experimental methods II imply measurements of operation loads, deformation (strain), stress and vibration. Operation load measurements incorporate the measurement of pressure in boiler and metal wall temperature of boiler components using appropriate sensors for pressure and temperature. Strain gauges are usually used for strain and stress measurement. Vibration measurement is performed by accelerometers. In experiments, the measuring points should be selected, values measured, and monitored loads, strain, stress and vibration level.

Experimental measurements may be required for a boiler current condition assessment, or performed to verify a calculation model for numerical calculation using FEM. Finite element method should be used in boiler designing to avoid resonance phenomenon, and it may be also used as a tool for the assessment of potential modifications for vibration problems identified through measurements.

The results of numerical and experimental structure analysis of boilers, designed strictly according to norms, are shown that the influence of thermal load is great and must be taken into account in the design and lifetime assessment of boiler constructions [8].

2.6 Diagnostics-expert assessment

The main aim of performing the methodology of condition and behavior diagnostics of boiler constructions presented in this paper is to evaluate the operational reliability in the further defined period and to determine actions as needed for the boiler life extension.

On the basis of diagnostics parameters obtained by visual inspection, experimental and/or analytical and numerical methods, behavior diagnostics-expert condition assessment is performed that gives information to boiler user necessary for making a decision concerning the boiler: overhaul, reconstruction, revitalization, and upgrade operating regime change or new equipment installation.

The methodology described in this paper is mainly related to older boilers, especially those approaching the legally regulated time for starting the condition assessment procedure. However, the discussion presented here may be also useful for new boilers, even when they are in the design stage.

3. EXAMPLES OF FEM APPLICATION

Hot water fire-tube boiler with capacity of 9.3 MW and calculation pressure of 8 bar that is in service has a reverse flame corrugated fire-tube. Numerical analysis of the boiler structure using FEM is performed in order to investigate if the corrugated fire-tube could be replaced by plain one. Two global models of the boiler are formed for calculation, one with the corrugated fire-tube that is shown in Figure 2, and the other with the plain fire-tube of the same wall thickness.

Due to the symmetry of the geometry and boundary conditions, the model represents only one half of the

real boiler structure. The substructures that are under surface pressure and thermal loads are discretized using shell elements, such as the boiler cylindrical shell with front and rear heads and supports, as well as the fire-tube with head and the internal reverse chamber. Tube-shaped substructures, which mean the smoke tubes and anchor tubes of boiler heads, are discretized using beam elements. This reduces significantly the number of model nodal points and time of calculation.
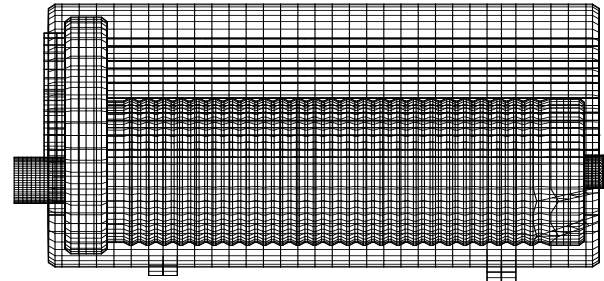

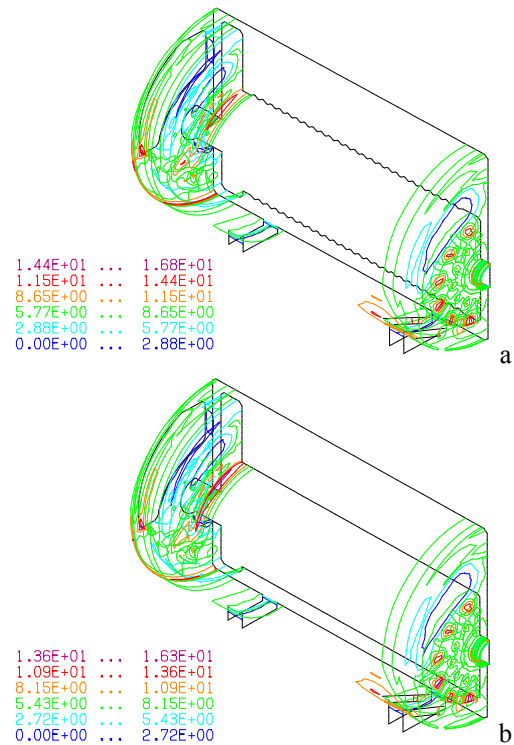**Figure 2. Finite element model of the boiler with the corrugated fire-tube**

1.44E+01	...	1.68E+01
1.15E+01	...	1.44E+01
8.65E+00	...	1.15E+01
5.77E+00	...	8.65E+00
2.88E+00	...	5.77E+00
0.00E+00	...	2.88E+00

a

1.36E+01	...	1.63E+01
1.09E+01	...	1.36E+01
8.15E+00	...	1.09E+01
5.43E+00	...	8.15E+00
2.72E+00	...	5.43E+00
0.00E+00	...	2.72E+00

b

Figure 3. Equivalent stress field [kN/cm^2] in the shells of the boiler with a) corrugated and b) plain fire-tube

The calculation temperature of a component shall be calculated by taking account of variations in heat transfer and fluid flow in the boiler. If such calculations are not carried out then, according to the boiler norms, the calculation temperature shall be equal to reference temperature increased by temperature allowance given in the norms [7].

Deformation and stress calculation of the boiler structure is performed by Komips program [9] for the total of pressure and thermal loads. Calculation pressure of 0.08 kN/cm^2 is addopted. Temperature field of the construction is defined in compliance with the calculation temperature according to the applicable norm, and it represents its thermal load.

For both boiler models the results of stress analysis are shown graphically in Figure 3 by equivalent stress isolines. Maximal stress that occurred in the shells of the boiler front head is insignificantly reduced from 16.8 to 16.3 kN/cm^2 by the construction modification. Maximal stress in the beams that occurred in the anchor tubes of both models is increased from 13.5 to 14.5 kN/cm^2. Maxsimal stresses in all substructures of both models are lower than the yield strength of the material of these components at their calculation temperature.

Typically, smaller capacity boilers are constructed with plain fire-tubes, while larger capacity boilers are constructed with corrugated ones. Behavior diagnostics of this boiler, which falls into larger capacity, is shown that in a new boiler of this type it could be installed the plain fire-tube instead of the corrugated one. This change contributes to the reduction of manufacturing cost without the reduction of reliability [10].

Water-tube boilers can be of larger capacity than fire-tube boilers and are mostly designed for high pressure and high steam temperature. Generally, only models of substructures of these boilers are formed and analysed, without modelling the whole boiler structure. Modern design of these boilers implies constructions with membraned wall or tube panels that are stiffened with buckstays. Discretization of the tubes and plate strips of these panels with shell finite elements would lead to the great number of nodal points and elements of global boiler model.

In PhD thesis [5] it is presented the procedure of defining a new subtype of thin orthotropic plate finite element that has two different thicknesses and material elasticity matrices, for membrane and bending loads. The element is programmed within Komips software package and is applied for the modelling of the membraned walls of water-tube boiler with steam capacity of 110 t/h. Global model of this boiler is given in Figure 4.

The boiler drums, as well as profiles and different plates of buckstays, are discretized using shell finite elements. The headers and tubes are discretized with beam finite elements. Numerical calculation of the boiler global model is performed for the calculation pressure of 0.55 kN/cm^2 (55 bar) and 0.558 kN/cm^2 in the upper and lower drum respectively, overpressure of $2.34 \cdot 10^{-4}$ kN/cm^2 (23.4 mbar) in the furnace, and thermal load. Temperature field of the boiler is defined in compliance with the calculation temperature according to the applicable norm.

Stress field in the shells of the model is shown in Figure 5. Maximal stress of 19.9 kN/cm^2 is occurred in the horizontal plates of buckstays at the boiler corners. Analysis is shown that the high stresses of about 17 kN/cm^2 are also occured in the membraned walls near the furnace rear wall and at the boiler corners at the elevation of buckstays, which are not covered by design norms. In regard to the yield strength of the material of these elements, it could be expected that plastic deformations occured at the mentioned locations. It is concluded that the construction of buckstays is not good, it should be improved, and FEM can be used to do that.
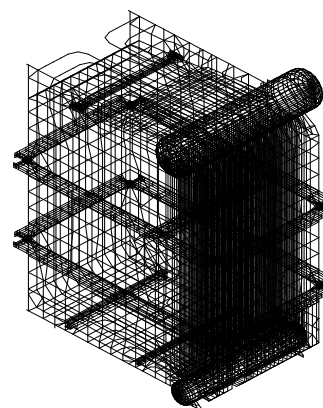
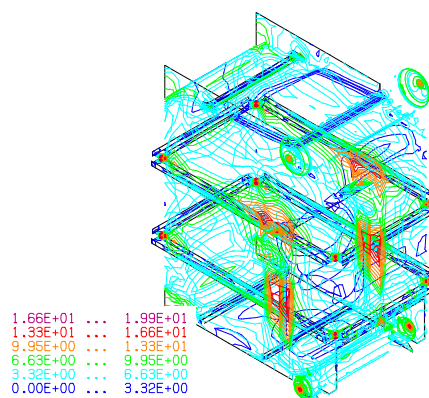

Figure 4. Finite element model of the water-tube boiler

1.66E+01	...	1.99E+01
1.33E+01	...	1.66E+01
9.95E+00	...	1.33E+01
6.63E+00	...	9.95E+00
3.32E+00	...	6.63E+00
0.00E+00	...	3.32E+00

Figure 5. Equivalent stress field [kN/cm^2] in the shells of the water-tube boiler

In the paper [11] it is presented the behavior diagnostics and improvement of the superheater construction of this boiler, which experienced failure due to cracking of the connecting tubes. Global structure of the superheater is discretized with beam finite elements. For the construction improvement it is suggested to release all the ends of the first three headers to reduce stress in the connecting tubes. Integrity assessment of the superheater construction is performed on the basis of the results of deformation and stress calculation using FEM, values of fracture mechanics parameters obtained by the examination of the samples of tube joint welds and critical crack length.

4. CONCLUSION

In the paper the methodology of condition and behaviour diagnostics of boiler constructions is presented. An algorithm is defined that illustrates methods for collecting data needed for the diagnostics. The methods from the algorithm are discussed: analysis of construction, visual inspection, non-destructive and destructive examinations, engineering analysis, experimental measurements and expert condition assessment-diagnostics of behavior.

The aim of performing the presented methodology of condition and behaviour diagnostics of boiler construction is to evaluate the operational reliability in the further defined period and to determine actions as needed for its life extension. The given algorithm is applicable as well for constructions that are already in

service, as for behaviour diagnostics of new constructions.

The diagnostics can be significantly improved by the application of finite element method-FEM. The main advantages of this numerical method over the calculation by boiler norms are expressed through possibilities of determining a nearly realistic image of deformation and stress and reliable assessment and prediction of boiler construction behavior under service condition.

Besides being used for the design of new boiler constructions, which should meet the applicable norms, FEM is also used for failure investigation by simulating the conditions present at the time of the incident, as well as for simulation of failure mechanism such as fatigue and brittle fracture. The results of detailed stress analysis by finite element method may be used as inputs to fracture mechanics and fitness-for-service assessments.

The application of FEM in designing boilers is illustrated by the example of reverse flame fire-tube boiler. Analysis has shown that in the new boiler it could be installed the plain fire-tube of the same thickness as the corrugated one installed in this type of boiler that is in service. This change contributes to the reduction of manufacturing cost.

The application of FEM in structural diagnostics of boilers that are already in service is illustrated by the example of water-tube boiler. Analysis has shown that the high stress concentration occurred in membraned walls at the boiler corners at the buckstay elevation, as well as in part of the buckstays, which are not covered by design norms. To solve the problem of deformations at the critical locations, the application of FEM is suggested.

REFERENCES

[1] Paoliello, F.A.: Guidelines for integrity evaluation and remaining life assessment of recovery boilers - CENIBRA´s experience, TAPPI Journal, Vol. 4, No. 2, pp. 17-22, 2005.

[2] Nakoneczny, G.J.: Boiler fitness survey for condition assesment of industrial boilers, Babcock&Wilcox, Barberton, Ohio, USA, Technical Paper Br-1635.

[3] Arsić, M., Aleksić, V. and Hut, N.: Analysis of state and integrity assessmemt of boilers, Structural Integrity and Life, Vol. 5, No. 1, pp. 3-17, 2005.

[4] Caligiuri, R., Foulds, J., Sire, R. and Andrew, S.: Thermal constraint consideration in design of a heat recovery boiler, Engineering Failure Analysis, Vol. 13, Issue 8, pp. 1388-1396, 2006.

[5] Gaćeša, B.: *Numerical and Experimental Strength Analysis of Boiler Constructions,* PhD thesis, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, 2011, (in Serbian).

[6] Serbian standards (for boiler plants): SRPS M.E2.030, SRPS M.E2.031, SRPS M.E2.041 and SRPS M.E2.213, (in Serbian).

[7] European norms EN 12952-3 and EN 12952-4: Water-tube boilers and auxiliary installations-Part 3 and Part 4 and EN 12953-3: Shell boilers-Part 3.

[8] Gaćeša, B., Milošević-Mitić, V., Maneski, T., Kozak, D. and Sertić, J.: Numerical and experimental strength analysis of fire-tube boiler construction, Technical Gazette, Vol. 18, No. 1, 2011.

[9] Maneski, T.: Structure behavior analysis and diagnostics, FME Transactions, Vol. 33, No. 2, pp. 89-95, 2005.

[10] Gaćeša, B: Analysis of the fire tube geometry influence on boiler construction behaviour, in: *Proceedings of the 37th International Congress on Heating, Refrigeration and Air-conditioning,* 2006, Belgrade, pp. 103-109, (in Serbian).

[11] Maneski, T., Sedmak, A., Burzić, Z. and Gaćeša, B.: Integrity of steam boiler constructions, in: *Proceedings of the 33rd International Congress on Heating, Refrigeration and Air-conditioning,* 2002, Belgrade, pp. 327-333, (in Serbian).

ДИЈАГНОСТИКА СТАЊА И ПОНАШАЊА КОТЛОВСКИХ КОНСТРУКЦИЈА

Бранка Гаћеша, Ташко Манески, Весна Милошевић-Митић

У раду је приказана методологија дијагностике стања и понашања котловских конструкција, која је неопходна при доношењу одлука о њиховом даљем раду. Дефинисан је алгоритам који илуструје методе прикупљања података неопходних за дијагностику: анализа конструкције, визуелна контрола, испитивање без и са разарањем, инжењерска анализа, експериментална мерења и експертска оцена стања – дијагностика понашања. Дијагностика се може значајно побољшати применом методе коначних елемената. Основна предност ове нумеричке методе у односу на прорачун дефинисан нормама је приказана кроз могућност одређивања скоро реалне слике деформација и напона, и поуздане процене и предвиђања понашања котловске конструкције у условима оптерећења. Примена методе коначних елемената је илустрована на примеру пројектовања новог пламено-димноцевног котла и при дијагностици понашања водоцевног котла при одржавању.