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IMPROVEMENT OF STEAM BOILER PLANT EFFICIENCY BASED ON RESULTS OF ON-LINE PERFORMANCE MONITORING

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Preliminary notes

A process of performance monitoring of a steam boiler means continuous evaluation of plant's efficiency over time using measured plant data. These evaluations are repeated at regular time intervals using data readily available from on-line instrumentation. The objective of performance monitoring is continuous evaluation of degradation, i.e. a decrease in performance of the steam boiler. These data enable additional information which is helpful in problem identification, improvement of plant performance and making economic decisions about maintenance schedule. All these actions are aimed towards optimization of boiler performance. Every performance monitoring system involves comparison between current (measured) and expected parameters of performance. The procedure to calculate expected performance of a steam boiler is to start with the expected performances at the reference operating conditions and then use a model to predict the change in boiler performance when it is operated at conditions different from the reference operating conditions. In this paper, a GateCycle™ physically based computer model of existing 200 MW coal-fired steam boiler is presented. Further use of this model is multiple: prediction of boiler performance parameters for different loads or changes of single or multiple input parameters, comparison of model predictions with real measured data in order to track problems and optimize boiler performance, predictions of possible re-engineering effects of the existing plant when changing one or more of its equipment elements.

Key words: *efficiency, steam boiler, coal, performance monitoring, computer model*

Poboljšanje stupnja korisnosti parnog kotla uporabom rezultata konstantnog praćenja parametara performansi

Prethodno priopćenje

Monitoring performansi parnog kotla je proces kontinuirane ocjene proizvodne sposobnosti i efikasnosti postrojenja tijekom promatranog razdoblja uporabom mjernih podataka s promatranog objekta. Ocjene performansi se ponavljaju periodično i koriste podatke koji su trenutno dostupni na postrojenju s postavljenih on-line instrumenata. Cilj monitoringa performansi je kontinuirana ocjena degradacije tj. pogoršanja performansi u parnom kotlu. Ovi podaci predstavljaju osoblju kotlovskog postrojenja dodatnu informaciju koja pomaže u identifikaciji problema, poboljšanju performansi i donošenju ekonomskih odluka o rasporedu održavanja. Sve ove aktivnosti za cilj imaju optimizaciju performansi parnog kotla. Bilo koji sustav monitoringa performansi podrazumijeva usporedbu između trenutnih (izmjerenih) i očekivanih pokazatelja performansi. Procedura proračuna očekivanih performansi parnog kotla počinje s određivanjem očekivanih performansi pri nominalnim radnim uvjetima te se uz korištenje modela vrši predviđanje očekivanih promjena u performansama kotla kada on radi pri uvjetima koji se razlikuju od nominalnih. U ovom radu je prikazan jedan GateCycle™ računarski model, utemeljen na fizikalnim karakteristikama postojećeg parnog kotla s izgaranjem uglja, koji radi u bloku s turbinom snage 200 MW. Uporaba ovog modela je višestruka: predviđanja pokazatelja performansi rada kotla za slučaj različitih opterećenja ili promjena pojedinačnih radnih uvjeta kao i istovremene promjene više radnih uvjeta, usporedba predviđanja modela sa stvarnim izmjerenim podacima na postrojenju kao i optimizacija rada kotla, predviđanja mogućih mjera reinženjeringa na postojećem postrojenju kako bi se utvrdili problemi i optimizirao rad parnog kotla kada se vrši zamjena jednog ili više elemenata kotlovskog postrojenja.

Ključne riječi: *korisnost, parni kotao, ugalj, monitoring performansi, računarski model*

1 Introducion
Uvod

A steam boiler in its original meaning is an object in which thermal energy, resulting from combustion of organic fuels, is transferred through heat surfaces to a working fluid which evaporates in the boiler with the steam further overheated to a certain temperature. Over the time, the steam boiler became more complex, in order to fulfil constant demands for more efficient transformation of fuel chemical energy into thermal energy and its efficient transfer to a working fluid. With such an aim, the steam boiler was improved with additional equipment and such a complex assembly of different machines and devices connected to the classical furnace and heat exchangers was named a steam boiler plant. During the last decades, due to boiler plants of large capacities and high parameters with intensification and automation of all processes inside the plant, a term "steam generator" was adopted, which mainly refers to large power units.

The basic element of a steam boiler is a furnace, in which fuel combustion takes place in presence of oxygen, usually from air, releasing energy of a chemical reaction which raises enthalpy of a heat receiver to a level suitable for transferring the heat to a heat exchanger surface. In other elements of a steam boiler flue, gas is being cooled by

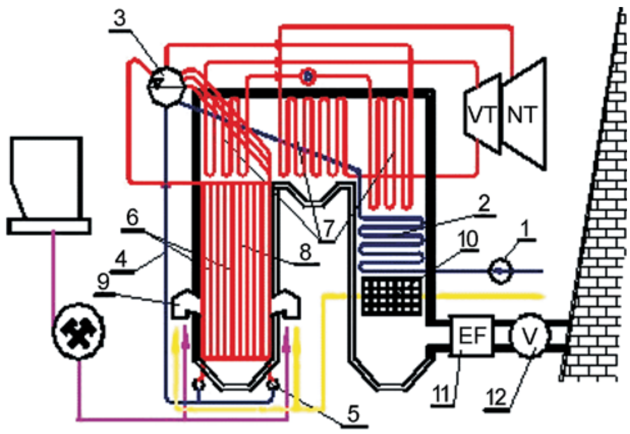

Figure 1 Scheme of a steam boiler plant (1- feed pump, 2 - economiser, 3 - boiler drum, 4 - cold pipes, 5 - lower collector, 6 - evaporator pipes, 7 - steam super-heaters, 8 - furnace, 9 - burners, 10 - air heater for the furnace air, 11 - electric filter, 12 - fan)
Slika 1 Shematski prikaz strmocijevog parnog kotla (1- napojna pumpa, 2 - ekonomajzer, 3 - bojlerski rezervoar, 4 - hladne cijevi, 5 - donji kolektor, 6 - cijevi isparivača, 7 - pregrijači kotla, 8 - ložište, 9 - plamenici, 10 - grijač zraka ložišta, 11 - električni filter, 12 - ventilator)

giving heat to heat receivers through heat surfaces. Those elements are: economizers, evaporators, steam super-heaters and re-heaters as well as air heaters. The most common working fluid (heat receiver) is water, which evaporates in the boiler, and is being further over-heated so the final product is saturated or super-heated steam. Figure 1 shows a scheme of a coal-fired steam boiler [2].

2
Computer modelling of steam boiler performance parameters
Racunarsko modeliranje relevantnih parametara kotlovskog postrojenja

Although the use of simplified models still gives satisfactory results it is recommended to use computer codes directly to calculate expected and corrected performance. Computer software applications like GateCycle™, contain complex, physically based models of equipment performance that can be used instead of correction curves. Those models enable modelling of interactions between different operating conditions and can provide detailed information about expected performance. Some advantages of using the computer codes are listed below:

- Interaction of varying operating conditions can be modelled,
- Physically based models can allow wide variations (far from reference) in operating conditions.
- Physically based models can compute impacts of parameters for which no curves are available.
- Physically based models give detailed information about the expected performance, not available from the curves. This additional information may help the engineer to diagnose the problems.

The individual operating conditions may not have independent effects on equipment performance, which is an assumption of the curve-based method. Such assumption may not be valid over a wide range of operating conditions. However, computer models can handle wide variations of environmental parameters and operational modes for which curves do not exist or do not accurately model. In particular, as conditions change over time, the interaction between environmental parameters becomes more and more important, and computer codes are often built specifically to handle these interactions.

The methodology for a model-based performance analysis is:

- Build a computer model of the equipment being monitored. The procedure to build such a model is specific to the software used.
- Test the model versus vendor guarantee data and/or plant-measured data over a wide range of operating conditions. Correct the model where necessary.
- At each performance monitoring calculation interval input the measured equipment operating conditions into the model. Measured data need to be collected at previously chosen time intervals, then statistically processed, and then used as input values.
- Run the model and obtain the expected equipment performance as a model output.
- Evaluate degradation by comparing the expected performance from the model to the measured performance.

If it is necessary corrections may be made on a design-point model with the verification process repeated until the model data matched the measured rated data to within 1 % over the entire operating range. Only then, the resulting model can be used to give predictions of the expected performance as operating conditions change [3, 4].

3
Influence of input parameters on performance of boiler No. 5 in Tuzla thermo-power plant
Utjecaj ulaznih radnih parametara na performanse parnog kotla 5 u TE Tuzla

- After the off-design model had been designed a plan of simulations was created. From the complete set of operating parameters, only those whose influence will be tested should be taken and analysed. In case analysed in this paper, the following parameters were chosen:
- H_d - lower heating value of the fuel, kJ/kg
- B_g - fuel consumption, kg/s
- p - feed water pressure at the feed water inlet, bar
- t - feed water temperature at the feed water inlet, °C
- λ - combustion air surplus coefficient at the furnace inlet, -.

From the set of operating conditions it is possible to choose other parameters whose influence on the stem boiler performance will be analysed, but the above mentioned parameters were chosen because their monitoring and regulation in real-time are available on the observed steam boiler. For each of the mentioned parameters a single version of the off-design model was created. The observed parameter was changed within an interval created upon the exploitation observations, and in this case it was an one-year long monitoring of measured values on the steam boiler plant. The only exception is combustion air surplus coefficient at the furnace inlet, which does not change so much in regular plant operation, but its interval was this extensive in order to have an easier analysis of this parameter's influence on performance parameters. Table 2 gives an overview of the chosen intervals for the observed parameters [1].

Table 2 Variation intervals of operating parameters
Tabela 2 Intervali promjene izabranih parametara

Parameter	min	max
H_d, kJ/kg	7000	11000
B_g, kg/s	50	66
p, bar	146	161
t, °C	199	234
λ, -	1,1	1,25

Finally, a single version of the off-design model was created for the purpose of analysis of simulation results in the case of simultaneous change of all chosen operating parameters. However, the combination of input operating parameters' values is chosen so that it matches the real-time measured values, as recorded in the database of previously measured parameters. The performance parameters whose values were taken from simulations output data and later analysed and used in evaluation of steam boiler performance are:

- D_s - steam production-superheated steam, kg/s
- t_{dp} - flue gas temperature at the stem boiler outlet, °C
- η - coefficient of steam boiler efficiency, -.

After an analysis of parameters' influence on the steam boiler performance, it was concluded that the least influence was made by the feed water pressure, followed by feed water temperature, taking into account that these two parameters are dependant. Although, combustion air coefficient has a significant influence on performance parameters, in everyday work of the observed steam boiler this coefficient is kept more or less constant or the changes are so small that they do not cause any bigger oscillations of the performance parameters. Furthermore, out of five analysed parameters, the biggest changes are caused by the two remaining parameters (lower heating value of the fuel and amount of fuel consumption). This is an obvious conclusion, since the mentioned two parameters are those that have a direct influence on the amount of energy brought into the furnace, and therefore also to the boiler efficiency coefficient.

Also, an interpretation of simulation results is something that needs to be addressed at this point. If a time interval, for which an average value of a parameter is calculated, is too wide, that average value will not be adequate in portraying the real changes that were happening during the operation processes at the plant. On the other hand, too short time interval is not good in terms of following the parameters response to an input change as well as inert characteristic of some processes. In such cases, it is possible that, based on wrongfully calculated average values of input parameters, wrong decisions regarding operating procedures at the plant are made. This can only make performance characteristics worse. It is an design engineer's task to, based on the observed plant's and process' characteristics, determine the adequate time intervals for the monitoring of the chosen parameters, as well as minimum and maximum value of the same parameters that are taken into account when determining the average value.

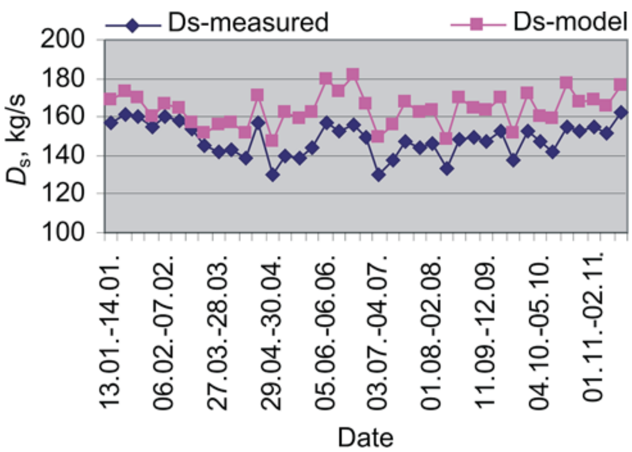

Figure 2 Superheated steam production - comparison of measured and simulation values
Slika 2 Proizvodnja svježe pregrijane pare - usporedba mjernih i simulacijskih vrijednosti

All other values of the parameters are not taken into account when calculating the average value, because they do not give a realistic overview of the plant condition. However, these values represent a signal to a plant operator that something happened which caused such values of parameters, and further inspection is needed.

Figure 2 shows values of the superheated steam, results of the performed computer simulations of the steam boiler work, as well as measured values of this performance parameter in case of the same change of input parameters and for the observed period of one year. It is obvious that during the whole year measured values of steam production were lower than their simulation values respectively, and the difference was not always the same.

Figure 3 shows values of the flue gas temperature at the boiler outlet, both simulation results and measured values. It is obvious that measured values were higher than simulation results during the whole observed period, while the difference was variable during this period.

However, monitoring of steam production and flue gas temperature is not enough for a complete evaluation of a steam boiler performance. Therefore, steam boiler efficiency needs to be monitored too. Figure 4 shows how

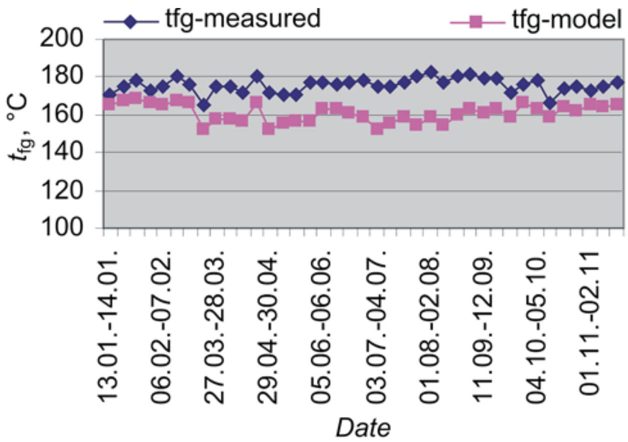

Figure 3 Flue gas temperature-comparison of measured and simulation values
Slika 3 Temperatura dimnih plinova usporedba mjernih I simulacijskih vrijednosti

the value of boiler efficiency predicted by a computer model changes when all observed operating conditions change. Real value of boiler efficiency, calculated for the same measured operating conditions, is shown on the same diagram. It is clearly visible that the actual value of the steam boiler efficiency is lower than predicted value of the model, at all times during the one-year monitoring period.

As in the case of monitored steam production and flue gas, the difference between actual efficiency and its respective model value is not always the same during the monitoring period. Such results are expected and they show that there is a degradation in plant operation and it changes over time. The degradation in boiler efficiency is actually a difference between real efficiency and its expected value, predicted by a computer model.

Data shown in Figure 4 are given for different operating conditions and therefore it is complicated just to compare values of efficiency for different time periods. One of the very practical methods used in such cases is a method of corrected performance. Instead of monitoring absolute value of performance parameter, its degradation is being monitored and analysed in order to determine the causes of degradation.

Accordingly, the expected values of boiler efficiency predicted by computer model simulations need to be converted to their corrected values. Those are the values that boiler efficiency would have if operating conditions, for which the efficiency is determined, were equally rated. Only then, a difference between nominal and corrected value of boiler efficiency represents the actual degradation no matter whether the degradation increases, decreases or remains unchanged over the observed time period.

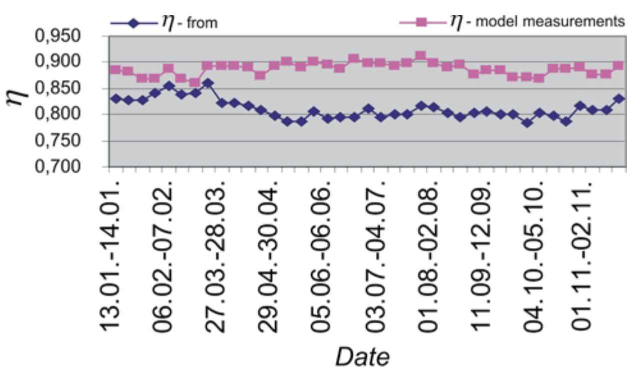

Figure 4 Boiler efficiency- comparisons of actual and model results
Slika 4 Stupanj korisnosti kotla-usporedba stvarnih I modelskih vrijednosti

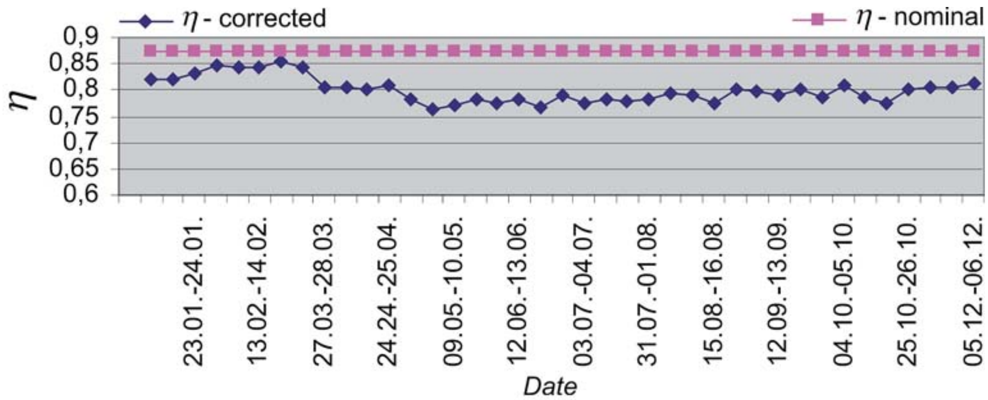

Figure 5 Corrected boiler efficiency - monitoring of degradation over time
Slika 5 Korigirani stupanj korisnosti kotla - praćenje degradacije u vremenu

Figure 5 shows the results of the method of corrected performance applied to data shown in Figure 4. All values of boiler performance coefficient were converted to their corrected values, as if the plant was working under nominal operating conditions all the time. Results shown in Figure 5 show the constant value of the model predicted efficiency, and it equals the nominal value. This is expected, since all operating conditions are converted to their nominal value, and therefore expected boiler performance has to have nominal value too, which was the main condition when designing the model.

Also, it is obvious from Figure 5 that corrected values of boiler performance coefficient are lower than its nominal value during the complete monitoring period. That was also expected, which means that there is a degradation in boiler performance. In the beginning of the monitored period it was lower, while later it increased and then remained more or less unchanged. However, the degradation is not so big which would point to some malfunctions in plant elements. Rather, the recorded evaluation was created due to improper operation of the steam boiler and its elements, meaning setting of operating parameters when the plant loads changes. In other cases, damage on plant equipment, fouling, etc. would cause much bigger degradation of boiler performance, which would point to a need for diagnostic procedures in order to locate the cause, as well as an appropriate maintenance procedure.

As it is obvious from Figure 5, the method of corrected performance is very suitable for interpretation of monitoring results. Based on the difference between nominal and corrected value of boiler performance it is possible to evaluate the amount of additional energy that needs to be combusted in the boiler furnace in order to achieve required performance parameters at the boiler outlet, such as required steam production and flue gas temperature. This additional amount is required due to the existing degradation and difference between actual and nominal values of boiler efficiency. It should be noted that, in order to get an accurate calculation, measured data should be available for everyday change of operating parameters. In the case which is discussed in this paper, data were constantly for one year, which makes this calculation approximate.

However, calculated relative deviation of corrected coefficient of the steam boiler performance, comparied to its nominal value, is approximately 8,5 %. This number is a signal that performance monitoring system is a necessity on every plant, and the costs of its installation will definitely pay off in a short period of time, especially in big power plants [1].

4 Conclusion
Zaključak

On-line evaluation of performance parameters of the steam boiler plant and its elements is becoming more and more important in the power production sector due to search for ways or methods for the optimization of plant operation in order to make it competitive on the global power market. Accuracy of on-line systems directly depends on input data and generally there is a problem with accuracy of already installed measurement equipment.

However, this situation can be overcome using readily available computer codes for heat balance in a combination with appropriate solver for statistic analysis of resulting data. When deciding on which parameters should be monitored, those data that reflect better the actual situation should be chosen, and in sach a way output data from the model will be equally adequate. It is almost impossible to have a complete, i.e. closed, mass and heat balance based on measurements data performed on a plant. Actually, in a number of cases there are opposite data, such as feed water measurement, which does not match steam production measurement.

The biggest advantage of a steam boiler performance monitoring is a possibility of using complex computer codes for prediction of change of performance parameters when operating conditions change. In such situations, for example if it is known that a steam boiler will work with a decreased load in the coming period, by using computer model simulations, it is possible to determine which combination of operating conditions would result in the least deviation of actual boiler efficiency compared to its nominal value. Of course, degradation always exists but, the goal is to minimize it. Cases of bigger degradations point to malfunctions, fouling and similar on boiler elements that require inspection, determination of degradation causes and maintenance actions.

In this era of globalization, all power generating companies are out on the same market competing for their customers. In such a situation, even the slightest improvements of efficiency lead to a better position and higher competitiveness.

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