

ASSESSMENT OF ASH FOULING AND SLAGGING IN COAL FIRED UTILITY BOILERS

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ABSTRACT

The mathematical model of a steam boiler has been developed, showing the influence of water-wall slagging and superheater fouling on the boiler performance. With traditional methods, operators often are not able to detect the critical build-up of deposits on the specific heating surfaces of the boiler. The mathematical model can be used as a boiler slagging and fouling simulator to monitor the boiler operation when the boiler heating surfaces become covered with ash deposits. In addition, the computer-based boiler performance system, presented in reference [1], has been implemented to provide a quantitative assessment of cleanliness of the surfaces in the furnace and the convective pass. Measurements of temperatures, pressures, flows, and gas composition are used to perform heat transfer analysis in the boiler furnace and evaporator. The on-line measurements of ash deposit loadings can be used to guide sootblower operations for the combustion chamber and steam superheaters. This contributes to the lowering of the medium usage in the sootblowers and an increase of the water-wall lifetime.

INTRODUCTION

When coal is burned, a relatively small portion of the ash will cause deposition problems. Due to the differences in deposition mechanisms involved, two types of high temperature ash deposition have been defined as slagging and fouling [2]. Sootblowers are the primary means of dealing directly with furnace wall slagging and convection pass fouling. At present, the alternative of blowing at preset times has little to commend it except convenience. Furnace-wall sootblowers are operated the most frequently of all types installed, typically between once a day and three times a shift. Clyde Bergemann has recently developed a strain-gauge based measurement system for slag deposits [3-4]. The system uses strain gauges to measure a load on the rods that suspend the pendant steam superheaters. The increased weight due to the build up of deposits causes the recorded strain to increase. Other procedures for monitoring and prediction of fouling in coal-fired steam boilers are described in [4-8]. They are used to perform heat transfer analysis in the furnace and convection section using heat and material

balances [1, 4-8]. For a given boiler, measured steam and water flow rates, flue gas and steam temperatures the cleanliness factors are varied until calculated and measured values converge. Local slagging and fouling at a particular location are detected by heat flux measurements using the sensors welded to the water-wall tubes or the heat flux tubes [4 - 9]. The system for monitoring the build-up of ash deposits in boiler furnaces and steam superheaters, which is presented in [1], has been operating at the Skawina Power Plant in Poland since 2007. Power boiler efficiency is calculated by an indirect method. The calculated saturated steam mass flow rate is adjusted to measured steam mass flow rate to calculate the average water-wall effectiveness η of a combustion chamber wall in an on-line mode. Heat absorption by the furnace walls ζ_f and by superheaters ζ_{sup} are also determined based on the measured data.

First, the furnace gas exit temperature and heat absorption rate by the furnace are calculated to determine the influence of the effectiveness of the furnace walls on the heat-transfer rate to the evaporator. Water-wall slagging in the furnace can cause a number of problems. Slag deposits reduce furnace heat absorption (water-wall effectiveness) and raise flue gas temperature at the furnace exit.

Then, the heat transfer in the convection pass is modeled using the Finite Volume Method (FVM). The effect of ash deposits on the superheater surfaces can be accounted for by assuming that high-temperature bonded deposits remain attached to the tube surfaces. The mathematical model of the boiler for simulation of slagged and fouled boiler heating surfaces can assist in quantifying the surface cleanliness and in training new staff about how to operate the steam boiler. Also, the results obtained by means of the developed computer system which provide a quantitative assessment of furnace and convective surface cleanliness, are presented.

SIMULATION OF FURNACE SLAGGING AND SUPERHEATER FOULING

A mathematical model of the steam boiler will be presented (Fig. 1) which takes into consideration ash deposits on the furnace walls and superheater surfaces.

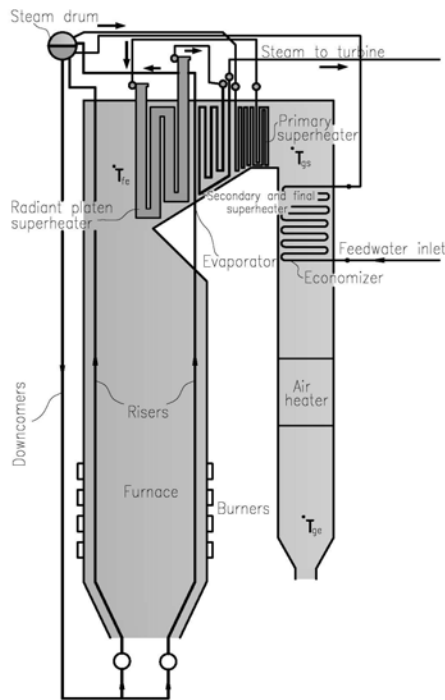


Fig. 1. 50 MW coal-fired utility boiler with steam flow rate of $210 \cdot 10^3$ kg/h: T_{fe} , T_{gs} , and T_{ge} denote flue gas temperatures at the furnace exit, after the superheaters and after the air heater, respectively.

Furnace wall slagging

The mass flow rate of live steam is determined in the on-line mode from mass and energy balance equations (Fig. 2). Combining the mass and energy balance equations, which are not included here, gives:

$$\begin{aligned} \dot{m}_s &= \frac{\dot{Q}_{ev}}{h''(p_d) - h_{fwh}} - \\ &\quad - \dot{m}_b \frac{h'(p_d) - h_{fwh}}{h''(p_d) - h_{fwh}} + \dot{m}_{w1} + \dot{m}_{w2} \end{aligned} \quad , \quad (1)$$

where $\dot{Q}_{ev}$ denotes rate of heat transferred by radiation and convection from combustion chamber to the surrounding water-walls.

Heat transfer rate $\dot{Q}_{ev}$ can be calculated from the expression:

$$\dot{Q}_{ev} = \dot{Q} - \dot{m}_g \cdot c_{p,g} \Big|_0^{T_{fe}} \cdot T_{fe}, \quad (2)$$

where $\dot{Q}$ is the heat transfer rate entering the combustion chamber with coal and air given by:

$$\dot{Q} = \dot{m}_g \cdot c_{p,g} \Big|_0^{T_{ad}} \cdot T_{ad}, \quad (3)$$

The adiabatic temperature of combustion T_{ad} expressed in °C is given by:

$$T_{ad} = \frac{\dot{m}_F (H_{LV} + h_F) + \dot{m}_a \cdot c_{p,a} \int_0^{T_a} \cdot T_a}{\dot{m}_g \cdot c_{p,g} \int_0^{T_{ad}}}, \quad (4)$$

The well stirred boiler furnace model is used to determine the flue gas temperature exiting the furnace.

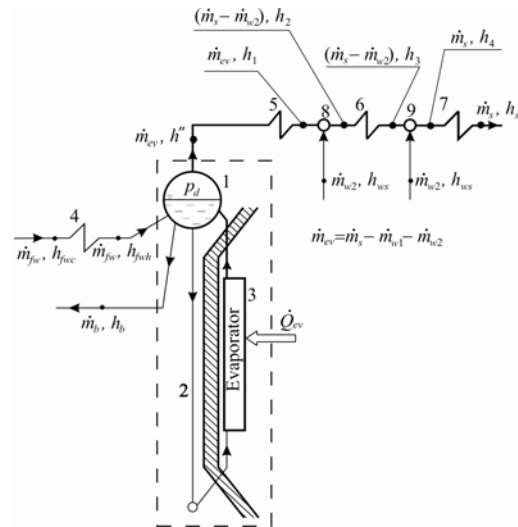


Fig. 2. Control volume for mass and energy balance of boiler evaporator: 1 - drum, 2 – downcomers, 3 – evaporator, 4 – economizer, 5 – 1st stage superheater, 6-2nd stage superheater, 7- final superheater, 8 - 1st stage superheater spray attemperator, 9 – 2nd stage superheater spray attemperator.

The rate of heat transfer $\dot{Q}_r$ transferred by radiation to the water-walls with the surface area A_w and temperature T_w can be calculated from the following expression:

$$\dot{Q}_r = \sigma \varepsilon_f \psi A_w T_{fl}^4, \quad (5)$$

where $\sigma=5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ is the Stefan-Boltzmann constant. Taking into account that $\dot{Q}_{ev} = \dot{Q}_r$ and substituting Eq. (3) and (5) into Eq. (2) gives:

$$\frac{T_{fe}}{T_{ad}} = 1 - \frac{\varepsilon_f}{Bo} \left(\frac{T_{fl}}{T_{ad}} \right)^4, \quad (6)$$

where Bo is the Boltzmann number defined as:

$$Bo = \frac{\dot{m}_g \bar{c}_{p,g}}{\sigma \psi A_w T_{ad}^3}. \quad (7)$$

where $\bar{c}_{p,g}$ is the mean specific heat at constant pressure over the temperature range $[T_{fe}, T_{ad}]$.

Based on extensive experimental results, the modified relation (6) is used for the outlet flue gas temperature T_{fe}/T_{ad} [7]:

$$\frac{T_{fe}}{T_{ad}} = \frac{1}{M \left(\frac{\varepsilon_f}{Bo} \right)^{0.6} + 1}, \quad (8)$$

where M is a parameter accounting for the kind of fuel (coal, oil or gas) and burners location.

The emissivity of the combustion chamber is given by:

$$\varepsilon_f = \frac{\varepsilon_{fl}}{\varepsilon_{fl} + (1 - \varepsilon_{fl})\psi}, \quad (9)$$

where ε_{fl} is the flame emissivity and ψ is the average water-wall effectiveness, which is defined as the ratio of the heat flow rate absorbed by the furnace water-walls to the incident heat flow rate. The water-wall effectiveness is defined as :

$$\psi = \frac{\dot{Q}_r}{\dot{Q}_{inc}} = \frac{\dot{q}_r A_w}{\dot{q}_{inc} A_w}, \quad (10)$$

where the heat flux $\dot{q}_r$, which is absorbed by the water-wall, is given by:

$$\dot{q}_r = \dot{q}_{inc} - [\varepsilon_z \sigma T_z^4 + (1 - \varepsilon_z) \dot{q}_{inc}] = \varepsilon_z \dot{q}_{inc} - \varepsilon_z \sigma T_z^4 \quad (11)$$

The water-wall effectiveness ψ takes into account the conductive and radiative heat transfer in the deposit layer, which influences the temperature of the deposit surface T_z appearing in Eq. (11). Varying the effectiveness ψ we can simulate slagging of the furnace walls.

Simulation of superheater fouling

To study the impact of superheater fouling on flue gas and steam temperatures, a numerical model of the entire superheater, has been developed. It was assumed that the outer tube surfaces are covered with bonded ash deposits with a uniform thickness. The temperature of the flue gas, tube walls, and steam were determined using the Finite Volume Method (FVM) [10]. The individual stages of the superheater were modeled as cross-parallel-flow or cross-counter-flow heat exchangers. As an example, the numerical model of a platen superheater will be presented in detail (Figs. 1 and 3). The platen superheater is a pendant four-pass heat exchanger. There are fourteen platens situated at the exit of the boiler combustion chamber at the distance of $s_f = 0.52$ m to each other (Fig. 1). The superheated steam and the combustion products flow at right angles to each other. The platen superheater can be classified according to flow arrangement as a parallel-cross-flow heat exchanger. Each individual platen consists of thirteen tubes through which superheated steam flows parallel. The division of the pendant superheater into control volumes is shown in Fig. 3.

In the following, finite volume heat balance equations will be formulated for the steam, the tube wall, and the flue gas. A steam side energy balance for the i th finite volume gives (Fig. 4):

$$\begin{aligned} & \dot{m}_s c_{ps} \Big|_{T_{s,i}}^{T_{s,i+1}} T_{s,i} + \pi d_{in} \Delta x \alpha_s \times \\ & \times \left(T_{w1,i} - \frac{T_{s,i} + T_{s,i+1}}{2} \right) = \dot{m}_s c_{ps} \Big|_0^{T_{s,i+1}} T_{s,i+1} \end{aligned} \quad (12)$$

Rearranging Eq. (12) gives

$$\begin{aligned} & \dot{m}_s c_{ps} \Big|_{T_{s,i}}^{T_{s,i+1}} (T_{s,i+1} - T_{s,i}) = \\ & = \Delta A_{in} \alpha_s \left(T_{w1,i} - \frac{T_{s,i} + T_{s,i+1}}{2} \right), \end{aligned} \quad (13)$$

where the mesh tube inner surface is

$$\Delta A_{in} = \pi d_{in} \Delta x. \quad (14)$$

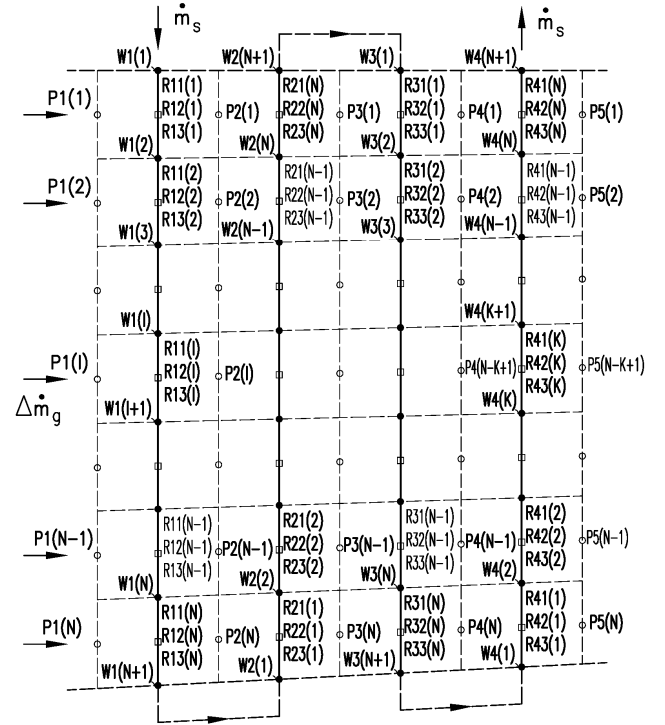


Fig. 3. Division of cross-parallel-flow platen superheater with four passes into finite volumes: P1(I), P2(I), P3(I), P4(I), P5(I) – flue gas temperature, R11(I), R12(I), R13(I), ... , R41(I), R42(I), R43(I) – temperature of the inner and outer tube surfaces, and the outer temperature of the ash deposit, respectively, W1(I), W2(I), W3(I), W4(I) – steam temperature.

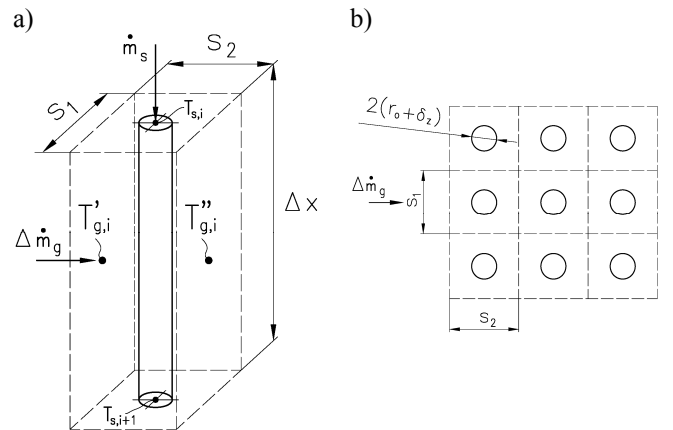


Fig. 4. Finite volume for energy balance on the steam and gas sides (a) and in-line array of superheater tubes (b).

The steam average specific heat at constant pressure is given by

$$c_{ps} \Big|_{T_{s,i}}^{T_{s,i+1}} \approx \frac{c_{ps}(T_{s,i}) + c_{ps}(T_{s,i+1})}{2} = \bar{c}_{ps,i} . \quad (15)$$

After rewriting Eq. (13) in the form

$$T_{s,i+1} = \frac{\alpha_s \Delta A_{in} T_{w1,i} + T_{s,i}}{\dot{m}_s \bar{c}_{ps,i} + \frac{1}{2} \alpha_s \Delta A_{in}} \times \left(\dot{m}_s \bar{c}_{ps,i} T_{s,i} - \frac{1}{2} \alpha_s \Delta A_{in} \right) \quad i = 1, \dots, N, \quad (16)$$

the Gauss-Seidel method can be applied for an iterative solving nonlinear set of algebraic equations (16).

Introducing the mesh number of transfer units for the steam:

$$\Delta N_{s,i+\frac{1}{2}} = \frac{\alpha_s \Delta A_{in}}{\dot{m}_s \bar{c}_{ps,i}} = \frac{2 \alpha_s \Delta A_{in}}{\dot{m}_s [c_{ps}(T_{s,i}) + c_{ps}(T_{s,i+1})]} \quad (17)$$

and dividing Eq. (17) by $\dot{m}_s \bar{c}_{ps,i}$, we have:

$$T_{s,i+1} = \frac{1}{1 + \frac{1}{2} \Delta N_{s,i+\frac{1}{2}}} \times \left[\left(1 - \frac{1}{2} \Delta N_{s,i+\frac{1}{2}} \right) T_{s,i} + \Delta N_{s,i+\frac{1}{2}} T_{w1,i} \right], \quad i = 1, \dots, N \quad (18)$$

where: $\Delta x = L_r / N$ - the mesh size, L_r - the tube length.

The energy conservation principle for the flue gas applied for the finite control volume (Fig. 4) is:

$$\Delta \dot{m}_g c_{pg} \Big|_0^{T'_{g,i}} T'_{g,i} = \Delta \dot{m}_g c_{pg} \Big|_0^{T''_{g,i}} T''_{g,i} + \pi (2r_o + 2\delta_z) \Delta x \alpha_g \left(\frac{T'_{g,i} + T''_{g,i}}{2} - T_{z,i} \right) \quad (19)$$

After rearranging Eq. (19), we obtain:

$$\Delta \dot{m}_g \bar{c}_{pg,i} (T'_{g,i} - T''_{g,i}) = \Delta A_z \alpha_g \left(\frac{T'_{g,i} + T''_{g,i}}{2} - T_{z,i} \right) \quad (20)$$

where the mesh outer surface of deposits is (Fig. 5):

$$\Delta A_z = \pi (2r_o + 2\delta_z) \Delta x . \quad (21)$$

The flue gas average specific heat at constant pressure is given by:

$$\bar{c}_{pg,i} = \frac{c_{pg}(T'_{g,i}) + c_{pg}(T''_{g,i})}{2} . \quad (22)$$

Equation (20) can be written as:

$$T''_{g,i} = \frac{\left(\Delta \dot{m}_g \bar{c}_{pg,i} - \frac{1}{2} \alpha_g \Delta A_z \right)}{\Delta \dot{m}_g \bar{c}_{pg,i} + \frac{1}{2} \alpha_g \Delta A_z} \times (T'_{g,i} - \alpha_g \Delta A_z T_{z,i}) \quad (23)$$

Introducing the mesh number of transfer units for the gas:

$$\Delta N_{g,i+\frac{1}{2}} = \frac{\alpha_g \Delta A_z}{\Delta \dot{m}_g \bar{c}_{pg,i}} = \frac{2 \alpha_g \Delta A_z}{\Delta \dot{m}_g [c_{pg}(T'_{g,i}) + c_{pg}(T''_{g,i})]} \quad (24)$$

and dividing Eq. (24) by $\dot{m}_g \bar{c}_{pg,i}$ we obtain:

$$T''_{g,i} = \frac{1}{1 + \frac{1}{2} \Delta N_{g,i+\frac{1}{2}}} \times \left[\left(1 - \frac{1}{2} \Delta N_{g,i+\frac{1}{2}} \right) T'_{g,i} - \Delta N_{g,i+\frac{1}{2}} T_{z,i} \right], \quad i = 1, \dots, N. \quad (25)$$

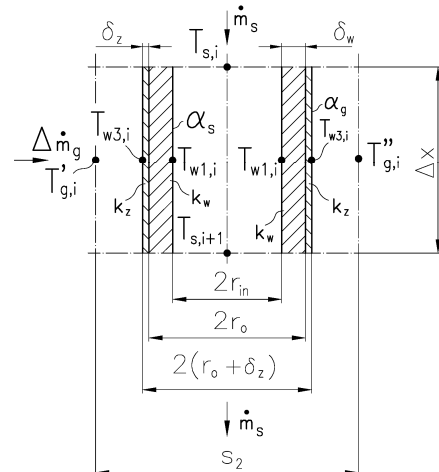


Fig. 5. Tube wall with a layer of deposits at the outer tube surfaces.

Subsequently, energy conservation equations for the tube wall (Fig. 5) will be written. The tube wall and the deposit layer are divided into three finite volumes (Fig. 6).

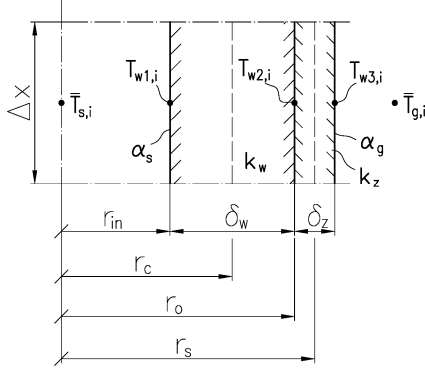


Fig. 6. Division of the tube wall and deposit layer into three control volumes.

Energy conservation equations may be written as:

- node 1

$$\alpha_s (\bar{T}_{s,i} - T_{w1,i}) \pi d_{in} + \frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{T_{w2,i} - T_{w1,i}}{\delta_w} \pi d_c = 0, \quad (26)$$

where: $d_c = (d_{in} + d_o)/2 = r_{in} + r_o$, $\bar{T}_{s,i} = \frac{T_{s,i} + T_{s,i+1}}{2}$.

- node 2

$$\frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{T_{w1,i} - T_{w2,i}}{\delta_w} \pi d_c + k_z \frac{T_{w3,i} - T_{w2,i}}{\delta_z} \pi d_s = 0, \quad (27)$$

where: $d_s = d_o + \delta_z = 2r_o + \delta_z$.

- node 3

$$\alpha_g (\bar{T}_{g,i} - T_{w3,i}) \pi (d_o + 2\delta_z) + k_z \frac{T_{w2,i} - T_{w3,i}}{\delta_z} \pi d_s = 0. \quad (28)$$

Algebraic equations (26) – (28) can be rewritten in a form which is suitable for solving equation sets by using the Gauss – Seidel method:

$$T_{w1,i} = \frac{1}{\alpha_s d_{in} + \frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{d_c}{\delta_w}} \times \left[\alpha_s \bar{T}_{s,i} d_{in} + \frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{d_c}{\delta_w} T_{w2,i} \right], \quad (29)$$

$$T_{w2,i} = \frac{1}{\frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{d_c}{\delta_w} + \frac{k_z}{\delta_z} d_s} \times \left[\frac{k_w (T_{w1,i}) + k_w (T_{w2,i})}{2} \frac{d_c}{\delta_w} T_{w1,i} + k_z \frac{d_s}{\delta_z} T_{w3,i} \right], \quad (30)$$

$$T_{w3,i} = \frac{1}{\left[\alpha_g (d_o + 2\delta_z) + k_z \frac{d_s}{\delta_z} \right]} \times \left[\alpha_g (d_o + 2\delta_z) \bar{T}_{g,i} + k_z \frac{d_s}{\delta_z} T_{w2,i} \right], \quad (31)$$

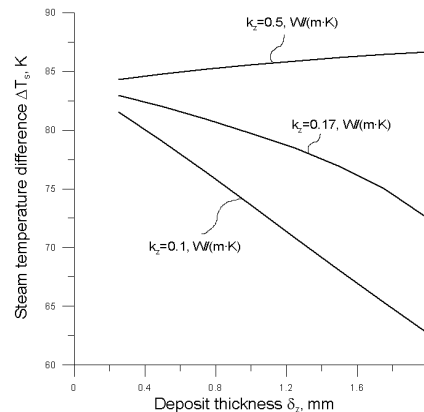
Equations (29) – (31) can be used for building mathematical models of steam superheaters.

To solve Eqs. (18), (25) and (29) – (31) two boundary conditions are prescribed: inlet steam temperature $T_{s,in}$ and flue gas temperature T_{fe} before the superheater, e.g. (Fig. 3):

$$W1(1) = T_{s,in} \text{ and } P1(I) = T_{fe}, I = 1, \dots, N. \quad (32)$$

The convective heat transfer coefficient at the tube inner surface α_s and the heat transfer on the flue gas side α_{cg} were calculated using correlations given in [12]. The effect of radiation on the heat transfer coefficient α_g at the external tubes is accounted for by adding the radiation heat transfer coefficient α_{rg} [11] to the convective heat transfer, e.g. $\alpha_g = \alpha_{cg} + \alpha_{rg}$. Figure 7 illustrates the predictions of the mathematical model assuming arbitrary but reasonable thermal conductivities of the deposits and a range of deposit thicknesses. The calculations are based on the following data: $d_o = 0.032m$, $d_{in} = 0.024m$, $T_{fe} = 1125^\circ C$, $T_{s,in} = 374^\circ C$, $\dot{m}_s = 51 kg/s$, $\dot{m}_g = 66.4 kg/s$. It can be seen from the inspection of the code output shown in Fig. 7 that the fouling layer is predicted to have a great influence on the steam and flue gas temperatures with the exception of the high thermal conductivity of the deposits.

a)



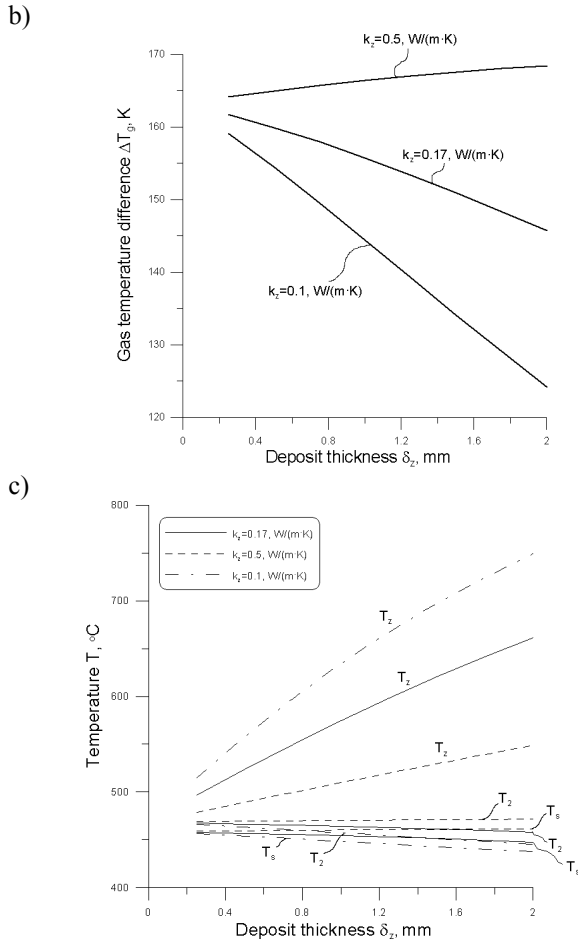


Fig. 7. Influence of the deposit layer at the outer surface of the platen superheater tubes on the increase of steam temperature in the superheater (a), flue gas temperature drop over the superheater (b), and temperature of the outer surfaces of the tube and deposit layer at the superheater exit. With an increasing ash deposit layer the heat flow rate from the flue gas to the steam grows since the heat transfer surfaces goes up under the condition that the thermal conductivity of the ash deposits is high. When the thermal conductivity of ash deposits is low, then the temperature of deposits increases significantly with deposit growth what results in a reduction of heat transfer between the flue gas and steam.

The measured steam temperature increase in the fouled platen superheater is: $\Delta T_s = 66.6 \text{ K}$.

MONITORING OF THERMAL – HYDRAULIC OPERATING CONDITIONS

The following will be discussed: the determination of boiler efficiency, fuel and live steam mass flows, and the furnace wall effectiveness.

The computer based boiler performance system, presented in this paper, has been developed to provide a direct and quantitative assessment of furnace and convective surface cleanliness. Measurements of temperatures, pressures, flows, and gas analysis data are used to perform heat transfer analysis in the furnace and convective pass on a bank by bank basis. With a quantitative indication of

surface cleanliness, selective sootblowing can be directed at a specific problem area. Sootblower sequencing can be optimized based on actual cleaning requirements rather than on fixed time cycles which can waste blowing medium, increase cycle time and cause erosion by blowing clean tubes. The boiler monitoring system is also incorporated to provide details of changes in boiler efficiency and operating conditions following sootblowing, so that the effects of a particular sootblowing sequence can be analyzed and optimized later.

Boiler efficiency

Boiler efficiency is calculated in on-line mode. The boiler operator can observe time changes of the boiler efficiency and change the selected parameters, for example, the mass flow of the air supplied to the boiler furnace to enhance the efficiency. Two different techniques for determining the thermal efficiency of the boiler were developed. The first is based on the calorific value of coal, and the second on the ultimate chemical analysis of coal on “as received” basis. The ultimate analysis specifies, on a mass basis, the relative amounts of carbon, sulfur, hydrogen, nitrogen, oxygen, ash, and the relative amounts of moisture. The thermal efficiency of the boiler is determined using an indirect method

$$\eta = 1 - \sum_{i=1}^n S_i \quad (33)$$

where the dimensionless losses S_i denote:

S_1 -dry flue gas loss, S_2 -loss due to CO content in flue gas (unburned gas loss), S_3 -combustible in pulverized-fuel ash, S_4 -combustible in furnace bottom ash, S_5 -radiation and unaccounted loss, S_6 -sensible heat loss in furnace bottom ash. In addition, twenty thermocouples are installed in four tubular type heat flux meters [9] for monitoring thermal effects of outer and inner scale deposits at water-walls. These meters were placed at four different elevations along the height of the combustion chamber. The heat flux meters are used to measure local effects of the slag deposits. The tubular heat flux meters [9] are very useful instruments for monitoring local slagging in spite of the fact that they can affect the local heat transfer and fouling. If local heat flux meters are installed in the regions where local slagging occurs, e.g. near the burner mouth, they immediately indicate the build-up of slag.

Fuel mass flow rate at steady-state conditions

Based on the boiler efficiency evaluated in on-line mode, a coal mass flow rate will be determined from the definition of the boiler thermal efficiency (Fig. 2):

$$\eta = \frac{\dot{Q}_h}{\dot{Q}_f} = \frac{(\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2})(h_s - h_{fvc})}{\dot{m}_f H_{LV}} + \frac{(\dot{m}_{w1} + \dot{m}_{w2})(h_s - h_{ws}) + \dot{m}_b(h' - h_{fvc})}{\dot{m}_f H_{LV}} \quad (34)$$

After simple transformations of Eq. (34), we have

$$\dot{m}_F = \frac{(\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2})(h_s - h_{fwc})}{\eta H_{LV}} + \frac{(\dot{m}_{w1} + \dot{m}_{w2})(h_s - h_{ws}) + \dot{m}_b(h' - h_{fwc})}{\eta H_{LV}} \quad (35)$$

The symbols: h_{fwc} , h'' , h_b , h_{fwb} , h_{ws} , h_s in equations (34) and (35) denote enthalpy of: feed-water, saturated steam at drum pressure, blow-down water, feed-water after the economizer, spray-water in attemperators, and live steam at outlet of the boiler, respectively (Fig. 2).

Calculating the ratio of actual air flow to theoretical air flow λ , from the expression $\lambda = 21 / (21 - O_2)$, the mass and volumetric flows of humid flue gas are calculated. Equation (35) is valid only for steady-state conditions.

Slagging of furnace waterwalls and fouling of superheaters

The heat absorption by the evaporator and superheater is monitored by calculating the following factors in on-line mode

$$\zeta_{ev} = \frac{\dot{Q}_{ev}}{\dot{Q}_{ev}^0(\dot{m}_s)}, \quad (36)$$

$$\zeta_{sup} = \frac{\dot{Q}_{sup}}{\dot{Q}_{sup}^0(\dot{m}_s)}, \quad (37)$$

The symbols $\dot{Q}_{ev}^0(\dot{m}_s)$ and $\dot{Q}_{sup}^0(\dot{m}_s)$ stand for heat flow rates absorbed by the clean evaporator and clean superheaters, respectively [1]. Since the factor ζ_{ev} is independent of slagging degree, it should be constant provided the steam mass flow rate $\dot{m}_s$ does not change in time. The heat flow rates $\dot{Q}_{ev}$ and $\dot{Q}_{sup}$ are determined using the measured data from the following expressions (Fig. 2)

$$\dot{Q}_{ev} = (\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2})h''(p_d) + \dot{m}_b h'(p_d) - \dot{m}_{fw} h_{fwh} \quad (38)$$

$$\dot{Q}_{sup} = (\dot{m}_s - \dot{m}_{w1} - \dot{m}_{w2})[h_1 - h'(p_d)] + (\dot{m}_s - \dot{m}_{w2})(h_3 - h_2) + \dot{m}_s(h_5 - h_4) \quad (39)$$

The existing sootblower system is traditionally activated in response to an increase in flue gas temperature T_{gs} after the steam superheaters, as noted by the operator. This kind of sootblower operation can result in blowing when it is not necessary, wastes blowing water or steam and can erode tubes. On the other hand, based on the measured temperature T_{gs} , the temperature of the flue gas T'_{fe} at the furnace outlet can be calculated and compared to the flue gas temperature T_{fe} obtained from the calculations of the combustion chamber. The temperature T'_{fe} of the flue gas leaving the furnace is given by

$$T'_{fe} = T_{gs} + \frac{\dot{Q}_{sup}}{\dot{m}_g c_{p,g} \Big|_{T_{gs}}^{T'_{fe}}}, \quad (40)$$

where $c_{p,g} \Big|_{T_{gs}}^{T'_{fe}}$ is the mean specific heat capacity of the flue gas. The temperatures T_{fe} and T'_{fe} should be equal if the measurements and calculation methods are accurate.

Mass flow rate of live steam and furnace wall effectiveness at steady - state conditions

The effectiveness of the water-walls ψ is estimated in the on-line mode from the following nonlinear equation:

$$\dot{m}_s^m = \dot{m}_s^c(\psi), \quad (41)$$

where $\dot{m}_s^m$ and $\dot{m}_s^c$ are measured and calculated steam mass flow rates, respectively. The mass flow rate $\dot{m}_s^c$ is calculated using Eq. (1) as a function of the water-wall effectiveness ψ . The symbol $\dot{m}_s^m$ stands for measured flow rate with the orifice plate at the outlet of the boiler.

RESULTS

The computer-based on-line system for monitoring boiler performance, described above, has been installed on a power boiler of $210 \cdot 10^3$ kg/h capacity. The boiler is fired by a mixture of the pulverized coal and biomass. The results are calculated in on-line mode and presented graphically, enabling selected parameters to be monitored continuously for several hours. Selected results obtained by means of the developed monitoring system are shown in Figs. 8-13. The measurement data and evaluation results are plotted over the time period of 40 hours. The furnace water-walls and superheaters were cleaned simultaneously at times 400 min and 2300 min, whereas the sootblowers of the superheaters were activated at time 1530 min. Vertical lines in figures indicate when water lancing and sootblowing or only sootblowing were initiated. It can be seen from the analysis of the results presented in Figs 8-13 that slag deposits built up on the platen superheater and water-wall surfaces. Presented results show the effectiveness of the developed system in detecting deposits early enough to remove them before they reduce boiler efficiency or cause damage. The cleaning of the superheaters results in a sudden increase of water mass flow rate $\dot{m}_{w1}$ into the attemperator situated before the platen superheater, after the first stage convective superheater (Fig.8a). The increase of the mass flow rate of the water injected into the second stage attemperator after the sootblowing is not affected so strongly because of a lower flue gas temperature (Fig. 8b). In the region of convective superheaters the amount of ash deposited on the tube surfaces is smaller. The fouling results in a loss of boiler efficiency. When the sootblowers are operated the boiler efficiency increases (Fig. 9). It can be seen that simultaneous water lancing of the furnace water-walls and the steam sootblowing of the superheaters (the first and third vertical line in Fig. 9) is much more effective in increasing the boiler efficiency than the removing of ash deposits only from the superheater surfaces (second vertical

line in Fig. 9). The cleaning of the furnace water-walls resulted in an increase of the water wall effectiveness ψ (Fig. 11) and heat flow rate $\dot{Q}_{ev}$ absorbed by the evaporator (Fig. 12). The effectiveness ψ , which is determined from Eq. (41), ranges from $\psi = 0.33$ to $\psi = 0.45$.

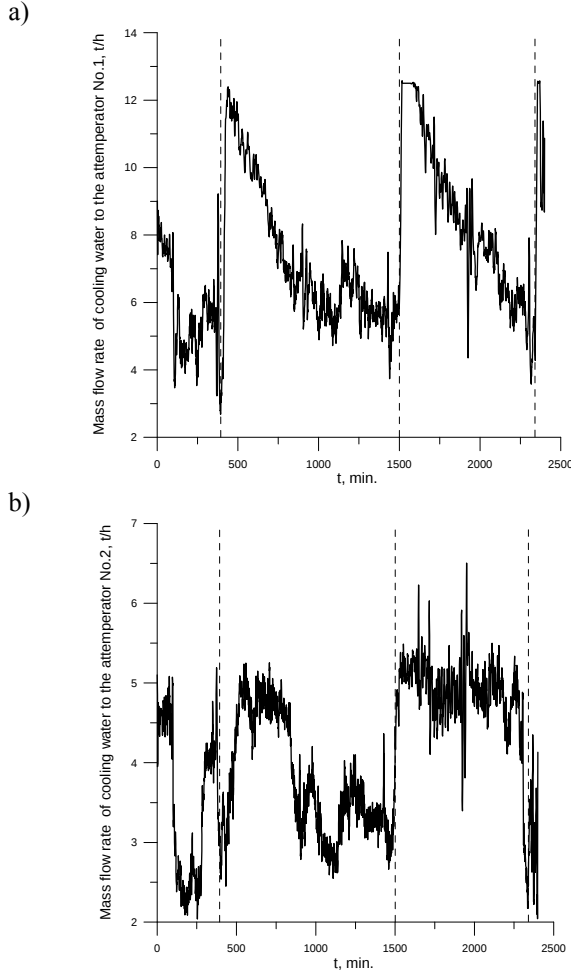


Fig. 8. Mass flow rate of spray water injected into attenuators before the pendant superheater (a) and the second stage of the convective superheater (b).

It is worth mentioning that for clean furnace water-walls of coal fired boilers, the water-wall effectiveness is $\psi = 0.45$ [12]. The temperature drops in flue gas temperature T_{gs} after the first stage superheater (Fig. 1) are observed after each sootblowing (Fig. 10). These flue gas temperature drops can be used in conjunction with other parameters as a trigger for the sootblower operation. Fig. 10 shows that the discrepancies between the temperature of the flue gas exiting the combustion chamber calculated according to Eq. (8) and Eq. (40) are small. When slag deposits had been removed from the water walls after water lancing the steam mass flow rate $\dot{m}_s$ from the evaporator became greater (Fig. 10), since heat flow rate from the combustion chamber to the clean water walls increased. Heat flow rates $\dot{Q}_{ev}^0$ and $\dot{Q}_{sup}^0$ absorbed by clean evaporator and clean steam superheaters, respectively, were determined for the excess air number $\lambda = 1.2$. When the coal and biomass mixture is

fired in the boiler, then the excess air number should be increased to $\lambda = 1.6$ to decrease the mass flow rate $\dot{m}_s$ of the saturated steam from the evaporator and to increase the heat absorption by the superheaters.

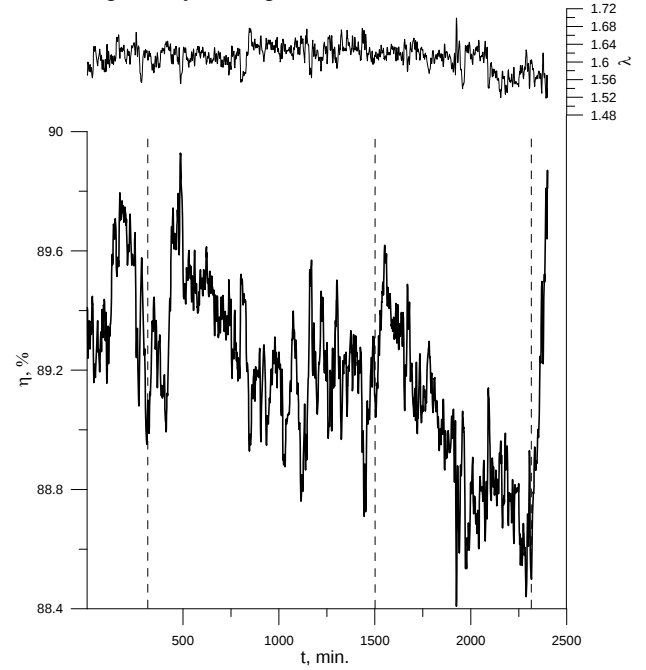


Fig. 9. Excess air number λ and boiler efficiency η .

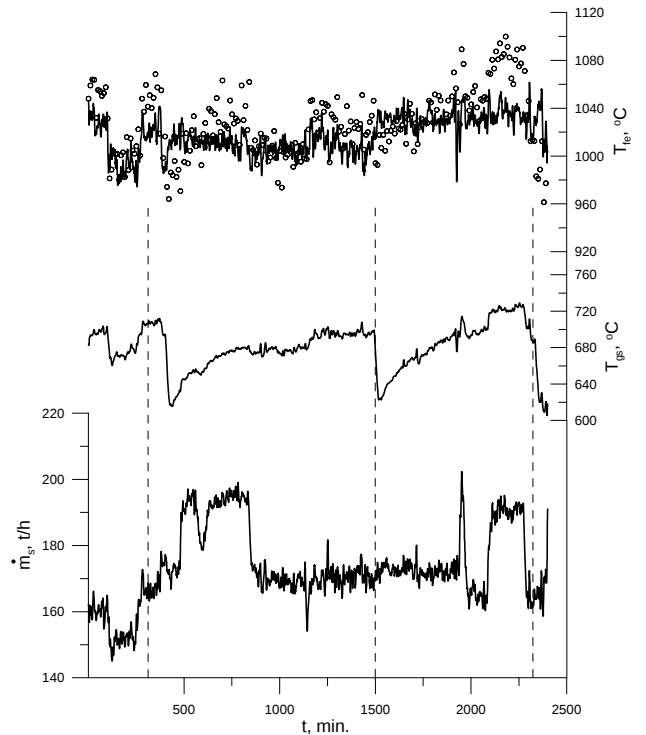
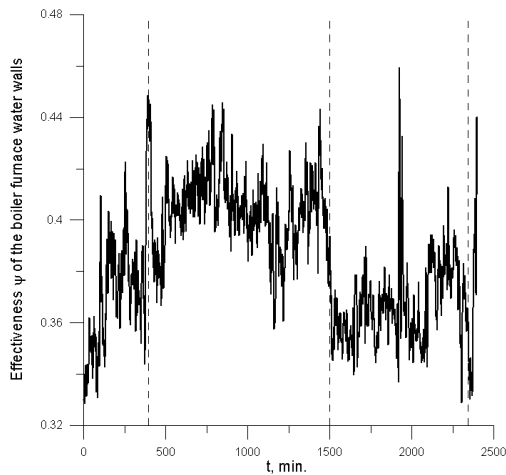
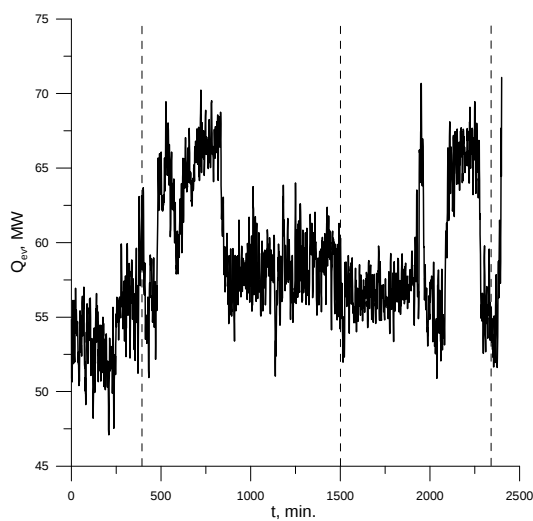
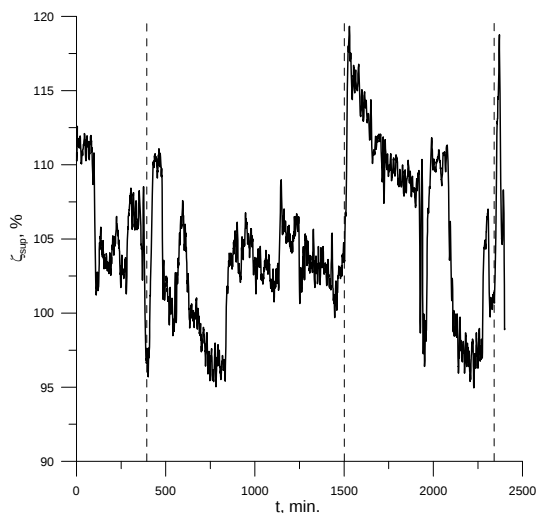


Fig. 10. Flue gas temperatures T_{fe} and T'_{fe} at the exit of the furnace, flue gas temperature T_{gs} after the steam superheaters, and steam mass flow rate $\dot{m}_s$; T'_{fe} - temperature calculated using Eq. (40), T_{fe} - temperature calculated using Eq. (8).

Fig. 11. Effectiveness ψ of the boiler furnace water walls.Fig. 12. Heat flow rate $\dot{Q}_{ev}$ absorbed by evaporator.Fig. 13. Heat absorption degree ζ_{sup} for the steam superheaters.

In this way the design value of the live steam temperature can be attained for the coal - biomass mixture with low calorific value. For this reason the heat absorption degree ζ_{sup} for the steam superheaters can be greater than 100

percent. The parameter ζ_{sup} can be used for early detection of the deposits on the superheater surfaces.



Fig. 14. Local slag deposit adjacent to the burner.

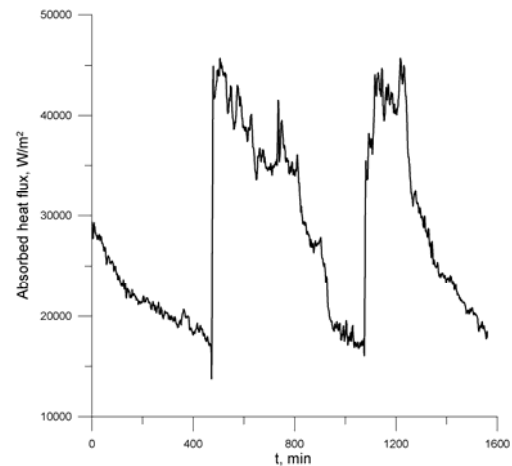


Fig. 15. Water-wall local heat flux indicated by the heat flux tube at an elevation of 23m.

Figure 13 shows noticeable increases in the heat absorption degree ζ_{sup} upon ending the sootblowing cycle. Local slagging (Figs. 14 and 15) is monitored by heat flux tubes. By knowing more precisely where slagging and fouling are beginning to occur, the operation of the sootblowing system can be adjusted to remove deposits before they become large enough to deteriorate a boiler's efficiency. The system developed can also be used for automatic operation of the sootblowers.

CONCLUSIONS

The mathematical model of a steam boiler has been developed to analyze water-wall slagging and superheater fouling. The computer based boiler performance monitoring system has been designed to perform thermal-hydraulic calculations of the boiler in on-line mode. Measurements of temperatures, pressure, flows, and gas analysis data are used to perform heat transfer analysis in the furnace and convection pass. The state of boiler slagging and fouling, including optimization of sootblowing, can be evaluated from practical plant measurements. The slag monitoring system can be used to detect the build-up of slag and ash deposits in boiler furnaces and steam superheaters and to guide sootblower operation. In order to raise the boiler efficiency and to reduce fuel cost, the sootblower can be run according to the information obtained from the developed system.

NOMENCLATURE

A	projected water-wall area, m^2 ,
Bo	Boltzmann number, dimensionless,
c_p	specific heat at constant pressure, $J/(kg \cdot K)$,
h	specific enthalpy, J/kg ,
H_{LV}	net calorific value (heating lower value), J/kg ,
k	thermal conductivity, $W/(m \cdot K)$,
$\dot{m}$	mass flow rate, kg/s ,
N	number of finite volumes on the pass length
p	pressure, Pa ,
$\dot{Q}$	heat flow rate, W ,
r	radius, m ,
S	heat loss, $\%$,
T	temperature, K or $^{\circ}C$,

GREEK SYMBOLS

α	heat transfer coefficient, $W/(m^2 \cdot K)$,
δ	thickness, m ,
Δx	control volume length, m ,
λ	ratio of actual air to theoretical air (excess air number)
$\Delta \dot{m}_g$	flue gas mass flow rate through , the control volume , kg/s ,
ΔN	number of transfer units for the control volume, dimensionless,
ε	emissivity, dimensionless,
ζ	heat absorption degree, dimensionless,
η	boiler efficiency, dimensionless,
ψ	water wall effectiveness, dimensionless,
ρ	density, kg/m^3 ,
σ	Stefan - Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8} \text{ W}/(m^2 \cdot K^4)$,

SUBSCRIPTS

a	air,
ad	adiabatic,
b	blowdown water,
d	steam drum,
e	furnace outlet,
ev	evaporator,
f	furnace,
fl	flame,
fw	feed water,
fwc	feed water before economizer,
fwh	feed water after economizer,
F	fuel,
g	flue gas,
in	inner,
inc	incident
o	outer,
s	steam,
sl	slag,
sup	superheater,
w	wall,
ws	water spray,
$w1$	spray water after the 1 st stage superheater,
$w2$	spray water after the 2 nd stage superheater,

$'$	saturated water or inlet temperature,
$''$	saturated steam or outlet temperature,
c	calculated,
m	measured,
z	outer surface of ash deposit,

REFERENCES

- [1] J. Taler, D. Taler, 2009, Slag monitoring system for combustion chambers and steam boilers, *Heat Transfer Engineering*, Vol.30, No. 10 – 11.
- [2] S. C. Stultz, J. B. Kitto, Editors, 1992, *Steam/Its Generation and Use*, The Babcock & Wilcox Company, Baberton, Ohio, U.S.A.
- [3] R. Johnson, B. Subasavage, Ch. Breeding, 2004, Superheater fouling monitor system, *Electric Power 2004*, Baltimore, Maryland, March 30 – April 1, , pp. 3 – 10.
- [4] St. Simon, M. Frach, B. Jochum, A. Lang, 2006, Increase of steam generator output firing coal qualities through new intelligent on – load cleaning technology, *VGB PowerTech*, Vol. 86, No. 11, pp. 40 – 45 (in German).
- [5] A. Paist, A. Poobus, T. Tiikma, 2002, Probes for measuring heat transfer parameters and fouling intensity in boilers, *Fuel*, Vol.81, pp. 1811 – 1818.
- [6] E. Teruel, C. Cortés, L.I. Diez, I. Arauzo, 2005, Monitoring and prediction of fouling in coal-fired using neural networks, *Chemical Engineering Science*, Vol. 60, pp. 5035 – 5048.
- [7] L.I. Diez, C. Cortés, A. Campo, 2005, Modelling of pulverized coal boilers: review validation of on-line simulation techniques, *Applied Thermal Engineering* Vol. 25, pp. 1516 – 1533
- [8] J. Taler, M. Trojan, 2008, Computer system for on – line assessment of fouling of boiler heating surfaces, *Energetyka*, Vol. 55, No. 10, pp. 675 – 679 (in Polish).
- [9] J. Taler, P. Duda, B. Węglowski, W. Zima, S. Grądziel, S. Sobota, D. Taler, 2009, Identification of local heat flux to membrane water-walls in steam boilers, *Fuel*, Vol. 88, pp. 305 – 311
- [10] D. Taler, 2002, *Theoretical and Experimental Analysis of Heat Exchangers with Extended Surfaces*, Polish Academy of Sciences, Cracow Branch, Vol. 25, Monograph 3 , Cracow, Poland.
- [11] D. Taler, J. Taler, 2009, Simplified analysis of radiation heat exchange in boiler superheaters, *Heat Transfer Engineering*, Vol. 30, No. 8, pp. 661 – 669
- [12] N. V. Kuznetsov, V.V. Mitor, I.E. Dubovskij, E.S. Karasina, Editors, 1973, *Standard Methods of Thermal Design for Power Boilers*, Central Boiler and Turbine Institute, Energiya, Moscow (in Russian).