ON-LINE MONITORING OF THE FOULING OF THE BOILER HEATING SURFACES

by

Marcin TROJAN[a*], Dawid TALER[b], and Szymon WIELGUS[a]

[a]Institute of Thermal Power Engineering,
Cracow University of Technology, Cracow, Poland
[b]Department of Thermal Processes, Air Protection, and Waste Utilization,
Faculty of Environmental Engineering, Cracow, Poland

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The designed system for the monitoring of the fouling of the furnace and superheaters/reheaters, presented in the paper, will make it possible to operate the boiler with high efficiency. Measurements of temperatures, pressures, flows, and gas analysis data are used to perform heat transfer analysis in the boiler furnace and evaporator. Power boiler efficiency is calculated by an indirect method. The local and average degree of the combustion chamber slagging is determined in an "on-line" mode. In the case of superheaters, the fouling coefficient is determined for each superheater stage, due to big differences in ash-related fouling of individual stages. Fouling processes deteriorate the boiler capacity and efficiency and increase the rate of corrosion of the boiler heating surfaces. The energy consumption of flue gas fans rises as well because the accumulation of slag and ash involves higher pressure losses at individual superheater stages.
In addition, examples of ash fouling of individual boiler heating surfaces are presented and discussed in the paper.

Keywords: *ash fouling, steam boilers, monitoring system, steam superheaters, mathematical modelling*

Introduction

In coal-fired boilers, a serious problem is the accumulation of ash and slag fouling on their heating surfaces [1]. Slag and ash deposits are usually deposited on combustion chamber walls and platen superheaters. The problem of fouling heating surfaces has become even more important due to the necessity of co-combustion of biomass in power boilers fired with pulverized coal or fluidized bed boilers. According to the obligations assumed by Poland, the share of energy from renewable sources should amount to 15% in 2020 [2]. This obligation is currently being implemented, among other things, by co-combustion of sawdust, woodchips and waste from the wood industry in boilers fired with hard coal dust. Co-combustion of biomass causes not only accelerated corrosion of boiler tubes [3] but also intensifies the processes of fouling of boiler heating surfaces [4]. Slag and ash fouling conditions are critical factors influencing thermal efficiency and availability of the combustion

[*] Corresponding author, e-mail: marcin.trojan@pk.edu.pl

chamber and superheaters in the boiler. The largest number of systems for monitoring the fouling degree of the boiler combustion chamber water-walls is based on local heat load meters located at several points on all walls of the boiler [5-9]. The advantage of monitoring systems which used local heat load meters is the high accuracy of fouling detection, and the disadvantage is the high cost due to the very large number of meters. The disadvantage of this method of assessing the combustion chamber water-walls fouling degree is also the lack of a global assessment of fouling, expressed by a decrease in the heat-flow rate taken over by the evaporator, individual superheater stages and a decrease in boiler efficiency.

Clyde Bergemann Company has developed a measuring system based on strain gauges to detect the build-up of slag and ash deposits on hanging steam superheaters [10, 11]. The system uses strain gauges to measure the deformation of rods on which steam superheaters hang. The increased weight of the superheater, due to the build-up of ash deposits, causes higher deformations of rods, which are registered by strain gauges. This method of assessing the fouling degree of heated surfaces from the flue gas side is suitable only for hanging superheaters. They are more difficult to apply to combustion chambers or superheaters with a lying construction.

A new method of controlling the activation of the slag and ash blowers is presented in the paper. Also, a computer system for monitoring build-up of slagging and ash fouling in the boiler combustion chamber and steam superheaters installed on a coal-fired steam boiler, operating in one of the Polish power plants is presented. This computer system is based on measurements of pressure, temperature, working medium mass-flow rate and measurement of chemical composition and flue gas temperature. On the basis of the measured values, indices characterizing independently the fouling degree of the furnace walls and superheater tubes are determined. The decision to activation the slag and ash blowers is made on the basis of changes in time of the following values: flue gas temperature after the steam superheater (before the economizer), flue gas temperature at the outlet from the furnace, boiler efficiency, steam mass-flow (boiler efficiency), heat-flow rate taken over by the evaporator (furnace wall), thermal efficiency coefficient of the furnace walls, and superheater thermal efficiency coefficient. It should be emphasized that until now the slag and ash blowers are activated at fixed intervals, with the time interval between successive activations being selected on the basis of unspecified criteria. In the tested boiler with a capacity of 210 tonne per hours, the slag and ash blowers were activated at fixed intervals of 8 hours. Studies have shown that it is not necessary to start the slag and ash blowers as often. The task of the developed system for identifying the degree of fouling of the heating surfaces of the steam boiler is a separate assessment of the degree of fouling of the evaporator and superheater, as well as on-line control of the boiler efficiency, which is a measure of the global degree of fouling of the boiler. Local slagging of the walls of the combustion chamber is assessed based on the decrease in the local density of the heat-flow rate taken over by the water-wall at the slag deposition site.

Characteristics of slagging of the boiler combustion chamber walls and ash fouling of the steam superheater

Slag and ash fouling can be deposited evenly over the entire heating surface of the boiler or locally, often creating heavy overhangs. Slagging of the combustion chamber walls and ash fouling of superheater tubes have a significant impact on boiler operation, leading to a reduction in boiler efficiency, increase or decrease in steam temperature behind superheater stages and a reduction in the mass-flow rate of steam produced in the boiler.

Characteristics of symptoms of the boiler combustion chamber walls fouling

Examples of slagging the OP-650 boiler combustion chamber walls are shown in figs. 1-4. Figures 1 and 2 illustrate the almost uniform slag deposition of the combustion chamber walls, while figs. 3 and 4 show the local slag deposition of the furnace hopper and burner, respectively.

Figure 1. A side wall of the boiler combustion chamber (a large part of the water-wall surface with fouling)

Figure 2. A rear wall of evaporator and OFA nozzles very fouled by slag (level of about 25 meters)

Figure 3. Slagged cold boiler hopper; the slag extends evenly from the bottom of the boiler to the half of height of the burners Nos. 3 and 4 located in the first row

Figure 4. The surrounding area of the burner No. 4 in the second row and the slagged part of the evaporator wall (the lower part of the burner and the tip of the lance of the oil burner and steam nozzle are heavily covered with slag)

In the case of clean superheater tubes surfaces and slagged furnace walls, the following phenomena can be observed:

- a decrease in the waterwall heat efficiency coefficient,
- a decrease in the heat-flow rate absorbed by the boiler evaporator and an increase in the heat-flow rate absorbed by the superheater,
- a decrease in the steam mass-flow rate produced in the boiler (decrease in the boiler output),
- an increase in the temperature of flue gas at the exit from the furnace, which may lead to the intensification of superheaters fouling as a result of exceeding the ash melting temperature,

– an increase in the temperature of superheated steam at the outlet from the individual stages of the superheater, which increases the water mass-flow fed into steam attemperators, (the task of attemperators is water spray cooling of superheated steam),
– an increase in flue gas temperature behind superheaters and at the boiler outlet, and
– a decrease in boiler efficiency.

The boiler operator can identify that the walls of the combustion chamber are fouled by the observation of the water mass-flows fed into steam attemperators. These water mass-flows are much larger than the water mass-flows fed into steam attemperators at the clean walls of the furnace.

Characteristics of symptoms of ash fouling of superheater tubes

Ash fouling of superheaters reduces the heat-flow rate from the flue gas to the tubes. The energy consumption of flue gas fans rises as well because the accumulation of slag and ash involves higher pressure losses at individual superheater stages. In the case of ash fouling of the superheaters tubes and the clean walls of the furnace, the following phenomena are observed:
– a decrease in the heat-flow rate absorbed by the superheater,
– a decrease in the temperature of superheated steam behind the individual stages of superheaters, which decreases the water mass-flow fed into steam attemperators,
– an increase in the temperature of the flue gas behind steam superheaters, and
– a decrease in boiler efficiency.

Figure 5. The second stage of the live steam superheater, placed on the front wall of the evaporator fouled by slag

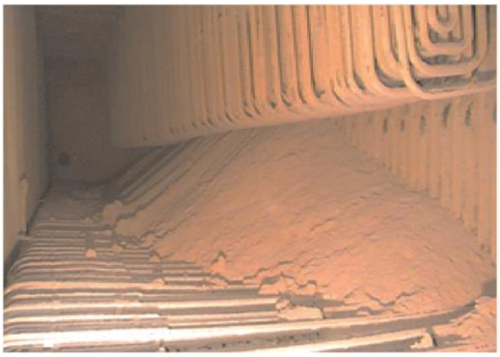

Figure 6. Strongly fouled convective duct (fouled tubes of the IV stage of live steam superheater)

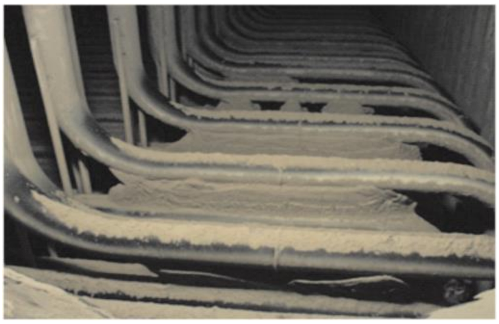

Figure 7. Coils of the first stage re-heater in the second boiler duct fouled by ash

Figure 8. Platen superheater fouled by slag

From the analysis of superheater fouling presented in figs. 5-8 it can be seen that in the area of higher flue gas temperatures the ash melts, and it is deposited as a slag on superheater tubes (figs. 5 and 8). In case of the lower temperature of flue gas the ash is loose (fig. 6) or hard baked (fig. 7).

Characteristics of symptoms of simultaneous fouling of the boiler combustion chamber walls and superheater tubes

In the case of simultaneous fouling of the combustion chamber walls and superheaters' surface, the following phenomena are observed:
- a decrease in the waterwall heat efficiency coefficient,
- a decrease in the heat-flow rate absorbed by the boiler evaporator and an increase in the heat-flow rate absorbed by the superheater,
- a decrease in the steam mass-flow rate produced in the boiler (decrease in the boiler output),
- an increase in the temperature of flue gas at the exit from the furnace, which may lead to the intensification of fouling of superheaters as a result of exceeding the ash melting temperature,
- an increase in the temperature of the flue gas behind the individual stages of the superheater,
- a decrease in boiler efficiency, and
- the temperature of superheated steam behind the individual stages of the superheater and the water mass-flow fed into steam attemperators may remain the same; this may mislead the boiler operator and suggest that the boiler is not fouled.

Parameters calculated in the computer programme

All parameters calculated in the program are determined in an on-line mode. The boiler efficiency is calculated using an indirect method based on the energy balance of the boiler. Next, the fuel mass-flow rate $\dot{m}_F$ [kgs^{-1}] is calculated. Calculation of combustion chamber parameters in on-line mode allows determining the heat-flow rate absorbed by the waterwalls. Based on the energy balance of the boiler evaporator, the superheated steam mass-flow is determined, taking into account the water mass-flow fed into steam attemperators. The waterwall heat efficiency coefficient, ψ, is determined by comparing the calculated and measured values of the steam mass-flow produced in the boiler in real time of the boiler operation. The degree of the furnace fouling and the degree of the superheater fouling are determined on the basis of measurement data. In addition, many other parameters are determined in an on-line mode, such as: fuel mass-flow rate, the excess air ratio, air mass-flow rate, wet and dry flue gas mass-flow rate, individual heat losses, and the heat-flow rate absorbed by the superheater.

Boiler efficiency

The boiler efficiency can be calculated in an on-line mode. In this situation, the boiler operator can follow the changes in the boiler efficiency in time and assess the impact of selected parameters of the boiler operation (*e. g*. the mass-flow of air fed into the boiler furnace) on its efficiency. The thermal efficiency of the boiler, η, is determined using the indirect method:

$$\eta = \frac{\dot{Q}_n}{\dot{Q}_h} = \frac{\dot{Q}_h - \dot{Q}_l}{\dot{Q}_h} = 1 - \frac{\dot{Q}_l}{\dot{Q}_h} \tag{1}$$

where $\dot{Q}_n$ [W] is the heat-flow rate transferred to the working medium (water and steam), $\dot{Q}_h$ [W] – the heat-flow rate delivered to the furnace with fuel and air, and $\dot{Q}_l$ [W] – heat losses (heat transfer to the surrounding)

The eq. (1) can be written:

$$\eta = 1 - \sum_{i=1}^{n} S_i \tag{2}$$

where S_i denotes the following losses, expressed in dimensionless form: S_1 – stack loss, S_2 – loss caused by the presence of CO in flue gases, S_3 – loss resulting from the presence of a combustible fraction in fly ash, S_4 – loss resulting from the presence of a combustible fraction in slag, S_5 – radiation loss and other losses difficult to calculate, and S_6 – losses of sensible heat in the slag and ash falling from the furnace walls.

A mathematical model of the boiler evaporator

The live steam mass-flow is calculated in on-line mode from the boiler evaporator mass and energy balance, fig. 9:

$$\dot{m}_{\mathrm{fw}} = \dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{w1}} - \dot{m}_{\mathrm{w2}} + \dot{m}_b \tag{3}$$

$$\dot{m}_{\mathrm{fw}} h_{\mathrm{fwh}} + \dot{Q}_{\mathrm{ev}} = \dot{m}_b \, h'(p_d) + \left(\dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{w1}} - \dot{m}_{\mathrm{w2}}\right) h''(p_d) \tag{4}$$

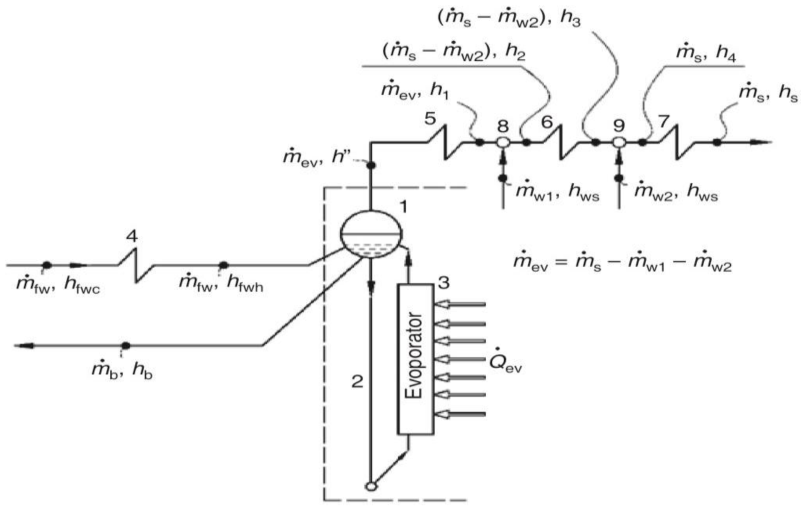

Figure 9. Diagram of control volume for the boiler evaporator mass and energy balance;
1 – drum, 2 – downcomers, 3 – evaporator, 4 – economizer, 5 – 1st stage superheater, 6 – 2nd stage superheater, 7– final superheater, 8 – 1st stage superheater spray attemperator, 9 – 2nd stage superheater spray attemperator

Substitution of (3) in (4) results in:

$$\dot{m}_{\mathrm{s}} = \frac{\dot{Q}_{\mathrm{ev}}}{h''(p_d) - h_{\mathrm{fwh}}} - \dot{m}_b \frac{h'(p_d) - h_{\mathrm{fwh}}}{h''(p_d) - h_{\mathrm{fwh}}} + \dot{m}_{\mathrm{w1}} + \dot{m}_{\mathrm{w2}} \tag{5}$$

where $\dot{Q}_{\mathrm{ev}}$ [W] – the heat-flow rate transferred from flue gas to the evaporator via radiation and convection, $\dot{m}_{\mathrm{fw}}$ [kgs^{-1}] – the feed water mass-flow, $\dot{m}_{\mathrm{s}}$ [kgs^{-1}] – the steam mass-flow,

$\dot{m}_{w1}$ [kgs^{-1}] – the water mass-flow fed into water spray after the 1st stage superheater (attemperator No. 1), $\dot{m}_{w2}$ [kgs^{-1}] – the water mass-flow fed into water spray after the 2nd stage superheater (attemperator No. 2), $\dot{m}_b$ [kgs^{-1}] – the desalted and blowdown matter mass-flow, $\dot{m}_{fw}$ [kgs^{-1}] – the feed water mass-flow, h_{fwh} [Jkg^{-1}] – the specific enthalpy of feed water after economizer, $h'(p_d)$ [Jkg^{-1}] – the specific enthalpy of saturated water at drum pressure, and $h''(p_d)$ [Jkg^{-1}] – the specific enthalpy of saturated steam at drum pressure.

The fuel mass-flow in the boiler operation steady conditions

Based on the boiler efficiency determined in an on-line mode, the coal mass-flow is calculated from the definition of the boiler thermal efficiency, fig. 10:

$$\eta = \frac{\dot{Q}_n}{\dot{Q}_h} = \frac{\left[\left(\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2} \right)\left(h_s - h_{fwc} \right) + \left(\dot{m}_{w1} + \dot{m}_{w2} \right)\left(h_s - h_{ws} \right) + \dot{m}_b \left(h'' - h_{fwc} \right) \right]}{\dot{m}_F H_{LV}} \tag{6}$$

where h_s [Jkg^{-1}] is the specific enthalpy of live steam at outlet of the boiler, h_{ws} [Jkg^{-1}] – the specific enthalpy of spray-water in attemperators, h_{fwc} [Jkg^{-1}] – the specific enthalpy of feed water, $\dot{m}_F$ [kgs^{-1}] – the fuel mass-flow, and H_{LV} [Jkg^{-1}] – net calorific value (lower heating value).

After simple transformations from eq. (6) one obtains:

$$\dot{m}_F = \frac{\left(\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2} \right)\left(h_s - h_{fwc} \right)}{\eta H_{LV}} + \frac{\left(\dot{m}_{w1} + \dot{m}_{w2} \right)\left(h_s - h_{ws} \right) + \dot{m}_b \left(h'' - h_{fwc} \right)}{\eta H_{LV}} \tag{7}$$

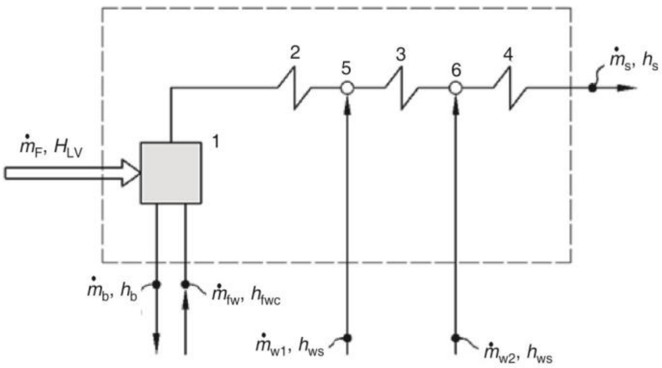

Figure 10. Diagram of control volume for the boiler mass and energy balance;
1 – boiler, 2 – first stage of the superheater, 3 – second stage of the superheater, 4 – third stage of the superheater, 5 – attemperator No. 1, 6 – attemperator No. 2

Assessment of the degree of water walls slagging and ash fouling of the superheaters

Slag is formed on the boiler waterwalls and the surface of the radiant superheater (platen superheater) if the flue gas temperature is higher than the ash melting temperature. Molten ash, *i. e*. slag, is deposited on the heating surfaces of the boiler when the flue gas temperature exceeds 1200 °C. The heat-flow rate absorbed by the evaporator and superheaters can be assessed by calculating the following two indicators in on-line mode:

$$\zeta_{ev} = \frac{\dot{Q}_{ev}}{\dot{Q}_{ev}^0 \left(\dot{m}_s \right)} \tag{8}$$

$$\zeta_{\text{sup}} = \frac{\dot{Q}_{\text{sup}}}{\dot{Q}^0_{\text{sup}}\left(\dot{m}_{\text{s}}\right)} \tag{9}$$

where the symbols $\dot{Q}^0_{\text{ev}}\left(\dot{m}_{\text{s}}\right)$ and $\dot{Q}^0_{\text{sup}}\left(\dot{m}_{\text{s}}\right)$ denote the heat-flow rate absorbed by the clean evaporator and the clean superheater, respectively; These heat-flow rates were determined for the clean boiler (after cleaning the walls of the combustion chamber and superheaters tubes) at different steam mass-flow rates, $\dot{m}_{\text{s}}$, produced in the boiler. The symbol $\dot{Q}_{\text{sup}}$ denotes the heat-flow rate absorbed by the superheater. The coefficient ζ_{sup} can be used to determine of the superheater ash fouling degree [12], because the fouled superheater absorbs a lower heat-flow rate compared to the heat-flow rate absorbed by the clean superheater at the same live steam mass-flow. In the case of an evaporator, the factor ζ_{ev} is equal to one, regardless of whether the walls of the evaporator are slagged or not. This is because the same heat-flow rate must be delivered to the evaporator in order for the steam flow rate to be equal to $\dot{m}_{\text{s}}$. For this reason, the slagging degree of the furnace walls can be assessed on the basis of changes in time of the heat-flow rate absorbed by the evaporator or other indicators.

A determination in on-line mode of parameters characterizing the degree of fouling of the boiler combustion chamber walls and superheater tubes

The results are calculated in on-line mode and presented on a computer monitor, allowing controlling changes in selected parameters characterizing the degree of boiler fouling in time. The following figures show selected results of on-line calculations with a time step of 1 minute. The walls of the furnace were cleaned by using water blowers, which were activated at a time equal to t = 400 minutes and t = 2300 minutes. The superheaters were cleaned by using steam blowers, which were activated at the time equal to t = 1530 minutes. The results presented in fig. 11 show that the platen superheater located above the furnace of the boiler is fouled with slag and ash. After cleaning the platen superheater with steam blowers, the heat-flow rate absorbed by this superheater increases quickly. The changes in the waterwall heat efficiency coefficient, ψ, are shown in fig. 12. When the ψ value decreases, the flue gas tem-

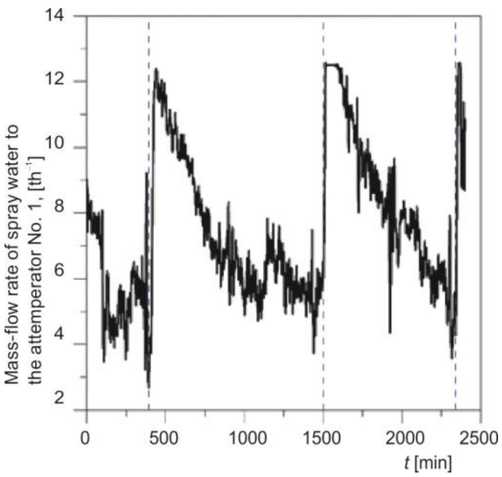

Figure 11. Changes in time of the mass-flow rate of spray water injected into the first attemperator

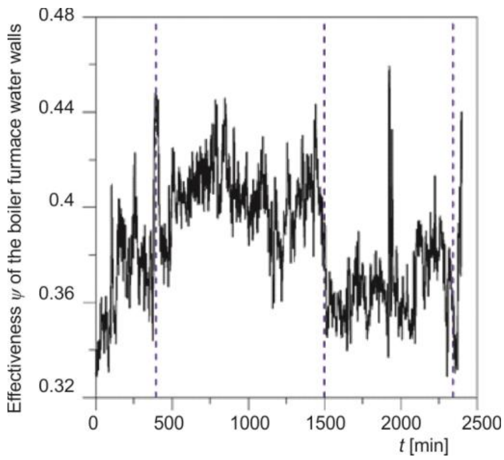

Figure 12. Changes in time of the waterwall heat efficiency coefficient, ψ

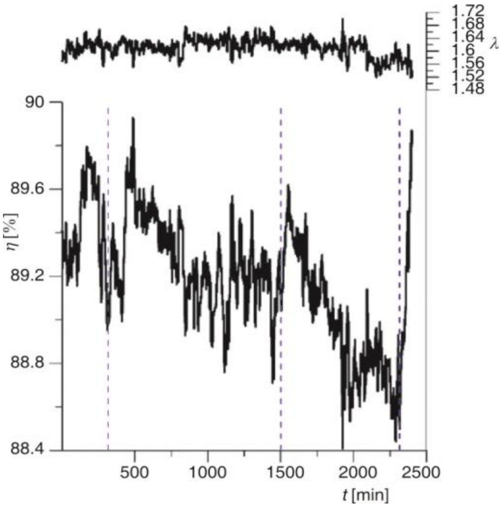

Figure 13. Changes in time of the excess air number and boiler efficiency

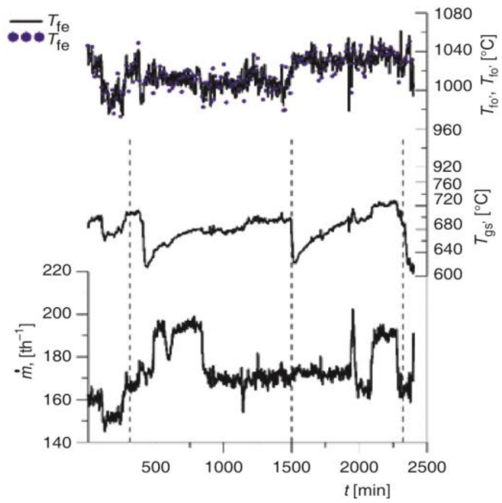

Figure 14. Changes in time of flue gas temperature, T_{fe}, and T'_{fe} at the exit from the combustion chamber, temperature T_{gs} after steam superheaters and steam mass-flow rate, $\dot{m}_s$

perature at the exit from the combustion chamber, T_{fe}, increases, fig. 14. After cleaning the walls of the furnace at t = 400 and t = 2300 minutes the water wall heat efficiency coefficient value increases. Figure 13 shows the changes in the excess air number, λ, at the outlet from the furnace and the boiler efficiency, η. It can be seen that after cleaning the walls of the combustion chamber and the surface of superheaters in time t = 400 minutes, the boiler efficiency after 1900 minutes decreases by about 1%. After the simultaneous cleaning of the chamber walls and superheaters' surface at t = 2300 minutes the boiler efficiency increases by about 1%.

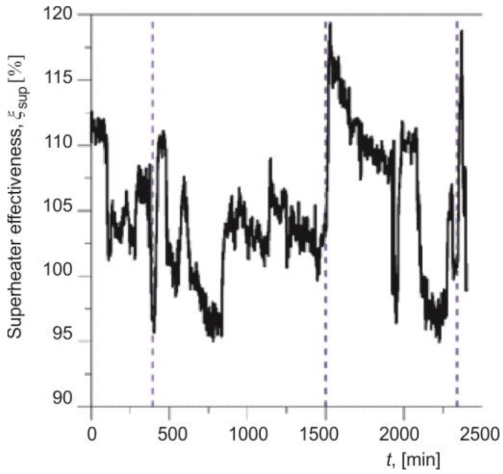

Figure 15. Changes of the heat absorption degree, ζ_{sup}, for the steam superheaters

Figure14 shows the time changes in the steam mass-flow rate, $\dot{m}_s$, and the time changes in the temperature of the flue gases T_{fe} and T'_{fe} at the outlet from the furnace. After cleaning the furnace walls at the time t = 400 and t = 2300 minutes the heat-flow rate absorbed by the evaporator increases, which increases the mass-flow of steam produced in the evaporator. Increasing the heat-flow rate transferred from the flue gas in the combustion chamber to the cleaned water walls lowers the temperature of the flue gas T_{fe} at the boiler outlet. It should be emphasized that the temperature of flue gas leaving the furnace T_{fe}, calculated based on the analysis of heat transfer in the combustion chamber, is well in accordance with the temperature calculated from the formula based on the flue gas temperature measured after the steam superheaters, fig. 14.

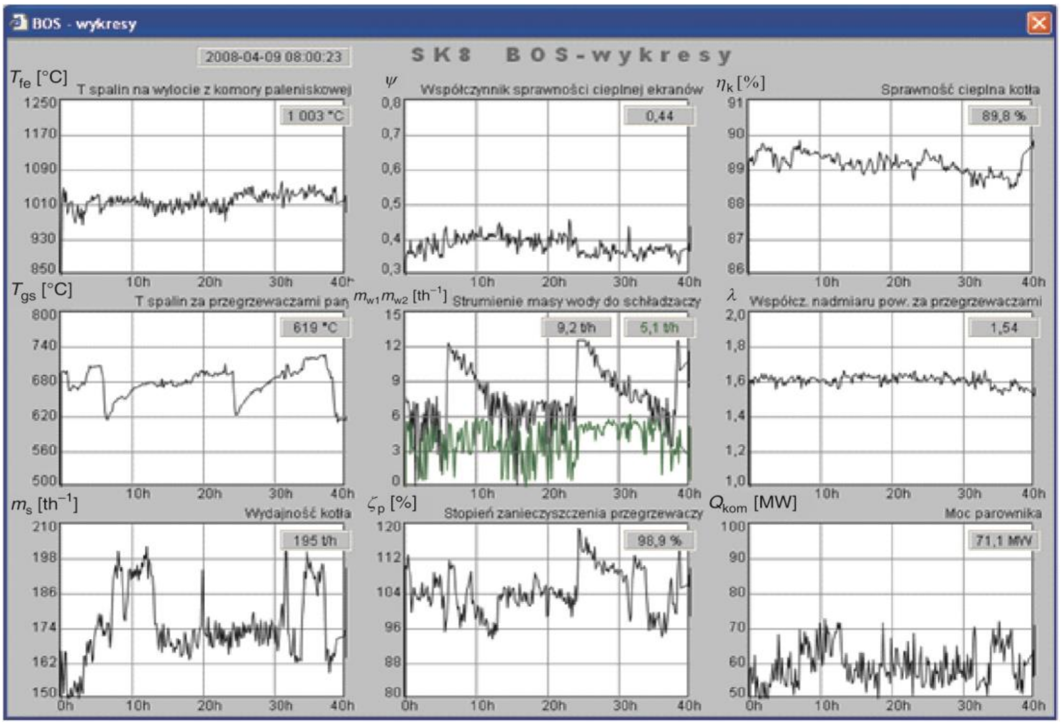

Figure 16. Calculation results presented on the monitor of the operator's station;
Explanation of descriptions: SKS BOS-wykresy – SKS BOS-diagrams, T. spalin na wylocie z komory paleniskowej - temperature of flue gas leaving the furnace, Współczynnik sprawności cieplnej ekranów - the water-wall heat efficiency coefficient, Sprawność cieplna kotła - thermal efficiency of the boiler, T. spalin za przegrzewaczami pary – flue gas temperature after steam superheaters, Strumienie masy wody do schładzaczy – mass-flow rates of spray water injected into the attemperators, Współczynnik nadmiaru powietrza - excess air number, Wydajność kotła - boiler output, Stopień zanieczyszczenia przegrzewaczy - fouling coefficient of the superheaters, Moc parownika - evaporator output

The heat absorption degree, ζ_{sup}, for the steam superheaters, fig.15, increases to a different degree depending on the efficiency of cleaning the surface of the superheater using steam blowers. A much higher increase in the ζ_{sup} coefficient is observed after cleaning the superheaters at a time t = 1530 and t = 2300 minutes. All calculation results are presented on the operator's station monitor, fig.16, in on-line mode and enable the boiler operator to activate water blowers in the furnace or steam blowers in superheaters at the right time, *i. e.* when the heating surfaces of the boiler are fouled.

Conclusions

The condition of the boiler characterized by clean walls of the combustion chamber and superheater is very important due to the high efficiency of the boiler and high mass-flow rate of steam produced in the boiler. The computer system for monitoring boiler operation, presented in the paper allows assessing the degree of fouling of the combustion chamber walls and convection surfaces of the boiler in on-line mode.

Slag and ash blowers are most often activated in fixed time cycles. The slag and ash blowers sequencing can be optimized on the basis of the actual state of fouling of the heating surfaces of the boiler, which is determined in on-line mode. Boiler cleaning only when needed will reduce water and steam consumption in slag and ash blowers and will increase the durability of superheater tubes and boiler waterwalls.

Computational modelling is an excellent way to optimize boiler design and performance [13, 14]. Implementation of the developed computer system in the systems of monitoring the operation of large power boilers will increase the efficiency of the boiler and thus reduce fuel consumption for the production of 1 kWh of electricity.

Nomenclature

$h'(p_d)$ – specific enthalpy of saturated water at drum pressure, [$\mathrm{Jkg^{-1}}$]
$h''(p_d)$ – specific enthalpy of saturated steam at drum pressure, [$\mathrm{Jkg^{-1}}$]
h_{fwc} – specific enthalpy of feed water, [$\mathrm{Jkg^{-1}}$]
h_{fwh} – specific enthalpy of feed water after economizer, [$\mathrm{Jkg^{-1}}$]
h_s – specific enthalpy of live steam at outlet of the boiler, [$\mathrm{Jkg^{-1}}$]
h_{ws} – specific enthalpy of spray-water in attemperators, [$\mathrm{Jkg^{-1}}$]
H_{LV} – net calorific value (lower heating value), [$\mathrm{Jkg^{-1}}$]
$\dot{m}_b$ – desalted and blowdown matter mass-flow rate, [$\mathrm{kgs^{-1}}$]
$\dot{m}_{\mathrm{F}}$ – fuel mass-flow rate, [$\mathrm{kgs^{-1}}$]
$\dot{m}_{\mathrm{fw}}$ – feed water mass-flow, [$\mathrm{kgs^{-1}}$]
$\dot{m}_{\mathrm{s}}$ – steam mass-flow rate, [$\mathrm{kgs^{-1}}$]
$\dot{m}_{\mathrm{w1}}$ – water mass-flow fed into water spray after the 1st stage superheater (attemperator No. 1), [$\mathrm{kgs^{-1}}$]
$\dot{m}_{\mathrm{w2}}$ – water mass-flow fed into water spray after the 2nd stage superheater (attemperator No. 2), [$\mathrm{kgs^{-1}}$]
$\dot{Q}_{\mathrm{ev}}$ – heat-flow rate transferred from flue gases to the evaporator via radiation and convection, [W]
$\dot{Q}_h$ – heat-flow rate delivered to the furnace with fuel and air, [W]
$\dot{Q}_l$ – heat losses, [W]
$\dot{Q}_n$ – heat-flow rate transferred to the working medium (water and steam), [W]
$\dot{Q}_{\mathrm{sup}}$ – heat-flow rate absorbed by the superheater, [W]
$\dot{Q}^0_{\mathrm{ev}}(\dot{m}_{\mathrm{s}})$ – heat-flow rate absorbed by the clean evaporator, [W]
$\dot{Q}^0_{\mathrm{sup}}(\dot{m}_{\mathrm{s}})$ – heat-flow rate absorbed by the clean superheater, W
S_i – losses, [–]
S_1 – stack loss, [–]
S_2 – loss caused by the presence of CO in flue gases, [–]
S_3 – loss resulting from the presence of a combustible fraction in fly ash, [–]
S_4 – loss resulting from the presence of a combustible fraction in slag, [–]
S_5 – radiation loss and other losses difficult to calculate, [–]
S_6 – losses of sensible heat in the slag and ash falling from the furnace walls, [–]

Greek symbols

η – thermal efficiency of the boiler, [–]
ψ – waterwall heat efficiency coefficient, [–]
ζ_{ev} – heat absorption degree for the evaporator, [–]
ζ_{sup} – heat absorption degree for the steam superheaters, [–]

References

[1] Wessel, B., *et al*., Operational Experience Gained with Unit K at the Niederaußem Power Plant, *VGB PowerTech, 11* (2006), pp. 47-51
[2] Taler, J., *et al*., An Assessment of Polish Power, *Modern Power Systems, 27* (2007), 5, pp. 13-17
[3] Balting, U., *et al*., Plasma Coatings against Corrosion and Abrasion on Pipes and Panels at Coal-Fired Power Plants, Biomass and Waste Incinerating Plants, *VGB PowerTech*, *11* (2006), pp. 74-79
[4] Savat, P., Operational Experiences in Co–Firing Coal and Different Biomass, *VGB PowerTech*, (2006), 11, pp. 79-83
[5] Cerri, G *et al*., Optimization of Cleaning Timing and Load Allocation in Steam Generator Managment, *Applied Thermal Engineering, 18* (1998), 3-4, pp. 763-775
[6] Taler, J., A Method of Determining Local Heat flux in Boiler Furnaces, *Brennstoff-Wärme-Kraft (BWK), 42* (1990), 5, pp. 269-277
[7] Taler, J., Taler, D., Tabular Type Heat Flux Meter for Monitoring Internal Scale Deposits in Large Steam Boilers, *Heat Transfer Engineering, 28* (2007), 3, pp. 230-239

[8] Taler, J., *et al*., Computer System for Monitoring Power Boiler Operation, *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *222* (2008), 1, pp. 13-24
[9] Neal, S. B. H. C., *et al*., The Measurement of Radiant Heat Flux in Large Boiler Furnances – II. Development of Flux Measuring Instruments, *International Journal of Heat Mass Transfer*, *23* (1980), 7, pp. 1023-1031
[10] Clyde, B., Slag Measurement Promises Better Sootblowing, *Modern Power Systems*, *24* (2004), 2, pp. 34-35
[11] Johnson, R., *et al.*, Superheater Fouling Monitor System, *Electric Power, 2004* (2004), Mar.-Apr., pp. 3-10
[12] Taler, D., *et al*., Numerical Simulation of Convective Superheaters in Steam Boilers, *International Journal of Thermal Sciences*, *129* (2018), Apr., pp. 320-333
[13] Raghavan, V., *Combustion Technology. Essentials of Flames Burners*, John Wiley and Sons Ltd., UK, 2016
[14] Ranade, V. V., Gupta, D. F., *Computional Modeling of Pulverized Coal Fired Boilers*, CRC Press, Taylor and Francis Group, Boca Raton, Fla., USA, 2015

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