Expert diagnostics of slagging of heating surfaces of coal-fired boilers

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Abstract. The article is devoted to the development of a system for the technical diagnostics of slagging processes and contamination of the heating surfaces of coal-fired steam boilers, which operates online based on the interpretation of the standard information of ACS TP and scientifically proved algorithms for processing balanced equations to evaluate the thermal efficiency of radiation, semi-radiation and convective heating surfaces. The system is implemented at the level of algorithmic data and software in the programming language C#, which is built into the current system of the automatic control system of the boiler unit. The project aims to increase the reliability, efficiency and economy of steam boilers by quick maintenance of heating surfaces in an operational clean state, ensuring optimal performance characteristics of the main technological equipment. This system is at the trial operation stage at the BKZ-500-140 boiler unit, station No. 6 of JSC Krasnoyarsk CHP-2. The expected effect of the introduction of this boiler due to the reduction of the blowing cycles and the decrease in the slagging intensity will amount up to 2.175 million rubles annually per one boiler unit.

Despite the huge amount of scientific research, the problem of slagging of heating surfaces of power boiler units remains relevant in the modern world energy at power plants operating on solid organic fuel. This problem is relevant due to the fact that it is impossible to monitor the exact composition of solid fuel, the composition of its mineral part, grinding fineness and other factors online, which influence on the behavior of power-generating boilers play a great role [1]. A confirmation of this problem is the statistics of equipment failures in boiler houses of coal-fired power plants. The failure rate of equipment for coal-fired boiler plants of Russian stations due to failures of heating surfaces is 79.4% of the total number of failures [2]. Moreover, the failure rate of heating surfaces due to problems caused by slagging is 31.1%. The net profit of large energy companies, lost due to underproduction of electric energy as a result of problems caused by slagging is 874.6 million rubles annually (excluding the loss of money as a result of the loss of power inconsistent in Competitive capacity outtake) [3].

In the world energy sector as well as in the Russian energy sector various foreign integrated software solutions have been widely used to determine online the degree of contamination of heating surfaces, for example, the technical diagnostic system for slagging and automatic control of blowing apparatuses “FACOS” of the German company “Clyde-Bergemann GmbH” on the boiler P-67 No. 1.
of the Berezovskaya state district power station and boiler PK-39 No. 6 of the Reftinskaya state district power station. The introduction of this system has allowed to increase the efficiency of the P-67 boiler by 1% on average and also to increase non-slag power by 50 MW. This system is quite effective, however, it does not take into account a number of operational factors, such as humidity or fuel quality. Another disadvantage of this system is the limited coverage of the heating surface with sensors. The slagged area in this system may not fall into the measurement area. Moreover, foreign systems require enormous costs, as well as the installation of a large number of equipment and sensors, which reduces their attractiveness.

As a simpler, cheaper and more reliable system for assessment of the intensity of slagging processes a developed system of technical diagnostics is offered. This system is based on the standard information of the automated process control system which has in its arsenal scientifically based methods for determining the degree of contamination of radiation, semi-radiation, and convective heating surfaces, for which the number of standard sensors and soot blowers installed on the boiler are enough. The diagnostic system has recommendations on the surface and time of cleaning and also there is the possibility predict slagging according to calculated data and to give recommendations on the installation location of blowing apparatuses.

To assess the slagging intensity, the most optimal from the point of on-line measurements is to measure the thermal efficiency coefficient $\Psi$ and the pollution coefficient $\varepsilon$ for heating surfaces due to their normalization and dimensionlessness [4]. The assessment of the coefficient of thermal efficiency is carried out according to the following ratio:

$$\Psi = \frac{K_{\text{fact}}}{K_{\text{clean}}}$$  \hspace{1cm} (1)

$K_{\text{fact}}$ – is the actual heat transfer coefficient of the real heating surface, $kw/(m^2 \cdot ^\circ C)$; $K_{\text{clean}}$ - heat transfer coefficient for a clean surface, $kw/(m^2 \cdot ^\circ C)$.

The actual heat transfer coefficient is found by equation 2:

$$K_{\text{fact}} = \frac{Q_{\text{fact},h}}{F \Delta t}$$  \hspace{1cm} (2)

$F$ – heating surface area, $m^2$; $\Delta t$ – logarithmic temperature head, $^\circ C$; $Q_{\text{fact}}$ – actual heat perception of the heating surface, $kJ/kg$; $B_p$ - estimated fuel consumption, $kg/s$.

In turn, the actual heat perception of various heating surfaces of the boiler unit are found according to equations 3-6:

$$Q_{\text{fact,platen}} = \varphi (H' - H'') + \Delta H_{ca} - Q_{add} = \frac{D_{ca}}{\rho_p} (h'' - h') - Q_{rad}$$  \hspace{1cm} (3)

$$Q_{\text{fact,air heater}} = \varphi (H' - H'') + \Delta H_{ca} - \beta_{ha} \left( \frac{D_{ca}}{\rho_p} \right) (H''_{ha} - H''_{ca})$$  \hspace{1cm} (4)

$$Q_{\text{fact,convective}} = \varphi (H' - H'') + \Delta H_{ca} - Q_{add} = \frac{D_{ca}}{\rho_p} (h'' - h') - Q_{rad}$$  \hspace{1cm} (5)

$$Q_{\text{fact,water heater}} = \varphi (H' - H'') + \Delta H_{ca} = \frac{G_{fw}}{\rho_p} (h'' - h')$$  \hspace{1cm} (6)

$H', H''$ means gas enthalpies before and after heating surface, $kJ/kg$; $D_{ca}$ – working environment consumption, $kg/s$; $h''$ and $h'$ - enthalpies of the vapor before and after the heating surface, $kJ/kg$; $\Delta H_{ca}$ – specific value of fuel suction, $kJ/kg$; $Q_{add}$ – thermal perception of additional (adjacent) surfaces, $kJ/kg$; $Q_{rad}$ – heat perception of the heating surface by radiation, $kJ/kg$; $\varphi$ - heat storage coefficient; $H''_{ha}, H''_{ca}$ – enthalpies of hot and cold air, $kJ/kg$; $\beta_{ha}$ – primary air fraction; $\Delta t$ – amount of suction in the air heater; $G_{fw}$ – feed water consumption for the boiler, $kg/s$, $\beta_{rec}$ – proportion off recycle burning gas [1][5].

A feature of the diagnostic system is the usage of the surface cleanliness coefficient $K_{\text{clean}}$ found by actual operational and structural parameters in the on-line mode. The novelty of the system is the ability to use the methodology for calculating the coefficient of thermal efficiency of all heating surfaces of the boiler unit, including the combustion chamber.

The principle of operation of the system is shown schematically in Figure 1. Data from the boiler sensors is fed to the controller every 30 seconds which converts the electrical signals into numerical values. Numeric
values are sent to the database storage server where they are stored for a long time. The system reads the data from the database, processes and verifies the data, calculates and displays the resulting values in the form of graphs on the operator’s monitor and gives an estimation of the slag level, as well as recommendations on the inclusion of cleaning agents.

Figure 1. The schematic diagram of a system for technical diagnostics of the intensity of slurry

Figure 2 presents the software components of the technical diagnostic system (TDS) which allows to ensure the proper level of control and organization.

Figure 2. Components of TDS

The software has three access levels separated by three different applications: the editor application, the administrator application and the user application. The editor has an access to the
program code, frameworks and databases (DB), in which some design and mode characteristics are written. The editor controls the correctness of the program from uninterruptable perspective, as well as makes adjustments to the program code in case of any changes in design characteristics or circuit diagrams. The administrator has an access to the database and visualization module. At any time, the administrator can look at all the calculated graphs of the dependence of the pollution coefficient and any calculated values for any period of time and he can also make changes to the database of conditionally constant values, such as the composition of the fuel. The user's automated workplace will have an access only to the visualization module where the user can monitor online the change in all indicators of slagging intensity and also he will have an access to see all values in the historic mode for the last 4 working shifts.

The expert diagnostic system consists of 5 separate modules:

- The module for the analysis of initial data and work with databases of industrial control systems which reads, verifies and replaces data from industrial control systems.
- The module for assessing the coefficient of thermal efficiency, the main module that calculates and evaluates slagging.
- A module for processing the results, which smooths out the graphs for ease of perception.
- Module for visualization and analysis of results
- Module of recommendations on the mode of operation and use of cleaning agents

The module for analysis and work with databases of automatic process control systems is a preparatory part of the program which should not only read and download the database but also perform an analysis of the sufficiency of data, analysis of the correctness of the data and rejection of incorrect data.

An analysis of the sufficiency of data is necessary so that in case of failure of one of the sensors the program does not stop its calculations and does not display the wrong coefficient of thermal efficiency, but it replaces the data with alternative ones or considers the coefficient of thermal efficiency by an alternative method. Correctness analysis and data rejection are necessary due to the fact that the sensors during operation run out of order and may show incorrect parameter values. The correctness analysis will be carried out by comparing the parameters with the minimum and maximum values of a given range of these parameters.

For example, in the case of a sensor failure with the code KKS 40HAH11CT004A - the temperature of the superheated steam of the first stream of the second stage before injection, the value can be replaced with the value with the code KKS 40HAH12CT004A - the temperature of the superheated steam of the second stream of the second stage before injection or it is possible to calculate the temperature of the steam taking into consideration the wall temperature of the steam collector to the desuperheater (cell KKS 40HAH12CT114 and 40HAH12CT113 - temperature of the upper and lower part of the collector wall after the second stage of the first superheater flow).

The interaction of all these modules taking the real object into account is schematically shown in Figure 3. Data from the boiler sensors are transmitted to the controller where they are converted from electronic signals to numerical values and sent to the server. From the server data is sent to the operator’s monitor, as well as for long-term storage in the form of a KKS database. The system of technical diagnostics using the module for working with the database and data analysis takes out the necessary values from the database, verifies them, and in case of successful verification sends it to the calculation module. The calculation module evaluates the intensity of slagging of the heating surfaces and, based on the calculated values of the pollution coefficient gives a recommendation where and when to blow. At the same time the results processing module smooths the graphs, making them more informative for the operator and sends the results to the monitor to the boiler operator.
The module for processing the obtained data is necessary to simplify the visualization of graphs and their smoothing because many sensors at the station measure the parameters of not averaged flow but they are point measuring instruments and the value on many flowmeters fluctuates due to the presence of turbulent vortices in the flow. For example, ultrasonic flow meters take measurements based on the time difference between the passage of ultrasound signals from the emitting sensors to the receiving sensors. When turbulent vortices appear sound signals passing through the medium change their speed in the vortex zone. Because of this, the signal travels from the emitter to the receiver, which affects the final result of the flow rate. The size and number of vortices also constantly change. It also affects the fluctuation of the flow rate.

Figure 3. The scheme of the program modules

Figure 4 shows a graph of the change in the coefficient of thermal efficiency for the convective superheater of the BKZ-500 boiler unit, station No. 4, from February 12 to February 13, 2018. The graph shows strong fluctuations in the value of the coefficient of thermal efficiency, which are caused by fluctuations in the values of the parameters in the ACS TP database. A sharp jump up corresponds
to steam blowing. At the same time, it can be noted that intense pollution after blowing occurs during the first 3 hours after the steam cleaning, which corresponds to the sticking of the outer initial layer. The influence of this layer on the coefficient of thermal efficiency relative to the external sintered layer is small, however, it is the basis for the beginning of intense slagging.

The expected effect of the introduction at the boiler unit BKZ-500-140 st. No. 6 of Krasnoyarsk CHP-2 by reducing the blowing cycles and decreasing the slagging intensity, as well as increasing the efficiency of the boiler due to lowering the temperature of the flue gases, according to preliminary estimates, will amount to 2.175 million rubles per year.

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